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THE KAIPAROWITS REGION

A GEOGRAPHIC AND GEOLOGIC RECONNAISSANCE OF PARTS OF UTAH AND ARIZONA

BY

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INTRODUCTION

HISTORY AND SCOPE OF INVESTIGATIONS

In their traverse of the Colorado River and of the rim of the High Plateaus the members of the Powell Survey outlined a large area between the Henry Mountains and the Kaibab Plateau within which the Kaiparowits Plateau is the dominating feature. Difficulty of access, dry climate, scant vegetation, small water supplies, and complete absence of human population prevented a study of this region under the conditions then prevailing, and the trappers and prospectors who preceded and followed these early explorers were little interested in making detailed examinations of the sandstones that constitute most of the bedrock. Largely for these reasons the Kaiparowits region has long remained geologically unknown, and probably parts of it at least have been seen by white men only within the last 10 years. Geologic surveys within this unmapped area were needed for correlating the formations and structure with those in surrounding areas, and it seemed desirable to know more of the physical features—the soil, water, climate, and vegetation—as a guide in determining the use to which this area of largely unappropriated land might be put. Furthermore, the very fact that the existing knowledge of the region was meager made a strong appeal.

With these ideas in mind field work designed to cover those parts of southeastern Utah that had not been examined by scientific parties was begun by Gregory in 1915. During that year a pack-train traverse was made from Lees Ferry along the north wall of Glen Canyon and thence northeastward across the Kaiparowits Plateau, through a region unmarked by trails. From the head of Collett Wash the traverse was continued to Escalante, where supplies and additional horses were obtained, thence down the Escalante River, across the Waterpocket Fold, and through the Henry Mountains to the mouth of Trachyte Creek, where the Colorado was crossed by swimming the horses and ferrying the equipment on a makeshift raft. The work of the season ended with the traverse of White Canyon and the slopes of Abajo Mountain. The purposes of this exploration—to determine routes, to locate water holes, and to select areas where detailed geologic study could profitably be undertaken—were successfully accomplished. It was found that the stratigraphic formations previously mapped in the Navajo country extended with little change throughout southeastern Utah.

During the summer of 1918 the exploratory survey by Gregory was continued. After leaving Green River, Utah, on May 2, three weeks was spent in the study of stratigraphic sections at Temple Wash (San Rafael Swell), Pleasant Valley, Tantalus Valley, and along the Waterpocket Fold to the Colorado River at the mouths of Halls and Hanson Creeks. After crossing the Waterpocket Fold at Muley Twist, the next five weeks was devoted to an investigation of the physiography and stratigraphy of the Escalante Valley, the rim of Glen Canyon, and the Kaiparowits Plateau and the examination of the geologic features of the Paria, Wahweap, and Warm Creek Valleys at places not previously visited. In 1922, after completing investigations in the Kanab and Parunaweap Valleys, Gregory and L. F. Noble extended their geologic traverse of Nevada and western Utah to include the Paria Valley and the south side of the Kaiparowits Plateau. The top and the east end of the Kaiparowits Plateau were examined, and sections were measured at Canaan Peak, Henrieville, and Tropic. In 1924 Gregory spent two weeks in a study of Mesozoic and Tertiary strata along the eastern tributaries of the Paria River, and in 1925 and 1927 he extended the survey eastward across Glen Canyon to correlate the geographic and geologic features of the Kaiparowits region with those of southeastern Utah and southwestern Colorado.

Because of the possibility that the Circle Cliffs region might contain oil pools, Moore was assigned to stratigraphic and structural studies in this part of southern Utah for three months in the summer of 1921. Assisted by A. C. Tester and P. C. Benedict, he mapped the Circle Cliffs dome, a part of the Straight Cliffs front, the Harris Valley southeast of Escalante, and the Halls Valley from Muley Twist Creek to the Colorado River. In addition to fairly precise though rapid geologic and structural mapping, numerous stratigraphic sections were measured and some fossils were collected. A reconnaissance study was made of the Tertiary and Mesozoic formations north of Kanab, where the party outfitted, of the Kaibab Plateau southward to the rim of the Grand Canyon, and along the route across the Paunsaugunt Plateau to Tropic and Henrieville in the upper Paria Valley and to Escalante by way of the road south of the Table Cliff Plateau. A trip was made from the lower Halls Creek Valley to the point on the Colorado River where the Waterpocket Fold reached Glen Canyon. In the later part of the field season a small area of coal land was studied in southern Wayne County on the northwest slope of Mount Ellen, the most northerly and highest of the peaks in the Henry Mountains. After passing through the Pleasant Valley and Capitol Reef Wash the party proceeded by way of Fruita and Loa to Richfield.

Beginning early in June, 1922, Moore's work was continued in the Kaiparowits region, with the primary object of classifying a large territory in south-central Garfield and eastern Kane Counties that had been withdrawn as possible coal land. A. C. Tester and N. W. Bass were assistants. In general the work was similar to that of the previous year, but in addition a reconnaissance topographic map was prepared. (See pl. 1.)

Investigations were directed chiefly to the Cretaceous rocks of the Kaiparowits Plateau and a part of the upper Paria Valley, but the older and younger rocks were studied and mapped throughout most of the region. Field work terminated September 7.

In July, 1923, as geologist of the party engaged in mapping the Colorado River in the Grand Canyon, Moore had opportunity to study the rock formations in the Lees Ferry area.

Although the work of Gregory was primarily a geographic and stratigraphic reconnaissance, and that of Moore consisted of basic studies for possible future economic development, the conditions that governed the work permitted both investigators to make observations relating to all subdivisions of geology. Parts of the area were studied by both geologists. Under these circumstances the results of the field studies may properly appear as a single report under joint authorship.

The authorship of the paper has been divided as follows: Chapter 1 and the sections on the Triassic, Jurassic, and Tertiary in chapter 2 have been written mainly by Gregory. Chapter 3 and the sections on the pre-Triassic and Cretaceous in chapter 2 have been written mainly by Moore, and the base map, geologic map, structure map, and geologic sections have been prepared under his direction. Chapters 4 and 5 represent a combination of manuscripts by both authors. This subdivision of work has been adopted for convenience only. The authors share responsibility equally for the observations recorded and the opinions expressed.

These investigations in the Kaiparowits region are by no means exhaustive. Much of the work is reconnaissance—some of it exploratory—but the text and maps should fairly well present the major features of the geography and geology of this interesting part of the Colorado plateaus.

PREVIOUS WORK

After the termination of the Powell and Wheeler surveys (see p. 7) a quarter of a century passed before the region that borders Glen Canyon became a field for geologic study.

In 1900 a party consisting of Tempest Anderson, R. L. Barrett, W. M. Davis, Richard E. Dodge, and Herbert E. Gregory visited Lees Ferry on their way from Flagstaff, Ariz., to Toquerville, Utah. Studies made by them of the physiographic features of Echo Cliffs and the Paria Plateau are recorded by Davis.[1] Lees Ferry was again visited by Johnson[2] and Shimer[3] in 1906.

In 1913 Lawson[4] published a paper on the economic aspects of the "Shinarump clays" (Chinle formation of present nomenclature) near the settlement of Paria, and brief notes on the coal at Escalante and Warm Creek and the placer gold along Glen Canyon have appeared in engineering and mining journals. With these exceptions, no geologic studies had been made in the Kaiparowits region prior to the field work on which the present report is based. On the borders of the area exploratory surveys and detailed reconnaissance surveys had been made, and for a large part of the area the atlas sheets of the Wheeler and Powell surveys, which indicate the supposed extension eastward of the geologic formations represented in the High Plateaus, are available.

[1] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zoology Bull., vol. 38 (geol. ser., vol. 5), pp. 107–198, 1901.

[2] Johnson, D. W., Report on the geological excursion through New Mexico, Arizona, and Utah, summer of 1906: Tech. Quart., vol. 19, pp. 408–415, 1906.

[3] Shimer, H. W., Permo-Carboniferous of northwestern Arizona: Geol. Soc. America Bull., vol. 30, pp. 477–479, 1919.

[4] Lawson, A. C., The gold in the Shinarump at Paria: Econ. Geology, vol. 8, pp. 434–448, 1913.

Since the beginning of the field studies on which the present report is based, twenty papers[5] that relate directly to this region have appeared. Several papers relating to bordering areas in which the stratigraphic sequence is closely similar to that of the Kaiparowits region have also been published.[6]

The papers by Noble, Reeside and Bassler, Gilluly and Reeside, and that published under the joint authorship of Longwell, Miser, Moore, Bryan, and Paige are of particular value for comparative studies.

[5] 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, 1925. Moore, R. C., Stratigraphy of a part of southern Utah: Am. Assoc. Petroleum Geologists Bull., vol. 6, pp. 199–227, 1922. Bryan, Kirk, Wind erosion at Lees Ferry: Am. Jour. Sci., 5th ser., vol. 6, pp. 291–307, 1923. Gregory, H. E., and Noble, L. F., Notes on a geological traverse from Mojave, Calif., to the mouth of the San Juan: Am. Jour. Sci., 5th ser., vol. 5, pp. 229–238, 1923. Bryan, Kirk, Discussion on rock-filled dam, Lees Ferry: Am. Soc. Civil Eng. Trans., vol. 80, pp. 1615–1627, 1923. La Rue, E. C., Water power and flood control of Colorado River below Green River, Utah: U. S. Geol. Survey Water-Supply Paper 556, 1925. Noble, L. F., A section of the Kaibab limestone in Kaibab Gulch, Utah: U. S. Geol. Survey Prof. Paper 150, pp. 41–60, 1928. Moore, R. C., Origin of inclosed meanders on streams of the Colorado Plateau: Jour. Geology, vol. 34, pp. 29–57, 1926. Moore, R. C., Significance of inclosed meanders in the physiographic history of the Colorado Plateau country: Jour. Geology, vol. 34, pp. 97–130, 1926. Berry, E. W., Cycads in the Shinarump conglomerate of southern Utah: Washington Acad. Sci. Jour., vol. 17, pp. 303–307, 1927. Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, 1916; Geology of the Navajo country—a reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Prof. Paper 93, 1917. Emery, W. B., The Green River Desert section, Utah: Am. Jour. Sci., 4th ser., vol. 46, pp. 551–577, 1918. Dake, C. L., Horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, pp. 634–646, 1919; The pre-Moenkopi (pre-Permian?) unconformity of the Colorado Plateau: Jour. Geology, vol. 28, pp. 61–74, 1920. Butler, B. S., and others, Ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, 1920. Noble, L. F., A section of the Paleozoic formations of the Grand Canyon at the Bass trail: U. S. Geol. Survey Prof. Paper 131, pp. 23–33, 1923. Reeside, J. B., jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 53–77, 1922. Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 115–156, 1924. Longwell, C. R., The pre-Triassic unconformity in southern Nevada: Am. Jour. Sci., 5th ser., vol. 10, pp. 93–106, 1925.

[6] Gilluly, James, and Reeside, J. B., jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, pp. 61–110, 1928. Longwell, C. R., Geology of the Muddy Mountains, Nev., with a section to the Grand Wash Cliffs in western Arizona: Am. Jour. Sci., 5th ser., vol. 1, pp. 30–62, 1921. Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, pp. 634–679, 1907.

Chapter 1. GEOGRAPHY

LOCATION AND EXTENT

The Kaiparowits region lies mostly in Garfield County and Kane County, southern Utah, but includes a small part of Coconino County, Ariz. (See fig. 1 and pl. 1.) It is approximately included between parallels 37° and 38° and meridians 110° 45′ and 112° 30′. Its south and southeast boundary is formed by Glen Canyon of the Colorado River; its west and north boundary follows the valley of the Paria River, the edge of the Paunsaugunt Plateau, the west base of the Table Cliff Plateau, and the rim of the Aquarius Plateau to its junction with the Waterpocket Fold; its northeast boundary is Halls Creek. As thus approximately outlined the region has a length of 90 miles, a breadth of 80 miles, and an area of 5,400 square miles, nearly all in Utah. It is a vast expanse of undeveloped grazing land utilized by a sparse population that clusters in a few small settlements where water for irrigation is available. It is remote from the population centers of Utah and Arizona. The villages of Tropic, Cannonville, and Henrieville, near the head of the Paria Valley, mark the terminus of an automobile road 90 miles long that reaches the Denver & Rio Grande Western Railroad at Marysvale, Utah. From Marysvale a highway also extends 80 miles to Escalante and continues 35 miles to Boulder as a wagon road.

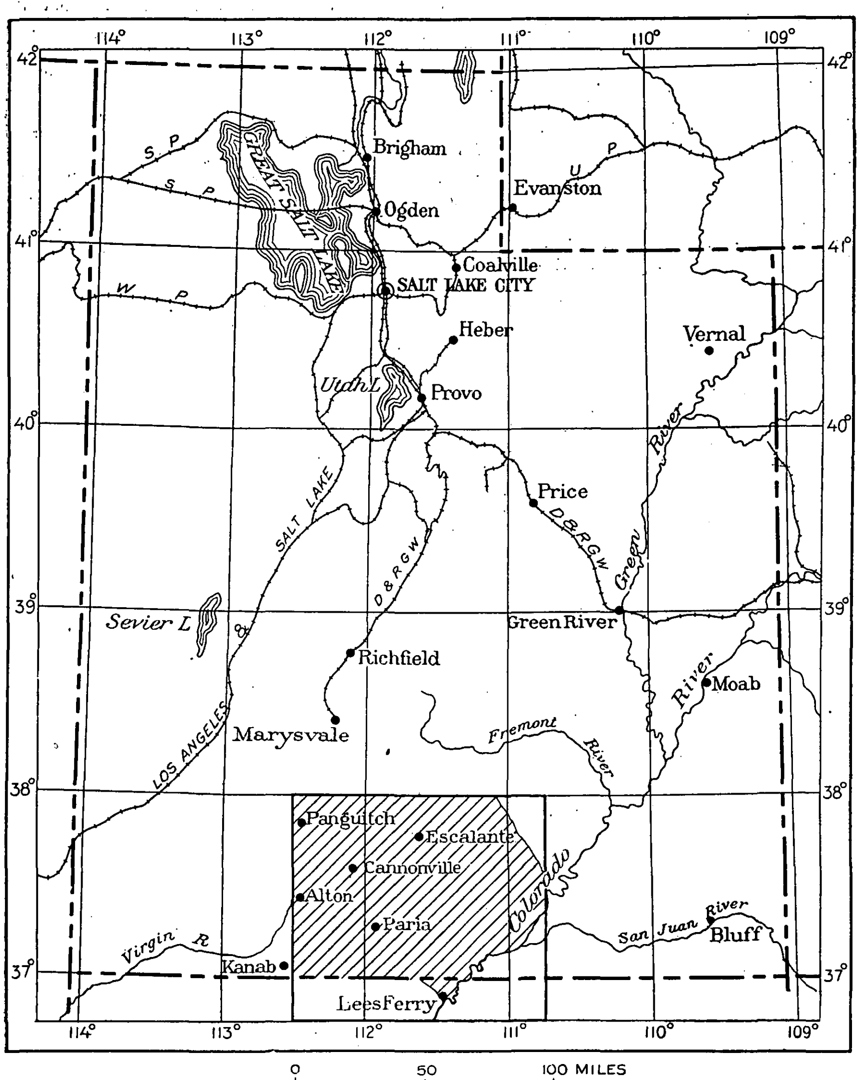


Figure 1.—Map showing the location of the Kaiparowits region (shaded area)

The five settlements—Tropic, Cannonville, Henrieville, Escalante, and Boulder, situated at the base of the High Plateaus—are the only permanent centers of population, and the roads to them are the only ones that are kept in repair. To reach the few intermittently cultivated dry farms and the temporary stock camps, roads have been marked out down the Escalante Valley, along Pine Creek and Halls Creek, and down Paria Creek. With suitable wagons it is possible to reach Warm Creek and the Circle Cliffs and to cross the Waterpocket Fold, and at times supplies have been brought to the settlements by wagons from Kanab, 40 miles west; from Green River, 150 miles north; and even from Flagstaff, Ariz., 250 miles south. Except for the county roads to Marysvale and to Panguitch and those in the immediate vicinity of the villages, however, the recognized "ways of going" may be called roads only for the want of a better name. They are in reality trails with alternating stretches of sand, bare rock, and steep inclines over which with few mishaps a skillful driver may conduct a strongly built, lightly loaded wagon. For most of the Kaiparowits region saddle horses and pack trains are the only practicable means of transport. (See pl. 4, *C*, *D*.) Only one established trail crosses the Kaiparowits Plateau.

The deep-cut interlocking canyons tributary to the Colorado, the buttressed walls of the Kaiparowits Plateau, and its distance from settlements make the eastern half of Kane County peculiarly difficult of access, and the information obtainable from the few stock men who have penetrated parts of this region is meager and unreliable. The explorer must rely on his experience and knowledge of topography to find routes and water holes.

THE MAP

The topographic base map that accompanies this report was prepared from plane-table surveys by Moore, supplemented by maps of the country along Glen Canyon made by the Colorado River surveys of 1921, by a map of the Powell National Forest made by the Forest Service, and by the reconnaissance maps of the Powell Survey. (See pl. 1.)

In the Circle Cliffs, along the Waterpocket Fold, and in the middle part of the Escalante Valley an area of about 650 square miles was mapped on a scale of 1 inch to the mile, with plane table and alidade. Altitudes were determined by vertical angles based on a bench mark of the United States Coast and Geodetic Survey in Halls Valley and locations by stadia traverse and triangulation. Section corners were located southeast of Escalante and northeast of the Circle Cliffs, and their positions and those of control points in the intervening area were established by primary triangulation. In the region east of the Paria River and along the south flank of the Kaiparowits Plateau about 1,450 square miles was mapped with plane table and alidade on a scale of 1 inch to the mile, and a reconnaissance topographic map was prepared. This survey showed that even the largest stream courses and the most prominent cliffs and mesas were inaccurately or quite erroneously represented on the earlier maps.

The geologic 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. The geologic boundaries in much of the region are based on mapping with plane table and alidade on a scale of 1 inch to the mile. Though the geologic map does not attain a uniformly high degree of accuracy, it probably records fairly the significant features in the geology of southeastern Utah. (See pl. 2.)

HISTORICAL SKETCH

SPANISH ENTRADAS

The occupation of central Mexico by the Spaniards in 1514 was followed by a series of exploratory expeditions to the regions that lie to the north. The first expedition, under Nuño de Guzmán, met with disaster before reaching the Rio Grande. Marcos de Niza was more fortunate. Accompanied by three other priests, the Barbary negro Estevanico, and a small body of soldiers, he traversed Sonora and western Arizona, reaching Zuñi in 1540. His descriptions of the scenery and especially of the interesting pueblo villages led to the elaborately organized expedition of Francisco Vásquez de Coronado, president of New Spain. From Zuñi as a base, Coronado dispatched expeditions into surrounding regions. Juan de Padilla and Pedro de Tovar discovered the unique Hopi villages, and García López de Cárdenas came, in his journey northwestward along the Moenkopi trail, to a great river whose banks extended "three or four leagues into the air" and were "broken into pinnacles higher than the tower of the cathedral of Seville." Undoubtedly Cárdenas was the first white man to see any part of the Colorado canyons.[7]

After the expedition of Coronado (1540), Spanish exploration included visits to the coast of California (Cabrillo, 1542–43; Velasco, 1564), excursions among the pueblos between the Rio Grande and the little Colorado (Espejo, 1582–83), and the founding of Santa Fe by Juan de Oñate (1611). Explorations in the Gulf of California were made by Vizcaino (1595–96), Iturbi (1615), Ortega (1632), Carboneli (1636), Canas (1642), Casanate (1648), and Pinadero (1664). The Jesuits (1642–1766) added little to the existing store of geographic knowledge, but the Franciscans (1767–1812) undertook many expeditions into unknown territory now included in New Mexico, Arizona, Utah, and California. So far as known only one of these famous entradas reached the lands beyond the canyons of the Colorado.

Silvestre Vélez de Escalante, ministro doctrinero of Zuñi, and Francisco Atanasio Domínguez, visitador comisario of New Mexico, set out from Santa Fe on July 29, 1776, for the purpose of discovering a better route from New Mexico to Monterey than the one by way of Gila, Mojave, and San Gabriel. In addition to these two priests the party included Juan Pedro Cisneros, alcalde mayor of Zuñi, Bernardo Miera y Pacheco, capitán miliciano of Santa Fe; and five soldiers—Joaquín Lane, Lorenzo Olivares, Lucrecio Muñiz, Andrés Muñiz, and Juan de Aguilar y Simón Lucero.[8] From the clear description by Escalante his route is readily traced. It led through the La Plata Mountains, across the eastern part of the Great Sage Plains to the base of the La Sal Mountains, thence northwestward across the Colorado and Green

[7] For additional details and references, see Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, 1916.

[8] Escalante S. V. de, Diario, in Documentos para la historia de México, ser. 2, vol. 1, p. 378.

Rivers and through the Wasatch Plateau to Utah Lake.

It is difficult to picture the motives that led Escalante to take this extremely circuitous route. He may have been influenced by current rumors of a great river north and east of Monterey, which might lead him to the California coast, and by vague accounts of tribes and villages north of Tusayan, but a reading of the Diario gives the impression that zeal for exploration, the pure joy of seeing unknown lands and unknown people, exerted a strong influence. Whatever the reasons that brought Escalante's party to the west base of the Wasatch, it was evident to the leader that further travel to the north and west would lead away from his prospective goal. He therefore turned south, crossing streams leading from the mountains. Finding that the Indians knew nothing of roads to the sea or to the Spanish settlements at the south, the contemplated journey to California was abandoned with keen regret and the decision reached to return to Santa Fe through the Moqui villages. This decision necessitated crossing the Colorado and long journeys through unknown lands. With the scant supplies remaining, supplemented by seeds and piñon nuts, the party made their way along the base of the Wasatch to the Virgin River, thence eastward from the vicinity of St. George, heading canyons, crossing plateaus, following dry valleys, and finally reaching the Colorado September 26. After a 12 days' search for a possible crossing among the cliffs and sharply cut tributary gorges of Marble Gorge and Glen Canyon, an old Indian ford was found at the point since known as the Crossing of the Fathers. The route southeast from the crossing presented no great difficulties, and the party reached Oraibi November 16, 1776, and Zuñi January 2, 1777. The traverse of the plateaus and gorges north of Grand and Glen Canyons and the crossing of the river is perhaps the most difficult undertaking credited to the intrepid Spanish padres. The Hurricane Cliffs and Kanab Canyon are formidable obstacles, and from the Paria eastward the region is desolate and abandoned even by Indians; it is a "no man's land" that separates the Utes from the roving Navajos. Access to the Crossing of the Fathers is through a narrow gorge, down precipitous slopes, and crossing is feasible only at low water or on ice during abnormal winters. (See pl. 4, *C*.) Lieutenant Marshall,[9] who in 1872 found the ford but did not cross, described the region as "one of remarkable grandeur and almost unique in its loneliness." So far as known Escalante was the first white man to traverse southern Utah and the only explorer to enter Glen Canyon before Powell's memorable traverse, nearly a century later.

[9] U. S. Geog. Surveys W. 100th Mer. Rept., vol. 1, p. 53, 1889.

THE TRAPPERS

During the second and third decades of the nineteenth century trappers and fur traders crossed the Rockies and pushed their way into the Valley of the Colorado, but their wanderings, which mark a noteworthy period in western exploration, added nothing to the knowledge of southern Utah. After the overthrow of Spanish power in 1821, a few traders extended their operations westward from Santa Fe perhaps as far as the lower San Juan, and Chittenden[10] expresses the belief that in 1824 William Bicknell, a trapper, wintered on the Colorado below the mouth of the Green River. The Mission Fur Co. and its successor, the American Fur Co., operated chiefly within the Missouri River Basin. The business of the Rocky Mountain Fur Co. centered on the Upper Green River in Wyoming and extended westward to Salt Lake and northwestward into Idaho.

Camps and winter quarters were established on the streams of the Uinta Mountains and on the Grand River, and parties were at work along the Colorado below Camp Mojave. The intervening stretch of about 600 miles was unmolested. It offered few attractions to the trappers. It was not beaver country nor buffalo range. The river "could not be approached," its bordering country was "desolate," "desert," and traversed by "impassable chasms." Little food was to be obtained, and few Indians were there to be robbed. The fur hunters were interested in beavers, not scenery. With the exception of James O. Pattie,[11] who in 1826 made his way northeastward from Mojave to the Green River along the general course of the Colorado, no trapper is known to have been on or near the great river between the mouth of the Green and the mouth of the Virgin. Pattie's narrative is a fascinating story of trapper life, but unfortunately it is so deficient in geographic description that the route followed can not be traced. After it leaves Black Canyon the trail is picked up with assurance only at the headwaters of the Platte.

Frémont[12] summarizes the knowledge of 1843 in the following terms:

> The Colorado is but little known, and that little derived from vague report. Three hundred miles of its lower part, as it approaches the Gulf of California, is reported to be smooth and tranquil; but its upper part is manifestly broken into many falls and rapids. From many descriptions of trappers, it is probable that in its foaming course among its lofty precipices it presents many scenes of wild grandeur; and though offering many temptations and often discussed, no trappers

[10] Chittenden, H. M., The American fur trade of the Far West, vol 2. pp. 506–507, 1902.

[11] Pattie, J. O., Personal adventures of James O. Pattie, of Kentucky, edited by Timothy Flint, 1833.

[12] Frémont, J. C., Report of the exploring expedition to the Rocky Mountains in 1842: 28th Cong., 2d sess., S. Doc. 174, pp. 129–130, 1845.

have been found bold enough to undertake a voyage which has so certain a prospect of a fatal termination.

Ives[13] pays his respects to the Grand Canyon in the vicinity of Cataract Creek in the following terms:

Ours has been the first and will doubtless be the last party of whites to visit this profitless locality. 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.

POWELL AND WHEELER SURVEYS

During 1867, 1868, and 1869 Maj. J. W. Powell was engaged in general scientific exploration in western Colorado and eastern Utah under the auspices of the Smithsonian Institution. While engaged in this work he made the memorable trip down the Green and Colorado Rivers. Leaving Green River, Wyo., the old Indian crossing, May 24, 1869, Gunnison's crossing of 1853, now Green River, Utah, was passed July 13, the mouth of the Green River July 18, the Dirty Devil[14] (now Fremont) July 28, the San Juan July 31, and the Little Colorado August 10. This extraordinary journey ended August 30 at the mouth of the Virgin River. The course of the Colorado from the mouth of the Green River to the mouth of the Virgin was covered in 23 days, a distance of 539 miles, more than 23 miles a day. The task of getting the boats along, overcoming obstacles, procuring food, and recording distances and directions left little time or energy for scientific observations beyond the immediate river banks. As stated by Powell:[15]

Our last trip was so hurried, owing to the loss of rations, and the scientific instruments were so badly injured that we were not satisfied with the results obtained, so we shall once more attempt to pass through the canyons in boats, devoting two or three years to the trip.

Although the scientific results were meager, this first traverse of the Colorado brought an end to the fantastic stories of swiftly revolving whirlpools, long underground passages, and plunging waterfalls. It proved that the river could be navigated by daring souls with less difficulty and perhaps less danger than is involved in traversing its banks across waterless tributary canyons and along dry cliffs perched thousands of feet above the stream. As expressed by the Piutes, the god Tav-woats had made the Colorado gorges as a trail across the arid lands and when later that trail was closed by sending a mighty stream to occupy it, no route to the beautiful land to the west remained.

To obtain fuller knowledge of the region obviously required more time, and this involved stores of provisions suitably placed along the river route. With these ideas in mind, Powell returned to Utah in 1870 and from headquarters on the upper Kanab explored the canyons of the Virgin and the Uinkaret Plateau, investigated a trail to the bottom of the canyon near Toroweap, and on his return crossed the river at the mouth of the Paria on a ferryboat built of lumber brought from Kanab. After consulting with the indispensable Mormon scout, Jacob Hamblin, it was decided to have supplies taken by pack train to the mouth of the Uinta, the mouth of the Dirty Devil, the Ute ford (Crossing of the Fathers), and the mouth of the Paria.

This second expedition left Green River, Wyo., May 22, 1871, and the mouth of the Green River September 19. Inability of the pack train to reach the mouth of the Dirty Devil with provisions compelled the expedition to abandon one boat and to hasten the journey to the Crossing of the Fathers, where supplies had been cached. The party continued to the mouth of the Paria and thence to Kanab for winter quarters. Powell left the river party at the Crossing of the Fathers, followed the Ute trail to Paria, and proceeded to Salt Lake City. He thus became the first geologist to traverse the southwest base of the Kaiparowits Plateau.

The plan to recover the boat left at the mouth of the Dirty Devil led to the first examination of the upper tributaries of the Paria, the headwaters of the Escalante, the Waterpocket Fold, and the Henry Mountains. Starting from Kanab in May, 1872, nine men in charge of A. H. Thompson made their way up to Johnson Canyon through Swallow Park and along the base of the Paunsaugunt Plateau, where Thompson says:

Travel was exceedingly slow and difficult. Our progress was often barred by a canyon, along whose brink we were compelled to follow till some broken-down slope afforded a way to descend, then up or down the canyon until another broken slope permitted us to ascend, then across a mesa to another canyon, repeating the maneuver a dozen times in half that number of miles.

The Paria was reached near the mouth of Yellow Creek and the traverse continued to the head of Table Cliff Creek [Henrieville Creek].

Here we climbed 1,000 feet up a steep clay ridge having an average slope of 20° and often not more than 5 feet [wide] at the top to the head of a narrow valley called Potato Valley [Upper Valley, a branch of the Escalante]. Down this we traveled 3 miles and made Camp 6 at a cool spring in the midst of a beautiful meadow.

From this camp at the base of the towering pink precipices of the Table Cliff Plateau, now the site of summer ranches, Thompson[16] studied the surrounding country. He says:

To the north and 3 miles distant Table Cliff Plateau rose 3,000 feet above us, its face a succession of inaccessible preci-

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

[14] The name "Dirty Devil," given by Jack Sumner, of Powell's party, seems appropriate for this exceptionally mud-laden alkaline stream.

[15] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, p. 106, Smithsonian Inst., 1875.

[16] Thompson, A. H., Report on a trip to the mouth of the Dirty Devil River, in Powell, J. W., Exploration of the Colorado River of the West and its tributaries, pp. 133–145, 1875.

pices, and steep, broken, tree-clad slopes. From the base of the cliffs long ridges run out to the edge of the valley. To the east, above camp, they roll off into a long, narrow plateau, bounded on the west by a well-marked line of cliffs, beginning near the foot of Table Cliff Plateau and continuing southeast 60 miles, to a point on the Colorado River opposite the Navajo Mountain. At the western terminus this line is somewhat broken, but toward the east it increases in height till at last it stands for 30 miles an inaccessible vertical wall, 2,500 feet high. Its eastern boundary is a line of cliffs, commencing at the foot of Potato Valley and presenting an almost unbroken front to the Colorado River at a point but 4 miles above the terminus of the western line, thus giving to the plateau a trapezoidal outline, having a length of 55 miles, a breadth at the base of 15, at the apex 4, and standing at an altitude of 9,000 feet above sea level. For 15 or 20 miles the western end is cut by a perfect network of canyons and short lines of cliffs, making travel across it almost impossible. The middle and eastern portions are quite level, and when once on the summit progress in any direction is easy. So far as I have been able to ascertain, we were the first white men to visit the plateau. The Indian name for a small elevation near the north end is Kāi-pâr-o-wits [Canaan Peak], so we called the whole plateau by that name.

Continuing the course down the upper valley, the party reached the stream which Hamblin had mistaken for the Dirty Devil and down which he had fought his way for 50 miles through quicksand and tortuous channels in an unsuccessful attempt to bring supplies for Powell's boat party of 1871. Thompson and his fellow topographer, Dellenbaugh, realized that the stream they had been following was not the Dirty Devil but a previously unknown tributary to the Colorado, the mouth of which had not been noted by the expeditions of 1869 and 1871. A view from the top of a cliff at the crest of the Escalante Fold, near the present village of Escalante, made their position clear. Thompson [17] writes:

On reaching the summit we found we were on the western rim of a basin-like region, 70 miles in length by 50 in breadth and extending from the eastern slope of the Aquarius Plateau on the north to the Colorado River on the south and from the Henry Mountains on the east to our point of observation on the west. A large portion of this area is naked sandstone rock, traversed in all directions by a perfect labyrinth of narrow gorges, sometimes seeming to cross each other but finally uniting in a principal one, whose black line could be traced, cutting its way to the Colorado a few miles above the mouth of the San Juan River.

Away to the east and 50 miles distant rose the Henry Mountains, their gray slopes streaked with long lines of white by the snow which yet remained in the gulches near their summits. On our voyage down the Colorado River in 1871 we had determined the mouth of the Dirty Devil River to be about 30 miles northeast from these mountains, making it at least 80 miles from our present camp and directly across the network of canyons before us. To proceed farther in the direction we had been pursuing was impossible. No animal without wings could cross the deep gulches in the sandstone basin at our feet. The stream which we had followed and whose course soon became lost in the multitude of chasms before us was not the one we were in search of but an unknown, unnamed river, draining the eastern slope of the Aquarius Plateau and flowing through a deep, narrow canyon to the Colorado River. Believing our party to be the discoverers, we decided to call this stream in honor of Father Escalante, the old Spanish explorer, Escalante River and the country which it drains Escalante Basin.

The western boundary of the basin is the vertical wall forming the eastern edge of the Kaiparowits Plateau. From the very base of the cliff the drainage is to the Escalante River by narrow, deep canyons, presenting apparently impassable barriers to travel toward the south. To the north and 20 miles away rose the eastern slope of the Aquarius Plateau. Its general trend is north and south, but away to the northwest and about 40 miles from our point of observation a great salient angle projects eastward toward the Henry Mountains, the slopes at its base seeming to continue out a long distance and form a low, broken ridge between canyons running southward to the Escalante River and others running northward. Here, if anywhere, this canyon region could be crossed, and I decided to go eastward along the slope of the great plateau to the salient spoken of and then attempt the passage along the ridge.

With the position of the Henry Mountains established, Thompson chose a route along the base of the Aquarius Plateau across the Waterpocket Fold to the Henry Mountains and Trachyte Creek and reached the Colorado near the place where the *Cañonita* had been cached the previous year. Finding the boat intact, four men of the party used it for an uneventful trip to the mouth of the Paria and later down the river to the mouth of the Kanab. Thompson with the remainder of the party retraced the route to the Escalante and after making astronomical observations, establishing topographic stations, and sketching the features of the Escalante Basin, continued on to Kanab.

Wheeler [18] states that Lieutenant Marshall of his staff made a traverse from the Paria settlement to the Crossing of the Fathers in 1872, and his "progress maps" [19] indicate that during the same year all of southern Utah and northern Arizona between Nevada and the Waterpocket Fold and north of the Colorado was mapped by his topographic parties, but there is no other evidence to show that the Wheeler survey of 1872 was extended to cover the Kaiparowits region, and Dellenbaugh [20] is authority for the statement that the data on this part of Wheeler's map were taken from sketch maps prepared by Thompson. The map itself is obviously the product of long-distance sketching. It is also probable that the map of the region from the mouth of the San Juan along the Waterpocket Fold, which is credited to Lieutenant Hoxie (1873), is in part at least based on Thompson's data. Gilbert [21] credits the triangulation of that region to Thompson and the topography to W. H. Graves. Strangely enough, no mention is made by Wheeler of the work of Thompson or of the observations made by

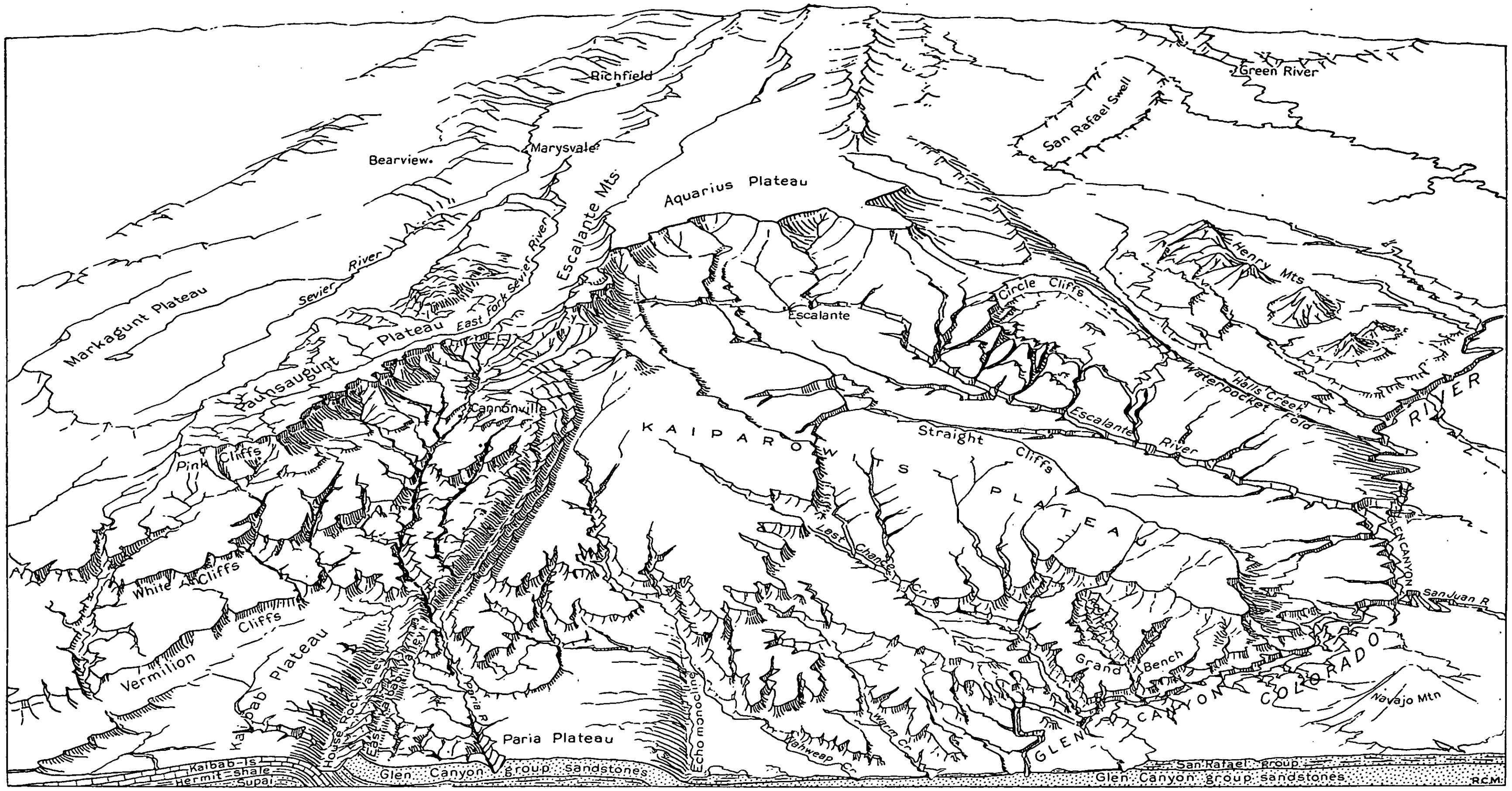
[17] Thompson, A. H., op. cit., pp. 137–139.

[18] U. S. Geog. Surveys W. 100th Mer. Rept., vol. 1, p. 52, 1889.

[19] U. S. Geog. and Geol. Surveys W. 100th Mer. Topographical Atlas, 1873.

[20] Dellenbaugh, F. S., personal communication, April 22, 1918.

[21] Gilbert, G. K., Report on the geology of the Henry Mountains, 2d ed., pl. 1, 1880.



GENERALIZED VIEW OF THE KAIPAROWITS REGION LOOKING NORTH FROM THE UTAH-ARIZONA BOUNDARY LINE

Powell's parties of 1869, 1871, or 1872. In fact, Wheeler ignores the work done by all the parties of the Powell Survey.

In 1874 Thompson, assisted by W. H. Graves and J. H. Renshawe, completed maps of the Aquarius Plateau and the northern tributaries of the Escalante and extended the survey to the Henry Mountains.

The following information regarding exploration and mapping in 1875 has been given by F. S. Dellenbaugh:[22]

I have Thompson's diary of the trip he made in 1875. Their supply camp this season was on the southeast side of Rabbit Valley. Gilbert started for the Henry Mountains on August 12, 1875. Thompson went to a camp about 12 miles above Paria settlement, then to a point about 3 miles below the "old settlement," then to a camp in Sentinel Rock [Wahweap] Creek "wash," about 20 miles. He had difficulty in finding the trail, showing that he was on one which was probably the El Vado trail, and he went to this place [El Vado] the next day. Then he went to Warm Creek, then to a point below Paria settlement again, then back to Panguitch, whence he had come some few days before. Earlier he was in Tantalus Valley (July 19) and worked his way to the slopes of the Aquarius, camping on July 20 at what we called Mosquito Camp in 1872 because we were eaten alive there on a rainy night. He then went to Boulder Creek, to head of Potato Creek, to False Creek [Harris Wash], and to Last Chance Creek [Collett Wash], arriving at this last on July 28, 1875.

On August 2, he was at his camp 26. "Gilbert, Graves, Jack [Hillers], and myself started for the end of the Kaiparowits Plateau. Came about 25 miles down the valley, climbed the first bench and up about 350 feet of the second, when we came to a place we could not get over. Worked on it and got the mule, Net, up. Came down to the lower bench and camped. Tied the mules up on account of no water. August 3. Finished our trail and got to the top of the plateau at 9.30. Rode till 2.30, making 15 miles before we reached the end of the plateau. Was on the end about two hours. Got geodetic bearings and a few topographical. Reached water that Walter [Graves] had found in the morning, about half past 7, when our mules had a chance to drink. The first water since yesterday morning.

"Wednesday, August 4 * * *. It took us about two hours to get down 900 feet of the first cliff, and our camp was some 6 miles from the comedown. We reached our camp of the 3d instant about 9.30 a. m. Reached camp at 5 p. m."

They then went on back from this camp on Last Chance Creek to a camp on Pine Creek a mile above its junction with the Escalante. "Saw Mormons from Panguitch, who are talking about making a settlement here. Advised them to call the place Escalante."

Thompson went out then across the Aquarius Plateau to the supply camp.

The work of the Powell Survey in the Kaiparowits region resulted in a reconnaissance topographic map on a scale of about 4 miles to the inch with a contour interval of 250 feet, published by the United States Geological Survey as the Henry Mountains, Escalante, Echo Cliffs, and Kanab maps. From the time of their appearance in 1886 until the maps showing the areas to be flooded by the proposed Lees Ferry dam were prepared by the Geological Survey, in 1921, these sheets have constituted the sole available information regarding the topography and drainage of this region. They present in bold outline the dominant features and admirably portray the quality of relief, but outside of the routes traversed by Thompson and prominent features visible from easily accessible viewpoints, the information they give is of little value as a guide to further explorations or as a base on which geologic data may be presented. The conditions that surrounded the work prohibited more than general reconnaissance. The short stops made by the river parties permitted only generalized observations along Glen Canyon and at the few places where the canyon wall could be scaled. The land parties likewise were hampered by lack of time. Thompson could give but eight days to a survey of the Escalante Valley and the Kaiparowits Plateau—about 3,000 square miles of intricately dissected and structurally complex country in which the relief exceeds 6,000 feet.

The geologic results of the early surveys may be summarized as follows:

Powell's trips down the Colorado canyons in 1869 and 1871[23] gave the first knowledge of the geologic features of Glen Canyon and its immediate vicinity. Howell[24] in 1873 recorded observations on the stratigraphy and structure of the region between the base of the Aquarius Plateau and the Henry Mountains, briefly described the Waterpocket and Escalante Folds, and measured a section in the upper Paria Valley. Gilbert[25] in connection with his study of the Henry Mountains, in 1875 and 1876, outlined the salient physiographic features of the Waterpocket flexure, the Escalante Basin, and the Kaiparowits Plateau. He remarks:

Two months would be far too short a period in which to survey a thousand square miles in Pennsylvania or Illinois, but among the Colorado plateaus it proved sufficient. A few comprehensive views from mountain tops gave the general distribution of the formations, and the remainder of the time was spent in the examination of the localities which best displayed the peculiar features of the structure. So thorough was the display and so satisfactory the examination that in preparing my report I have felt less than ever before the desire to revisit the field and prove my conclusions by more extended observation.

Dutton[26] in 1875, 1876, and 1877 mapped the west end of the Kaiparowits Plateau and the region about the headwaters of the Escalante and the Paria, but the age assigned to the strata and the descriptions of

[22] Personal communication.

[23] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, 1875.

[24] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 227–301, 1875.

[25] Gilbert, G. K., Report on the geology of the Henry Mountains, pp. 12–13, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

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

plateau walls and canyons suggest that his conclusions were based on observations made at viewpoints on the Aquarius Plateau, many miles distant.

CROSSINGS OF THE COLORADO

Cliff dwellings are found on both sides of the Colorado River and also within its canyons, and probably the Pueblo tribes and later the Navajos and Utes knew of several crossings of the Colorado which they occasionally utilized. The known movements of warring Indian bands significantly coincides with times of low water or times when the river was frozen over. Old trails lead to the Colorado at its junction with the Green, at the mouth of the Little Colorado, and down Bright Angel and Shinumo Creeks. Supai informants state that crossings by means of rudely constructed rafts were made at Grand Wash, at the mouth of the Virgin, and at points on the lower Colorado. The Spanish explorers, trappers, and hunters were familiar with the long-used ford at Green River, Utah, which was recommended by Gunnison (1853?) as a route for a railroad and later was utilized by the Denver & Rio Grande Railroad. The ancient Ute ford, now known as the Crossing of the Fathers, was rediscovered by Escalante on his eventful journey from Utah Lake to the Hopi villages of Tusayan in 1776.

Systematic search for a feasible crossing of the Colorado was the result of missionary enterprise of the Mormon Church. In 1858 the intrepid scout Jacob Hamblin

> received instructions from President Brigham Young to take a company of men and visit the Moquis, or town Indians, on the east side of the Colorado River. The object of this visit was to learn something of the character and condition of this people and to take advantage of any opening there might be to preach the gospel to them and do them good.[27]

Leaving Santa Clara (near St. George) on October 28, the party of 12 men, including a Spanish interpreter (and a Welsh interpreter!), proceeded by way of "Yellow Rocks Springs" (Pipe Springs),

> traversed the canyons and plateaus eastward, and after climbing dangerous cliffs and crossing extensive fissures in the rocks, the tenth day out from home we crossed the Colorado River at the Ute ford known in Spanish history as the Crossing of the Fathers.

The trail beyond was reported "not only difficult but sometimes very dangerous."

A second journey over this route was made in 1859, and a third in 1860, so timed as to cross the river at its low-water stage. The return from the uncompleted third trip, which was delayed by disastrous trouble with the Navajos, was accomplished in winter, and the crossing is described by Hamblin[28] as follows:

> Our route was a difficult one to travel in the winter season. The ford of the Colorado was deep and dangerous at any time but especially when the ice was running. Sometimes there were steep rocks to climb; at other times the trail ran along the almost perpendicular sides of deep rock fissures, narrow, with frequent short turns, where a misstep might plunge us or our animals hundreds of feet below. Sometimes the precipitous rocks were covered with ice, which had to be hacked with our hatchets before we could feel any surety of a foothold.
>
> At one time we waited until nearly midday for the sun to melt the frost and ice on a steep rock, that we might be able to get our animals out of a gulch onto the plain above. On this occasion my pack mule slipped and fell, then rolled and slid down to within about a yard of the edge of a chasm below. We fastened a long lariat to the animal and saved it and the pack.

Its extreme difficulty and the hostility of the Navajos discouraged further use of the Glen Canyon crossing, but the project of converting the Hopis to the Mormon faith, though delayed, was not abandoned.

Explorations in southwestern Utah, which resulted in the settlement of St. George and of fertile spots in the Virgin and Santa Clara Valleys in 1861 encouraged the search for a crossing which might make possible the expansion of the settlements into northern Arizona and which did not involve the long, difficult route to the old Ute ford.

A feasible crossing was found at the mouth of the Grand Wash. By swimming the horses and transporting the luggage on a homemade boat Hamblin crossed the river at this point in 1862, traversed the Coconino Plateau, and proceeded along the base of the San Francisco Mountains and across the Little Colorado to Oraibi. This route was found to be so long and the water holes so small and so far apart that the return from Oraibi was made over the old Ute trail. At the Crossing of the Fathers "fording was difficult and dangerous" but was successfully accomplished on New Year's Day, 1863, after the loss of eight horses.

On Hamblin's next visit to Tusayan, in 1863, the river was again crossed at the foot of Grand Wash but at a place near the base of the Grand Wash Cliffs, the site of Pierce Ferry (now abandoned). On returning from Oraibi by the same route in May, 1863, Hamblin reported: "We had explored a practicable though difficult route for a wagon from St. George to the Little Colorado." The length of this route and the scarcity of water west of the San Francisco Mountains led Hamblin to try a new route, which he had previously reconnoitered, and in 1869 a successful crossing was made near the mouth of the Paria—the present Lees Ferry.

[27] Little, J. A., Jacob Hamblin, a narrative of his personal experience, 2d ed., p. 64, Salt Lake City, Deseret News, 1909.

[28] Idem, p. 79.

With Hamblin for a guide the Lees Ferry route was used by Powell in 1871 and by Lieutenants Hoxie and Marshall, of the Wheeler Survey in 1873. It has become the established line of travel from Utah to Arizona and is the only crossing available for wagons along the 788 miles of canyon between Green River, Utah, and Needles, Calif. The Crossing of the Fathers, always dangerous, is no longer practicable; a portion of the landing has been blasted away to block the route of marauding Navajos.

In 1870 southeastern Utah, comprising about one-quarter of the State, was an unknown land. Powell had marked the course of the Colorado but found no feasible routes leading from it except those already known. Explorations by scouts of the Mormon Church had resulted in locating small tracts of irrigable land at the east base of the High Plateaus, along the Paria River, and at places south of the Colorado canyons. Paria was founded in 1871, Cannonville and Escalante in 1875, and " about 20 families were living in Potato Valley " in 1878.

To these isolated settlements at the end of long roads leading across the jagged cliffs of the High Plateaus came reports of good lands still farther east but separated from them by the impassable Glen Canyon. To confirm these reports an expedition was organized for the exploration of the San Juan Valley. In 1879 a party of 25 men under the leadership of Silas Smith crossed the Colorado at Lees Ferry and followed the marked trail through the Painted Desert to the Hopi village of Moenkopi. " Led by inspiration," the party reached Marsh Pass on the Navajo Reservation and, avoiding the canyon of the San Juan, made their way eastward to the mouth of Montezuma Creek. After exploring the San Juan Valley between McElmo Creek and Butler Wash and obtaining information from roving prospectors, the party turned northward to the Blue (Abajo) Mountains. Continuing along the base of the La Sal Mountains, they crossed the Colorado near the present town of Moab and followed the " Spanish trail " to Green River, Utah, and thence to Salt Lake City.

This expedition demonstrated that a route through the Navajo country from Escalante or Kanab to the San Juan Valley was impracticable. The country to be traversed consists of stretches of sandy flats alternating with areas of sharp-cut canyons; the water holes are far apart and the Navajos none too friendly; and even if a wagon road could be constructed and maintained, the distance, about 500 miles, is prohibitive. But the expedition also demonstrated that the San Juan Valley afforded opportunities for irrigation farming and that the Abajo and La Sal Mountains with their adjoining plateau lands were destined to become valuable grazing districts. It appeared that the region east of Glen Canyon was " better country " than that immediately west.

The officials of the Mormon Church were favorably impressed by the report of Silas Smith, and with characteristic foresight they promptly issued a " call for the Saints to occupy the San Juan Valley." The president of the church was firmly convinced that " our people will want all the choice places where there is water and grass." But to occupy this far-away region was a serious undertaking. Its climate, its agricultural possibilities, and the attitude of the few Indians who made their home in the adjoining regions were little known. The proposed settlement could be reached only by the exhausting trails through Moenkopi and Marsh Pass or by the still longer Green River route. It was recognized that the interests of the church demanded that the pioneers in the proposed settlement have their commercial and religious associations with their brethren in the Utah villages rather than with the gentiles of the Colorado mining towns; with Escalante rather than with Durango. With these ideas in mind, the prodigious task of constructing a wagon road from Escalante across Glen Canyon to the middle San Juan Valley was undertaken. After preliminary scouting on both sides of the canyon, a crossing was selected at the Hole in the Rock, at the lower end of the " 80-mile desert," 4 miles south of the mouth of the Escalante.

In October, 1879, a party led by Silas Smith, Platte Lyman, and Jess Nielson, with a large number of workmen, horses, and wagons, was established in three camps, building a road down the desert, collecting supplies, and assembling materials for a crude ferry boat. Between November 6 and December 29 about 70 miles of road was constructed, and early in January 80 wagons, nearly 200 men and women, 50 children, 200 horses, and 1,000 cattle had reached the rim of the canyon. Work then centered on blasting the canyon walls and building a flat-bottomed boat about 9 feet wide and 28 feet long with planks brought from Escalante. The Colorado was crossed in February, and the emigrants laboriously made their way to Fort Montezuma, near the present Aneth, and later to the mouth of Cottonwood Creek, where Bluff City was established. On April 5, 1880, this settlement enrolled 225 pioneers, and the foundation was laid for the control of southeastern Utah and adjoining areas in Colorado and New Mexico by adherents of the Mormon faith.

This crossing of the Colorado by the " San Juan missionaries " was a heroic undertaking. It is difficult enough for experienced men with a pack train; for parties that include women and children and loaded wagons it seems impossible. Except for snow in winter, water is available only at nine places on the 215 miles of road, and at three of these places it is strongly alkaline.

From Escalante to the Hole in the Rock the route presents no extreme difficulties. The "road" is of the sort common to southern Utah—a trail along which strongly built wagons may be dragged by 4, 6, or 8 horse teams under the guidance of experienced drivers and where progress is made by "hardening quicksands," removing talus blocks, cutting "dugways," "negotiating" sand dunes, and bumping along over knobs and sharp-cut depressions of extensive surfaces of bare rock. East of the Colorado the topography is forbidding. Short, box-headed tributaries lead from the river to the plateau above, and only at the rough, slippery "Clay Hill divide" is it feasible to cross the dissected uplands. East of the "divide" are the deep canyons that lead to the San Juan, the rough south slopes of Elk Ridge, and the sharply upturned rocks of Comb Wash.

The crossing itself is formidable. A break in the canyon wall marks its west end—a mere slit in the towering cliffs of massive Navajo sandstone. No canyon leads to it, and there is nothing in the surrounding topography to indicate its presence. It may now be found by tracing the marks of wagon wheels across 8 miles of wind-swept rock. After entering the slit the "road" descends by passing through notches in the tops of projecting ledges, down across cliff-faced benches to a platform 600 feet below. The slit originally was a V-shaped groove, too narrow even for a horse if the potholes and steps were absent from its bottom. At one place there is a sheer 40-foot drop into a depression. By blasting rock and building out platforms and by the skillful use of logs brought from the Kaiparowits Plateau, a path was made down which single horses and men on foot might make their way to the river. Wagons were taken apart and carried down on the backs of men and horses, or lowered by ropes. Rusty ringbolts embedded in the cliffs and the remains of a roughly made windlass bear witness to the method employed. Only necessity could induce one to take a horse down this trail; to descend on foot is a strenuous bit of exercise.

The impressions gained by a traverse of this first Escalante-Bluff City trail is confirmed by men who used it. Through the courtesy of the historian of the Church of the Latter-day Saints, the unpublished reports of the San Juan mission have been examined. Like most accounts of men who do much and say little and to whom hardships are part of the daily routine, these reports to headquarters are brief and matter of fact, but they tell of horses lost and died, of grain exhausted, of accidents, of sickness, and of nearness to starvation. The parties east of the river especially seem to have suffered. This crossing at the Hole in the Rock stands high in the list of pioneering achievements for which Utah is famous, and it is doubtful if anything but religious zeal would have made the undertaking possible. But, however difficult this route, there is no other place between Lees Ferry and the Waterpocket Fold where a crossing for wagons could be established without expensive and carefully planned engineering operations. A pack-train traverse of the rim of Glen Canyon makes comprehensible the feeling of these missionary explorers that "We were led as if by inspiration to find the only possible route where a road could be made."

The disadvantages of the road by way of the Hole in the Rock led to the search for a practicable crossing farther upstream. Scouts from Escalante found that the Colorado could be approached without much difficulty at the mouth of Hall Creek, and in 1881 the dangerous Hole in the Rock crossing was abandoned and the ferry boat dragged by horses to a new site—the present little-used Halls Crossing. The first connecting road from Escalante was marked out across Spencer Flat, down the "sand slide" into Escalante Canyon, and along the canyon floor to the mouth of Silver Falls Creek. It continued up Silver Falls Creek and through Muley Twist Canyon in the Waterpocket Fold, thence down Halls Creek to the Colorado.

With the settlement of the upper Fremont Valley and of the lands about the Abajo Mountains, the need developed for a crossing of the Colorado that would not require the long journey down Halls Creek or the still longer journey by way of Green River and Moab. By this time also placer miners were at work on the Colorado, and their operations called for a place on the river to which supplies could be brought either from Colorado towns or from Salt Lake City. In 1880 Dandy Crossing (Hite) was located near the mouth of Trachyte Creek, at a point where the canyon walls break down and an island midway in the current is exposed at low water. The crossings between Hite and Lees Ferry are utilized occasionally by scientific parties, prospectors, and stockmen, but Glen Canyon remains the same barrier across lines of travel that was encountered by the Spaniard, the trappers, and the surveyors for the Pacific railways.

TOPOGRAPHIC OUTLINE

In its larger geographic relations the Kaiparowits region forms part of the Colorado Plateau province, which comprises 100,000 square miles of strongly carved tabular relief emphasized by volcanic masses. The outstanding topographic features are terraced plateaus, cliff-bound mesas, monoclinal ridges, and straight-sided canyons—all impressive alike for magnitude and ruggedness. Land sculpture is developed on so enormous a scale that features in the landscape unnoticed here would be prominent and picturesque landmarks in other surroundings.

The region as a whole lies at an altitude of about 6,000 feet, and the downward departures from this level are approximately equal in amount to the upward departures. (See pl. 3.)

The crest of the Waterpocket Fold stands at 6,000 feet, and for a distance of more than 50 miles the Kaiparowits Plateau shows a level top at 7,000 feet and rises to 9,000 feet at Canaan Peak. But so deeply has the region been trenched that two-thirds of the Paria River, one-half of the Escalante River, and nearly all of Halls Creek flow in channels below 5,000 feet and Glen Canyon is cut to depths below the 4,000-foot contour line. The extreme points of the Kaiparowits region are Table Cliff, 10,500 feet, and Lees Ferry, 3,120 feet. Immediately bordering the region and forming, as it were, its western and northern wall are the High Plateaus—the Paunsaugunt (9,500 feet) and the Aquarius (Thousand Lake Mountain) 10,000 to 12,250 feet—the highest land in southern Utah. For the region as a whole changes in altitude are abrupt; gentle slopes are conspicuously absent. Above the valley floors the plateau benches rise by steps, bench after bench, and into the benches the streams are sunk an equal amount.

Most of these benchlike platforms terminate in cliffs hundreds or even thousands of feet in height. On the south face of the Paunsaugunt Plateau the Chocolate Cliffs, Vermilion Cliffs, White Cliffs, and Pink Cliffs, separated by broad platforms, form a terraced wall more than 5,000 feet high. A series of prominent benches are nearly continuous along the northeast and southwest slopes of the Kaiparowits Plateau, and the southeast end of the plateau forms a giant stairway descending 3,500 feet to the Colorado River, about 5 miles distant. Few benches interrupt the precipitous slope that leads to the top of the Paria Plateau, 3,000 feet above the stream at its base, or the wall that rises more than 4,000 feet in front of the Table Cliff Plateau.

The plateau benches are so continuous that canyons which cut their edges appear at a distance as insignificant breaks in a horizontal sky line. Some of the benches are so wide and level that canyons sunk into them are inconspicuous features. Even Glen Canyon appears from a distance as a narrow groove in a broad expanse of flat land.

Except for the lava flows that partly cover the limestones of the Paunsaugunt and Aquarius Plateaus, all the topographic features of the Kaiparowits region have been developed in sedimentary rocks; the volcanic piles, the laccoliths, and the necks of bordering regions are absent. The Kaiparowits Plateau is a slightly tilted sedimentary mass that extends as a narrow mesa from the High Plateaus to Glen Canyon, 70 miles distant. Its culminating point, Canaan Peak, is an outlier of the Table Cliff Plateau; the Paria Plateau is a huge block of sandstone, the Waterpocket monocline is a ridge of folded rock intricately dissected and flanked by hogbacks, and the broken "comb" in the vicinity of Paria is the edge of sandstone beds upturned in the East Kaibab fold. The Circle Cliffs are inward-facing walls of sandstone that rim an oval depression. These prominent features are but large-scale examples of the mesas, buttes, and ridges that characterize the landscape of southern Utah. The view from any vantage point gives a feeling of strength and solidity. Delicacy and grace of outline are lost in the general massiveness. The huge mesas ringed with high escarpments rise from horizontal benches, some of them miles in width, and the buttes are firmly based on broad expanses of rock. Except on the High Plateaus talus slopes are replaced by bare ledges. Even in detail erosion forms follow a common pattern of angles rather than of curves and slopes; pilasters, panels, and alcoves are bounded by straight lines. Canyons are everywhere. Many of them are trenches cut into a seemingly level surface and are seen only when their rims are reached; others are so intricately interlaced as to leave no space for trails. Near Canaan Peak the heads of 14 canyons were crossed in a distance of about 3 miles.

In general the surface slopes of the region extend from the High Plateaus southeastward to the Colorado; down these slopes the water is carried in bare rock canyons. The Escalante, with its many tributaries, carries the run-off from 1,840 square miles; the Paria drains 935 square miles and receives most of its water from its western tributaries. Halls Creek, 40 miles long, drains about 110 square miles. Rain that falls on the south side of the Kaiparowits Plateau goes directly to Glen Canyon. Few regions are so thoroughly drained. Flat-floored, wide washes are rare, and only on the tops and about the base of the Aquarius and Table Cliff Plateaus are there stretches of meadow, through which the tiny streams make their way. A shallow pond on the Kaiparowits Plateau is the only permanent body of water in the region east of the High Plateaus.

The streams that head in the Paunsaugunt, Table Cliff, and Kaiparowits Plateaus have permanent water in their upper courses, and a few of the boxlike heads of canyons in the Waterpocket Fold contain running water. The characteristic stream of the region is an intermittent one, which usually flows in places along its course but which becomes throughgoing only in response to seasonal rains and local showers. In exceptionally dry years the only water received by the Colorado between the Escalante River and the Paria River is probably contained in the liquid mud supplied by the San Juan. The Paria River and Halls Creek are at times without water in parts of their courses, and even in the Escalante Canyon stretches of bare sand have been recorded. The influence of the semiarid climate shown by the behavior of streams is reflected likewise in the soil and vegetation. There are no large areas of dunes, but sand is piled here and there in and beyond the stream channels. There are no areas of desert in the sense of widespread stretches of salt and alkali, but the lower Escalante Valley and parts of the Wahweap country are without water and show sparse and specialized vegetation, adjusted to sterile soil and low rainfall. The canyon walls, the faces of mesas and buttes, and expanses of rock many square miles in area seem remarkably naked. These wind-swept surfaces are so bare of vegetation that green tints and subdued tones resulting from plant covering are lacking in the landscape. The conspicuous colors seen are the colors of the rocks themselves—red, brown, yellow, and white, intensified by bands of dark gray.

For variety and interest of topographic forms no part of the plateau province offers more attractions. Distant and near-by views amply repay the necessary hardships of travel.

CLIMATE OF SOUTHEASTERN UTAH

GENERAL CONDITIONS

Statistics of rainfall and temperature within the Kaiparowits region are meager and unsatisfactory. Because of their position the three meteorologic stations in this region record data of little more than local value. Escalante is at the immediate base of the High Plateaus; Cannonville (including Losee and Tropic) is near the head of a broad, deeply intrenched valley; Paria is in a canyon. All three stations lie approximately in a north-south line, and their records tell little of the climatic conditions prevailing east or west of that line. However, the records of these three stations, when considered in connection with those of other stations in Kane and Garfield Counties and in adjoining counties, give a reasonably satisfactory picture of the climate of southeastern Utah, of which the Kaiparowits region forms a part.

Utah as a whole is deficient in rainfall. Only 16 out of 169 stations record averages that exceed 20 inches a year, and only 1 that exceeds 30 inches. Less than 10 inches of rain falls at 50 stations. The High Plateaus are relatively well watered and have severe winters; most stations in this district receive more than 10 inches of rain each year and record mean annual temperatures of about 43°. At the eastern foot of the High Plateaus the rainfall is as heavy as the average on top of the plateaus, but the mean annual temperatures are greater. Between the base of the plateaus and the Utah-Colorado line all stations record less than 10 inches of rain except Blanding and Monticello, on the slopes of Abajo Mountain. The mean annual temperature at Giles is 51.1° and at Hite 59.7°.

Snow may fall on the High Plateaus at any time between September 1 and June 1 and may lie for weeks or even months. Only in exceptional years are the roads to Kanab, to Cannonville, to Escalante, and to Boulder passable in winter without clearing the drifts that block the "dugways." In severe winters these settlements have been isolated for weeks at a time.

On the lower lands of the Escalante, Wahweap, and Warm Creek Valleys snow rarely remains long enough to interfere with grazing, but all parts of southeastern Utah receive some snow nearly every year. At Alton the mean annual snowfall is 75.6 inches, and even at Giles it is 10.2 inches.

In southeastern Utah clear skies prevail. The few records available indicate that the amount of sunshine is comparable to that in northern Arizona, for which the estimate of the United States Weather Bureau is 210 clear days, 85 partly cloudy, and 70 cloudy in a year. It is probable that few if any places in southeastern Utah have less clear skies than Flagstaff, Ariz., which receives 81 per cent of the posssible sunshine, and for parts of Garfield and Kane Counties the figure is doubtless greater. During May, June, October, and November the skies may be cloudless for 5 to 15 days in succession. In the sun the heat of summer is intense; but in the shade of a rock or tree coolness prevails, and this area is unlike humid regions in that the line between scorching heat and delightful temperature is drawn at the edge of the shadow. Fortunately hot air is also dry air, and the humidity of summer ranges from 30 to 50 per cent. The daily range of temperature is more than 40° and usually exceeds the difference between the means of the warmest and of the coolest months in the year; consequently cool or even uncomfortably cold nights follow the heated days.

In general, it may be said that southern Utah has a group of local climates of widely dissimilar aspects. The distribution of the sun's heat and the form and position of topographic features appear to outrank cyclonic storms and prevailing winds as controlling factors. The great variability in topographic expression is reflected in equally great differences in climate. Not only are the climates of high-lying areas contrasted with those of lower altitudes, but canyons that adjoin plateaus, two adjoining valleys, the opposite sides of plateaus and mesas, and even opposing canyon walls may have different climates. The summers are very hot, the winters are cold; daylight is accompanied by heat, darkness by chilliness. The annual, seasonal, monthly, and daily rainfall is subject to wide variations. During July and August rain may fall in quantities sufficient to flood the country; in most other months precipitation is deficient. During the hottest months moisture-laden clouds cross the sky but produce no rain, except perhaps a few scattering drops. To the Navajo and Piute mind the " rain hangs downward " and " sends messages to the earth."

PRECIPITATION

RECORDS

Some miscellaneous observations on the rainfall of southeastern Utah are contained in the reports of earlier scientific explorers, and others are recorded in unpublished reports in the archives of the Mormon Church. Additional general information has come from long-time residents of Kane and Garfield Counties. Fortunately volunteer observers have made instrumental records at stations within and bordering the Kaiparowits region; without these unselfish services a discussion of the climate would be wholly speculative.

Cannonville, including Tropic (1889–1919; 1925–26) and Losee (1893–94), furnishes the longest continuous record of precipitation in the Kaiparowits region. It affords nearly complete records for 35 years (1889–1923). At Alton, including Ranch (1902–1915), the precipitation has been recorded for 26 consecutive years (1902–1927). At Escalante the rainfall observations cover 27 years (1901–1927) but are neither consecutive nor complete. For Giles consecutive and complete records are available for 12 years (1895–1906). For Hite the records for 15 consecutive years (1900–1914) include 12 complete records. At Kanab records have been made since 1899, except during 1901 and 1908–1910, but for only 15 years are there complete records, and only three groups of 4 years in regular succession. Paria has records for 6 years (1895–1900), including 5 years consecutive and complete. The observations at Widtsoe cover 16 consecutive years, which include 10 years of full record, with two groups of 4 years in regular succession. The records for these eight stations are too fragmentary for general climatic studies; they suffice, however, to indicate the nature of the rainfall. They enable those interested in water development and agriculture to plan intelligently, for they indicate in a general way the total precipitation, its distribution with reference to the growing season for crops, and whether showers of brief duration or long-continued " soaking " rains normally occur.

Records of precipitation in southern Utah, in inches

[T=Trace]

Alton, Kane County

Altitude, 7,000 feet. Record from January, 1902, to May, 1915, inclusive, from Ranch, about 6 miles southwest of Alton]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1902	2.41	2.54	6.06	1.08	0.64	T.	0.05	2.25	0.25	0.50	5.59	1.66	23.03
1903	1.03	1.11	4.31	2.28	1.40	1.56	.88	.45	3.02	1.09	T.	T.	17.13
1904	T.	2.63	3.99	.44	1.80	.08	2.64	3.01	.27	T.	0	.10	14.96
1905	3.15	7.60	3.07	2.07	1.88	0	2.28	.24	3.26	.60	3.25	.26	27.66
1906	2.50	1.65	12.02	2.55	.64	T.	2.94	3.85	.70	T.	2.16	3.51	32.52
1907	6.69	2.01	3.87	2.02	2.58	.34	5.0	.77	.10	3.41	.35	2.01	21.65
1908	.80	3.08	2.88	1.00	1.08	T.	2.22	2.05	1.74	2.62	.22	2.34	20.03
1909	4.44	5.36	2.55	T.	T.	T.	1.46	7.68	3.80	0	4.67	4.89	34.85
1910	2.52	.81	.42	.44	T.	.46	2.88	2.28	3.76	2.97	2.01	1.32	19.87
1911	10.85	3.47	3.46	.24	.24	1.08	.90	.30	6.14	.24	.10	1.80	28.82
1912	.35	.55	8.23	3.10	.10	.14	1.39	1.30	0	7.78	.61	.44	23.99
1913	1.24	3.41	.86	T.	0	.69	3.09	2.40	1.70	.19	5.88	1.18	20.64
1914	6.69				.98	2.93	3.76	.30	.93	1.57	T.		
1915					2.81	.22	2.21	.63	1.80	0	1.96	2.53	
1916	8.38	1.48	3.91	.73	.35	0	4.72	2.06	1.23	3.73	0	1.81	28.40
1917	1.76	1.62	.29	3.05	1.62	.01	1.57	.76	1.32	.05	.17	0	12.22
1918	.55	2.00	6.81	.43	.40	.51	1.93	3.43	1.10	1.15	1.50	2.52	22.33
1919	.25	1.25	1.04	.40	1.67	.32	.99	.91	2.21	1.36		.75	
1920	1.09	3.26	3.33	.34	1.01	.69	.74	2.32	.60	3.46	.40	.67	17.91
1921	2.23	.53	.81	.98	1.10	.90	2.70	3.02	.13	1.51	.60	5.59	20.10
1922	1.90	1.13	.55	1.01	.53	0	.62	2.83	.86	.58	.80	2.52	13.33
1923	1.39	1.03	.38	2.58	.29	.16	1.82	1.58	.48	.45	.50	.79	11.45
1924	.61	0	2.38	1.37	.51	0	2.09	.19	1.43	.51	.84	1.68	11.61
1925	.12	.47	1.14	1.40	.17	1.06	.93	4.07	2.53	3.32	1.19	.93	17.33
1926	.14	2.00	.76	5.48	1.41	.13	.77	.76	1.45	.18	1.60	1.91	16.59
1927	1.29	3.75	1.43	.69	.20	1.16	.33	2.90	4.93	1.72	.61	1.26	20.27
Mean	2.50	2.20	3.11	1.36	.90	.47	1.78	2.01	1.76	1.50	1.40	1.69	20.86

Period	Mean	Total for driest year	Total for wettest year	Period	Mean	Total for driest year	Total for wettest year
December	1.69	0.79	4.89	June	0.47	0.16	T.
January	2.50	1.39	4.44	July	1.78	1.82	1.46
February	2.20	1.03	5.36	August	2.01	1.58	7.68
Winter	6.39	3.21	14.69	Summer	4.26	3.56	9.14
March	3.11	.38	2.55	September	1.76	.48	3.80
April	1.36	2.58	T.	October	1.50	.45	0
May	.90	.29	T.	November	1.40	.50	4.67
Spring	5.37	3.25	2.55	Fall	4.66	1.43	8.47
				Annual	20.68	11.45	34.85

Kanab, Kane County

[Altitude, 4,925 feet]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1899												0.60	
1900	0.10	0.00	0.00					0.00					
1901													
1902										0.00	3.98	1.37	
1903	.89	1.24	5.55	2.79	0.71	0.96	0.89	1.34	0.75	.80	.00	.00	15.92
1904	.10	1.00	1.01	.10	.90	T.	2.50	1.40	.70	.80	.00	.10	8.61
1905	2.10	4.30	3.10	1.40	1.20	.00	.30	1.10	1.80	.90	3.20	.50	18.90
1906	4.00	T.	8.50	.30	.10	.00	1.30	2.00	.30	.20	1.40	2.60	20.70
1907		1.00	1.30	1.40	2.30	.40	T.						
1911							1.04		2.70	.60	T.	.88	
1912	.03	.07	4.38	1.39	.29	.04	1.91	2.17	.35	4.13	.30	.20	14.26
1913	.60	2.50	.50	.40	.10	.35	1.20	.95	1.54	.25	2.40	.80	11.59
1914	4.65	1.25	.46	1.06	.80	1.96	1.93	.52	.79	.51	.05	1.14	15.12
1915	1.94	2.27	.10	1.88	1.33	.15	.76	.24	.00	.00	1.82	1.36	11.85
1916	5.51	.94	1.24	1.05	.40	.00	2.61	.70					
1917		.79	.13	3.30	1.50	.00	4.23		.71				
1918		1.21	5.04							.54	.58	2.67	
1919	.57	.52	.55			.15	3.22			.61			
1920	.60	3.30	1.41	.50	.54	.08	.00	.50	.83	2.41	.13	.92	10.62
1921	2.54	.00	1.53	.50	.71	.17	.82	3.52					
1922	1.19	1.28	.88	1.56	.59	.42	1.45	3.42	.55	.65	1.09	1.69	14.77
1923	1.18	.62	1.30	1.37	.32	.08	3.06	1.25	1.54	.21	.47	.95	12.35
1924	.21	.05	1.25	.65	.20	.00	.28	.68	1.51	.05	.10	2.31	7.29
1925	.10	.73	1.55	1.15	.07	.59	.47	.64	2.10	3.19	.42	.43	11.44
1926	.00	1.82	.59	4.51	.40	.03	.17	.49	1.37	.29	1.45	1.63	12.75
1927	.80	3.06	1.63	.12	T.	.68	.47	2.40	4.33	2.37	.87	1.27	18.00
Mean	1.43	1.27	2.05	1.34	.66	.30	1.36	1.30	1.26	.97	1.01	1.12	12.68

Records of precipitation in southern Utah, in inches—Contd.

Kanab, Kane County—Continued

Period	Mean	Total for driest year	Total for wet-test year	Period	Mean	Total for driest year	Total for wet-test year
December	1.12	2.31	2.60	June	0.30	0.00	0.00
January	1.43	.21	4.00	July	1.36	.28	1.30
February	1.27	.05	T.	August	.30	.68	2.00
Winter	3.82	2.57	6.60	Summer	2.96	.96	3.30
March	2.05	1.25	8.50	September	1.26	1.51	.30
April	1.34	.65	.30	October	.97	.05	.20
May	.66	.20	.10	November	1.01	.10	1.40
Spring	4.05	2.10	8.90	Fall	3.24	1.66	1.90
				Annual	14.07	7.29	20.70

Paria, Kane County

[Altitude, 4,700 feet]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1895	1.26	1.70	0.10	0.05	1.30	1.50	0.60	1.50	1.00	0.90	1.50	0.25	11.66
1896	.50	.05	.30	.50	.20	1.00	.73	1.90	.40	1.30	.20	.10	6.18
1897	1.50	1.30	1.00	3.25	.50	.00	1.70	1.00	2.20	1.10	.04	.50	14.09
1898	2.65	.20	T.	.60	1.10	1.20	.01	1.50	.00	.00	T.	.10	7.36
1899	.70	.80	.25	T.	T.	1.00	.60	.20	T.	1.10	.20	T.	4.85
1900	T.	.00	.12	----	----	----	----	----	----	----	----	----	----
Mean	1.10	.68	.30	.88	.62	.74	.73	1.22	.72	.88	.39	.19	8.45

Period	Mean	Total for driest year	Total for wet-test year	Period	Mean	Total for driest year	Total for wet-test year
December	0.19	T.	0.50	June	0.74	1.00	0.00
January	1.10	0.70	1.50	July	.73	.60	1.70
February	.68	.80	1.30	August	1.22	.20	1.00
Winter	1.97	1.50	3.30	Summer	2.69	1.80	2.70
March	.30	.25	1.00	September	.72	T.	2.20
April	.88	T.	3.25	October	.88	1.10	1.10
May	.62	T.	.50	November	.39	.20	.04
Spring	1.80	.25	4.75	Fall	1.99	1.30	3.34
				Annual	8.45	4.35	14.09

Cannonville, Garfield County

[Altitude, 6,000 feet]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1889 [a]	----	----	----	----	0.35	0.15	5.25	2.42	0.40	1.10	T.	8.50	----
1890	1.10	2.40	0.55	0.40	.40	.00	3.30	1.20	1.50	.90	1.15	.80	13.70
1891	T.	1.30	.45	1.00	1.10	1.20	1.40	1.50	3.60	.00	.00	1.50	13.05
1892	1.70	1.45	1.40	.10	2.20	T.	.50	T.	T.	1.00	.00	.20	8.55
1893	.90	.30	2.65	T.	.40	.00	1.20	4.50	.80	T.	.40	1.30	12.45
1894	.30	.40	1.40	T.	.03	T.	1.00	1.70	.80	.03	----	----	----
1897	----	----	1.30	.20	.92	.26	----	----	3.77	1.50	----	----	----
1898	1.00	.40	T.	.88	1.21	.81	.58	.52	T.	.00	T.	T.	5.40
1899	1.40	T.	.10	.34	.14	.69	1.50	.55	T.	1.34	.38	.18	6.62
1900	.06	T.	.22	4.83	.12	.27	.15	.76	3.40	.88	.98	.00	11.67
1901	1.20	4.80	T.	.30	.73	T.	1.20	1.72	.00	.52	T.	.20	10.67
1902	.30	.49	2.00	1.10	.86	.00	.57	1.31	.22	.22	1.93	.46	9.46
1903	T.	.95	.32	.74	.53	.87	.59	.20	1.98	.00	.00	T.	6.18
1904	T.	T.	T.	T.	1.25	.81	.92	2.69	T.	T.	.00	.10	5.77
1905	.90	2.71	1.25	.70	1.11	T.	.83	.10	2.00	T.	4.97	.40	14.97
1906	.67	.70	4.87	1.95	.86	T.	2.99	3.64	1.31	T.	1.90	2.89	21.78
1907	3.60	.16	.39	1.21	1.33	.67	.34	3.48	.26	2.97	T.	.08	14.49
1908	.19	.23	.07	.08	.90	.26	1.45	1.27	1.36	1.50	.01	.15	7.47
1909	.15	.25	.12	.01	T.	T.	.91	5.39	2.45	T.	1.79	3.62	14.69
1910	2.40	.14	1.13	.20	.00	1.08	1.04	1.45	3.47	2.18	1.45	.09	14.63
1911	2.88	1.30	.52	.00	T.	.99	1.73	.00	2.50	.84	.40	.17	12.33
1912	.30	.30	1.67	1.20	T.	.21	1.75	1.23	.00	4.25	.02	.10	11.08
1913	.08	1.70	.40	T.	T.	.48	1.30	1.38	1.69	.11	1.16	1.60	9.90
1914	2.41	1.20	.48	.97	1.30	1.05	5.17	.72	.05	.81	T.	.80	14.96
1915	2.59	3.72	T.	1.54	1.24	.12	.43	1.22	.84	.00	.92	1.84	14.46
1916	4.92	.39	.61	.34	.13	.00	2.32	----	----	----	----	----	----
1917	----	2.00	----	----	----	----	.39	.89	.00	.00	.00	.00	----
1918	.20	.10	1.50	.35	.00	.15	.93	.00	.10	.95	.23	T.	4.51
1919	.60	----	----	----	----	----	----	----	----	----	----	----	----
1920	----	----	----	.24	.82	----	----	----	----	----	T.	.75	----
1921	2.11	.50	.94	----	----	----	----	----	----	----	----	----	----
1922	----	----	----	----	----	----	----	----	T.	.71	.54	.90	----
1923	.79	.53	.38	1.47	.30	.03	1.18	2.08	.80	----	1.00	.50	----
1924	.60	T.	.96	----	----	----	----	----	----	----	----	----	----
1925	T.	.39	----	----	.00	.64	.71	3.37	3.03	2.21	.78	.19	----
1926	T.	.94	----	----	----	----	----	----	----	----	----	----	----
1927	----	----	----	.05	.00	.53	2.99	3.59	3.49	.19	.03	1.10	----
Mean	1.07	.96	.89	.70	.58	.38	1.39	1.69	1.28	.81	.67	.95	11.37

Records of precipitation in southern Utah, in inches—Contd.

Cannonville, Garfield County—Continued

Period	Mean	Total for driest year	Total for wet-test year	Period	Mean	Total for driest year	Total for wet-test year
December	0.95	T.	0.40	June	0.38	0.15	T.
January	1.07	0.20	.90	July	1.39	.93	0.83
February	.96	.10	2.71	August	1.69	.00	.10
Winter	2.98	.30	4.01	Summer	3.46	1.08	.93
March	.89	1.50	1.25	September	1.28	.10	2.00
April	.70	.35	.70	October	.81	.95	T.
May	.58	.00	1.11	November	.67	.23	4.97
Spring	2.17	1.85	3.06	Fall	2.76	1.28	6.97
				Annual	11.37	4.51	14.97

[a] Record prior to 1920 and for 1925 and 1926 for Tropic, 4 miles north of Cannonville.

Widtsoe, Garfield County

[Altitude, 7,000 feet. Post office formerly called Winder]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1912	----	----	2.86	1.80	0.10	0.22	0.85	----	----	----	----	----	----
1913	----	----	----	----	.03	.39	1.96	2.75	0.94	0.00	1.87	0.55	----
1914	0.95	1.02	.48	1.15	1.69	1.81	2.26	----	----	----	----	----	----
1915	1.00	.40	.25	1.98	1.52	.24	1.28	.28	.67	.01	.36	.53	8.52
1916	2.00	.11	.13	.04	.41	.00	2.75	3.40	.74	.96	.00	.98	11.52
1917	.67	2.60	.42	.20	1.26	.10	2.31	.13	.82	.00	.00	.00	8.51
1918	.80	1.00	2.20	.00	.01	.12	2.35	.20	.60	.20	1.00	.95	9.43
1919	.20	2.80	.95	----	----	.00	3.41	.06	----	.18	1.94	T	----
1920	.18	1.04	.85	.05	.35	.75	1.15	1.42	1.37	1.34	1.19	.46	10.15
1921	1.35	.10	.54	.55	.59	.00	.90	2.86	.09	2.15	.70	2.78	12.61
1922	.98	.60	.46	1.28	.35	.33	.38	1.88	.98	.13	.59	.21	8.17
1923	1.08	.13	.37	2.02	.39	.07	.89	2.60	1.31	.71	.29	.79	10.65
1924	.35	.07	.72	1.14	.57	.00	1.34	.52	1.32	.90	.15	1.46	8.54
1925	.00	.29	.44	1.25	.02	1.15	1.30	4.06	1.24	----	----	----	----
1926	T.	----	----	----	----	----	----	1.32	.84	.33	.50	.65	----
1927	.61	1.06	1.35	.71	T	1.10	1.40	2.68	3.95	.95	.60	1.00	15.41
Mean	.73	.86	.86	.93	.52	.42	1.64	1.73	1.14	.60	.71	.80	10.35

Period	Mean	Total for driest year	Total for wet-test year	Period	Mean	Total for driest year	Total for wet-test year
December	0.80	0.98	1.00	June	0.42	0.38	1.10
January	.73	.60	.61	July	1.64	1.88	1.40
February	.86	.46	1.06	August	1.73	.98	2.68
Winter	2.39	2.04	2.67	Summer	3.79	3.24	5.18
March	.86	1.28	1.35	September	1.14	.13	3.95
April	.93	.35	.71	October	.60	.59	.95
May	.52	.33	T.	November	.71	.21	.60
Spring	2.31	1.96	2.06	Fall	2.45	.93	5.50
				Annual	10.94	8.17	15.41

Escalante, Garfield County

[Altitude, 5,700 feet]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1901	----	----	----	----	0.16	----	----	3.46	T.	0.56	T.	T.	----
1902	1.90	0.30	2.55	0.90	.23	T.	1.00	1.40	0.25	.21	1.52	0.50	10.76
1903	1.50	.50	.30	.56	.60	1.43	1.87	.43	1.10	.41	.00	.00	8.70
1904	.10	.38	1.55	.54	.60	.21	.86	2.58	1.61	.46	.00	.10	8.99
1905	1.40	2.90	1.20	----	.87	T.	----	----	----	----	----	----	----
1906	----	----	----	----	.66	.00	----	----	1.21	.14	2.31	2.99	----
1907	2.90	1.58	1.06	.64	1.40	.35	.58	1.53	.33	2.70	.19	.40	13.66
1908	1.60	1.17	.05	.48	.63	.08	.20	1.06	1.61	1.39	.17	1.40	9.84
1909	1.31	.90	.23	.05	.03	.00	1.63	4.21	2.61	.00	1.40	1.24	13.61
1910	2.45	1.00	.32	.43	.00	.72	3.21	2.72	1.63	1.31	.22	1.04	15.05
1911	1.58	1.50	1.63	.00	.02	1.35	1.17	1.65	2.83	.32	.25	.55	12.85
1912	.00	.60	1.36	----	.00	----	----	----	.06	2.51	.03	.18	----
1913	----	.66	----	----	.00	----	2.14	.55	.90	----	----	----	----
1916	----	----	----	----	----	.01	3.13	1.25	.02	5.57	T.	1.09	----
1917	1.13	1.00	T.	1.00	1.56	.00	1.69	.82	1.53	.00	.00	.00	8.73
1918	.22	.66	3.46	.42	.00	2.39	2.40	.56	.46	.12	.53	.60	11.82
1919	.08	1.80	.90	.12	.55	T.	.16	----	----	.20	1.90	T.	----
1920	.71	1.17	1.00	----	.60	25	.00	----	----	----	----	----	----
1921	----	----	----	.00	----	.00	1.02	4.40	.00	.90	.30	4.30	----
1922	.80	.45	.60	1.35	.50	.00	.50	3.20	2.10	.20	1.10	.40	11.20
1923	1.05	.50	.20	.70	.20	.00	2.50	4.50	1.10	----	1.40	.33	----
1924	.20	.00	2.50	.60	----	.03	.13	.50	.92	.00	.02	----	----
1925	.00	----	.11	1.00	.00	----	.06	2.80	2.20	2.60	1.10	.00	----
1926	.03	.05	.07	2.20	.50	.50	1.90	2.80	1.20	.20	.40	1.00	10.85
1927	40	2.10	1.10	.00	.00	2.50	3.40	3.20	5.70	1.70	.20	1.40	21.70
Mean	.97	.96	1.01	.61	.46	.47	1.40	2.18	1.33	1.02	.59	.83	12.14

Records of precipitation in southern Utah, in inches—Contd.

Escalante, Garfield County—Continued

Period	Mean	Total for driest year	Total for wet-test year	Period	Mean	Total for driest year	Total for wet-test year
December	0.83	0.00	1.40	June	0.47	1.43	2.50
January	.97	1.50	.40	July	1.40	1.87	3.40
February	.96	.50	2.10	August	2.18	.43	3.20
Winter	2.76	2.00	3.90	Summer	4.05	3.73	9.10
March	1.01	.30	1.10	September	1.33	1.10	5.70
April	.61	.56	.00	October	1.02	.41	1.70
May	.46	.60	.00	November	.59	.00	.20
Spring	2.08	1.46	1.10	Fall	2.94	1.51	7.60
				Annual	11.83	8.70	21.70

Hite, Garfield County

[Altitude, 3,500 feet]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1900	----	----	T.	----	----	----	0.00	0.12	----	----	----	----	----
1901	----	----	----	----	----	T.	T.	.35	0.00	----	----	----	----
1902	0.30	0.60	T.	T.	0.40	0.00	.09	.87	.65	T.	1.23	0.20	4.40
1903	.30	.24	0.63	0.26	.23	.50	.63	T.	.32	T.	.00	.00	3.12
1904	.10	.60	.45	T.	.84	.08	.15	1.06	.55	0.36	.00	.25	4.44
1905	.76	1.52	1.31	.98	1.58	T.	.45	.19	1.59	.15	3.83	T.	12.36
1906	.74	.22	1.42	.39	.45	T.	.45	1.28	1.84	.11	1.75	.76	9.41
1907	.53	.45	.51	.82	1.41	.48	1.21	1.31	.21	.62	.45	.30	8.30
1908	0.31	1.43	.84	.20	.28	.14	1.06	1.14	.63	1.29	.18	1.83	9.33
1909	1.27	.84	.43	.63	.06	.00	.36	1.05	1.70	T.	.10	2.27	8.71
1910	.97	.21	.87	.12	T.	.77	T.	.58	.22	.67	.85	.74	6.00
1911	.78	.78	.53	.35	.00	1.22	.64	.26	1.12	2.92	.15	.68	9.43
1912	.08	.34	2.28	.44	.12	.03	.47	.14	.08	2.25	.14	.48	6.85
1913	.31	.81	.28	.14	T.	.05	.44	.50	.62	.58	.66	.77	5.16
1914	2.12	.82	.19	.37	1.10	1.06	1.41	----	----	----	----	----	----
Mean	.66	.68	.70	.33	.50	.31	.49	.63	.73	.75	.78	.69	7.28

Period	Mean	Total for driest year	Total for wet-test year	Period	Mean	Total for driest year	Total for wet-test year
December	0.69	0.00	T.	June	0.31	0.50	T.
January	.66	.30	0.76	July	.49	.63	0.45
February	.68	.24	1.52	August	.63	T.	.19
Winter	2.03	.54	2.28	Summer	1.43	1.13	.64
March	.70	.64	1.31	September	.73	.32	1.59
April	.36	.26	.98	October	.75	T.	.15
May	.50	.23	1.58	November	.78	.00	3.83
Spring	1.56	1.13	3.87	Fall	2.26	.32	5.57
				Annual	7.28	3.12	12.36

Giles, Wayne County

[Altitude, 4,000 feet]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1895	0.26	0.51	T.	T.	0.10	0.12	0.14	0.17	0.35	1.04	0.42	T.	3.11
1896	.10	.00	T.	T.	.30	T.	.61	.78	2.00	.17	T.	T.	3.96
1897	1.10	.89	0.24	1.57	.24	T.	.43	.69	1.02	3.20	.55	0.23	10.16
1898	.90	.20	T.	.46	.83	.47	.36	.59	T.	.00	.14	.25	4.20
1899	.28	T.	.56	.78	.03	.72	.93	.78	.18	.26	.23	.43	5.18
1900	.29	.00	T.	.54	T.	.07	T.	.39	.29	.27	.40	.00	2.25
1901	.18	.33	T.	.29	.44	.03	.04	1.56	.00	.25	T.	T.	3.12
1902	T.	.06	.41	.03	.25	.14	.30	.40	.57	.05	.70	.29	3.20
1903	.10	.42	.26	.72	1.12	.65	.85	.12	1.17	.27	.00	T.	5.68
1904	T.	T.	1.10	.23	.62	.47	.31	1.28	.88	.34	.00	.50	5.73
1905	.47	1.28	.48	.78	1.30	.05	1.50	1.15	.87	.42	3.57	.12	11.99
1906	.82	.20	1.03	1.22	.72	.00	.65	.43	1.27	.20	1.20	.50	8.24
Mean	.38	.32	.38	.55	.50	.23	.51	.70	.72	.54	.60	.19	5.62

Period	Mean	Total for driest year	Total for wet-test year	Period	Mean	Total for driest year	Total for wet-test year
December	0.19	T.	0.12	June	0.23	0.12	0.05
January	.38	0.26	.47	July	.51	.14	1.50
February	.32	.51	1.28	August	.70	.17	1.15
Winter	.89	.77	1.87	Summer	1.44	.43	2.70
March	.38	T.	.48	September	.72	.34	.87
April	.55	T.	.78	October	.54	1.04	.42
May	.50	.10	1.30	November	.60	.42	3.57
Spring	1.43	.10	2.56	Fall	1.86	1.80	4.86
				Annual	5.62	3.10	11.99

GEOGRAPHIC DISTRIBUTION

The influence of geographic position on distribution of rainfall is apparent on comparison of the records of the different stations. In the lower parts of valleys tributary to the Colorado the rainfall is low; at Giles, Hite, and Paria, with altitudes of 4,000, 3,500, and 4,700 feet, the mean annual rainfall is 5.62, 7.28, and 8.45 inches, respectively. The only record at Lees Ferry is 9.96 inches for the wet year 1916. Of these stations only Giles presents records considered typical for areas with altitudes below 4,000 feet. The rainfall at Hite is affected by nearness to the Henry Mountains and at Paria by the presence of converging valleys. For most places along Glen Canyon the rainfall is probably less than 5 inches; vegetation is unusually deficient. As the Colorado tributaries are ascended the rainfall increases. Along the Paria River Cannonville, 35 miles upstream from Paria and 1,300 feet higher, receives a third more rain, and along Kanab Creek Alton, 30 miles upstream and 2,000 feet higher than Kanab, receives nearly twice as much rain.

It is interesting to compare the rainfall of two counties, Sevier and Piute, wholly within the High Plateaus, with that of two adjoining counties, Emery and Wayne, that lie east of the plateau rim. (See fig. 2.) From the beginning of the record to 1920 the average rainfall of three plateau stations in Sevier County is 11.47 inches; of Emery County, 7.36 inches. In Sevier County Plateau station (altitude 7,000 feet) received 15.19 inches. In Emery County the rainfall decreases regularly eastward from Castledale (5,500 feet), with 9.03 inches of rain, through Victor and Woodside to Green River (4,080 feet), where 5.62 inches is recorded. East of Green River, in Grand County, the rainfall increases with the altitude. The record of Cisco (4,385 feet) is 6.33 inches, and for Thompson (5,150 feet) 8.17 inches.

A comparison of Piute County with Wayne County shows the same relations. The average rainfall for the stations of Piute County is 9.98 inches, for Wayne County it is 6.80 inches, and a decrease is recorded as the Fremont River is descended. At Giles the rainfall is 5.62 inches.

In crossing Garfield County from the heart of the High Plateaus to the Colorado the precipitation decreases from 11.52 inches at Panguitch (altitude 6,560 feet) to 7.28 inches at Hite, 115 miles east (3,500 feet).

VARIATION FROM YEAR TO YEAR

The variation in amount of rainfall from year to year ranges between less than half the normal and twice the normal, measured through a period of years. (See fig. 3.) The records for Alton show that 3 years of excessive rainfall occurred during a 26-year period—32.52 inches in 1905, 34.85 inches in 1909 (the heaviest rainfall for this station), and 28.82 inches in 1911. The precipitation preceding and following these

" wet " years was near normal. The driest year on record at Alton is 1923, with a precipitation of only 11.5 inches, or about half the normal, and this year was preceded and followed by other dry years. At Cannonville, where the mean annual rainfall is 11.37 inches, 4.51 inches was recorded for 1918 and nearly five times as much (21.78 inches) for 1906. The corresponding extremes for Hite are 3.12 and 12.36 inches; for Kanab, 7.29 and 20.70 inches; for Paria, 4.85 and 14.9 inches; and for Giles, 2.25 and 11.99 inches. Extreme variation in successive years is shown by records at Cannonville, 5.77 and 14.97 inches; at Hite, 4.44 and 12.36 inches; at Kanab, 8.61 and 18.90 inches; at Paria, 6.18 and 14.09 inches; and at Giles, 3.96 and 10.16 inches. The fragmentary records show that drought was general in southeastern Utah in 1896, 1899, 1902–1904, and 1916–1918, and 1922–1924 and that abnormal amounts of rain fell during the years 1905–1911, a period that includes the wettest years at Alton, Cannonville, Escalante, Giles, Hite, and Kanab. At all stations of record 1927 was a wet year. These dry and wet periods are not, however, made up of years that show corresponding records for all stations. Wide variations at one station are not matched by similar fluctuations at all other stations.

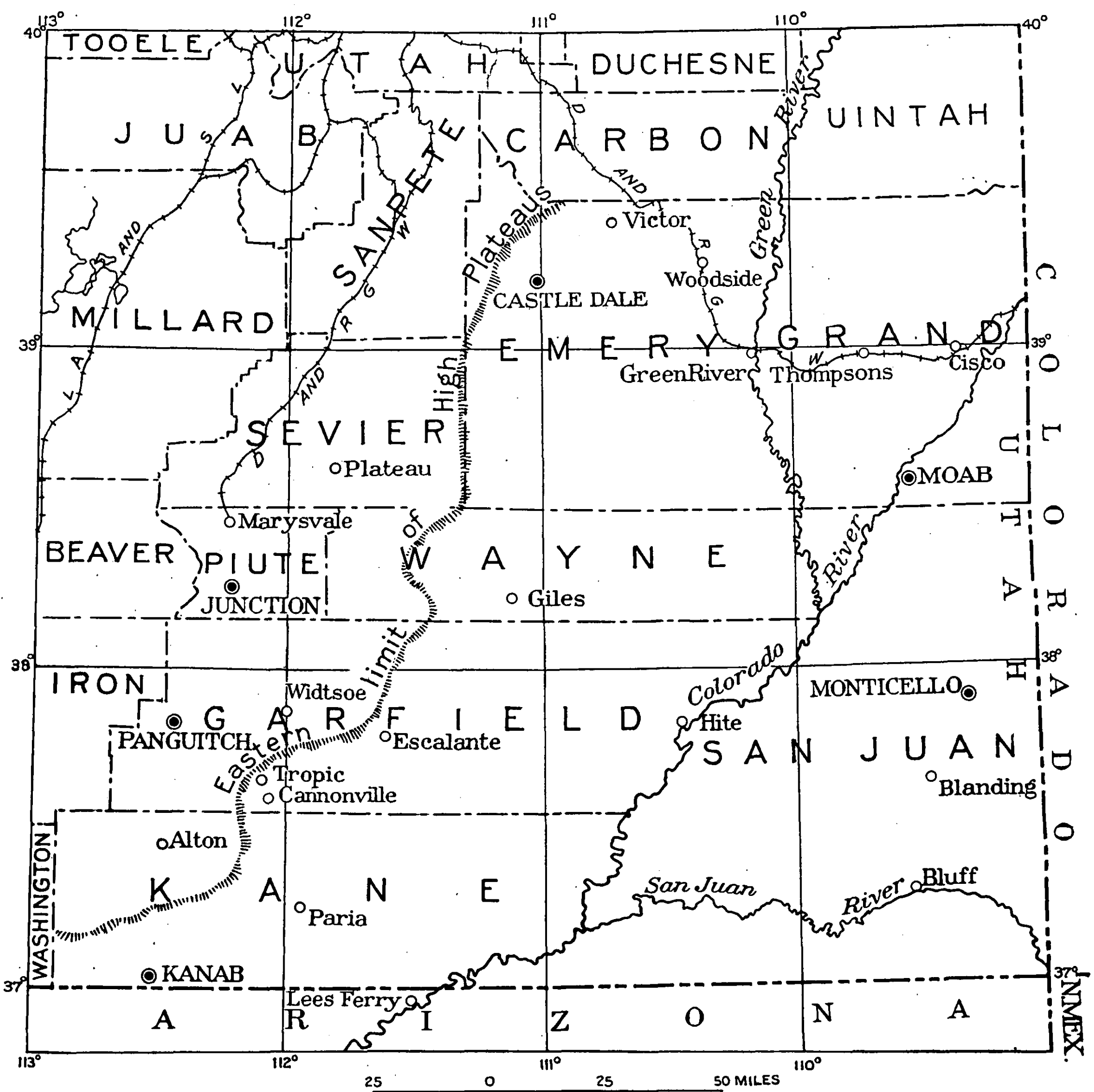


FIGURE 2.—Map of southeastern Utah showing location of meteorologic stations with reference to the rims of the High Plateaus and to Colorado Valley

SEASONAL DISTRIBUTION

For a region whose maximum precipitation is insufficient for agriculture and in places for grazing, without irrigation, great variations in rainfall from year to year are significant. Of even greater significance is the amount of rainfall received in corresponding months from year to year. In this respect southeastern Utah is seriously handicapped. (See fig. 4.)

At Escalante the precipitation for January ranges from 0 to 2.45 inches; for July from 0 to 3.40 inches;

and even for August, the wettest month of the year, from 0.43 to 4.50 inches. At Giles the difference for the months of different years is as follows: January, trace to 1.10 inches; February, 0 to 1.28 inches; March, trace to 1.10 inches; April, trace to 1.57 inches; May, trace to 1.12 inches; June, 0 to 0.72 inch; July, trace to 1.50 inches; August, 0.17 to 1.56 inches; September, trace to 2 inches; October, 0 to 3.20 inches; November, 0 to 1.20 inches; December, 0 to 0.50 inch. For some months the rainfall of the driest year exceeds that of the wettest year. Similar contrasts occur in the records of other stations.

The diagrams of seasonal distribution of rainfall (fig. 4) show that summer is the rainy season for Cannonville, Escalante, Paria, and Widtsoe, winter at Alton, winter and spring at Kanab, and fall at Giles and Hite. The records for Cannonville, Escalante, Giles, Hite, and Widtsoe indicate one dry season followed by one wet season with two seasons of intermediate grade. Alton and Kanab have a dry season, preceded and followed by wet seasons. Paria has three dry seasons. These periods, however, do not correspond with the seasons, as that term is conventionally used. The period July, August, and September is the season for maximum precipitation at Cannonville, Escalante, Giles, Paria, and Widtsoe, during which 36 per cent of the total rain falls; and April, May, and June constitute the driest group, with 20 per cent of the precipitation. Rainfall in January to March is slightly greater than in October to December; these seasons receive, respectively, about 23 and 21 per cent of the annual precipitation. For Alton and Kanab, January to March constitute the rainy season; for Hite, October to December.

The season of least rainfall, April to June, is the growing season for most crops, and therefore the seasonal distribution of rain is unfavorable for agriculture or vigorous reproduction of many grasses. Half an inch of rain a month for the period April to June is an unusually large precipitation for most parts of southeastern Utah, and during dry years the combined precipitation of these three months may be less than half an inch. Moreover, plants obtain only a portion of this meager supply, for evaporation is most effective during the clear, dry, hot days of early summer, and the efficiency of the rainfall is correspondingly lessened. The moisture in the ground, which is supplied by the rains of winter supplemented by the scattered showers of spring, is sufficient to allow seeds to germinate and to 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 grazing and agriculture. The tables show that for the period under observation less than 1 inch of rain falls during July in 10 years out of 26 at

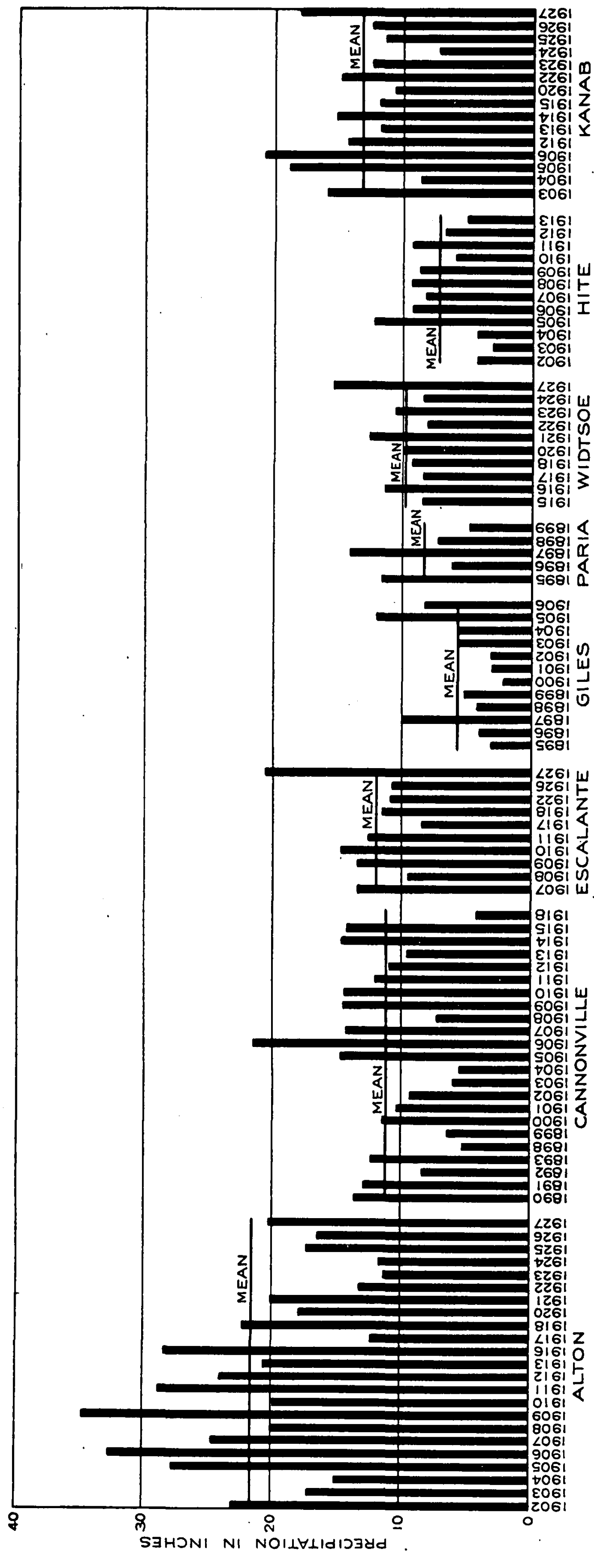


FIGURE 3.—Total and mean annual precipitation at stations in southeastern Utah

Alton, 13 out of 38 at Cannonville, 8 out of 21 at Escalante, 11 out of 12 at Giles, 12 out of 15 at Hite, 9 out of 21 at Kanab, 5 out of 6 at Paria, and 4 out of 15 at Widtsoe.

With deficient spring rains and great fluctuations in the July rainfall, natural agriculture in the Kaiparowits region is unprofitable. In exceptionally wet years some "dry farms" in the Butler, Dry, Round, and Escalante Valleys have produced small crops, but for most years the yields are insufficient to repay the cost of seed and tillage. On unirrigated land abandoned homesteads are common.

downpour, and the precipitation for a month may be the result of an hour's rain. Such showers seem actually to pour great quantities of water on the ground, and during their progress the flat surfaces become lakes, dry washes are converted into torrents, and cliff faces take the form of sheeted waterfalls. Usually these showers are separated by days or weeks. Much of the irregularity in distribution as recorded by individual weather stations is doubtless due to this very local distribution of rainfall.

The usual shower is local, shortlived, and sporadic. It covers but a few square miles, or even but a few

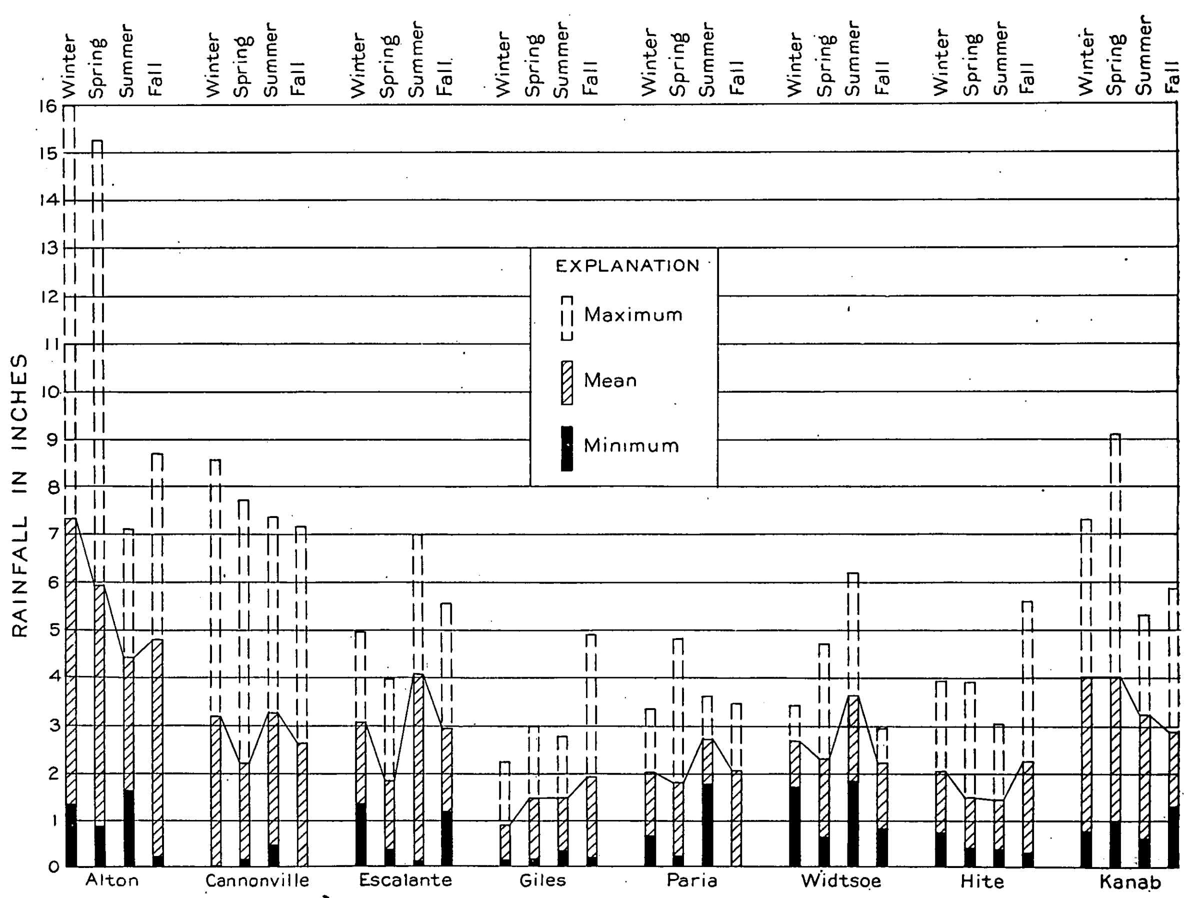


FIGURE 4.—Seasonal distribution of rainfall in southeastern Utah

hundred acres. It may thoroughly soak a small area on a canyon floor or mesa top without affecting adjoining areas beyond a clearly defined limit. Probably no single shower or series of consecutive showers has covered all of Kane or Garfield County. During June, 1915, no rain was encountered on a traverse from Lees Ferry to Hite, but the rain gages at Cannonville, Widtsoe, and Alton recorded two or more showers. In June, 1918, Escalante received five times its normal amount of rain, while Cannonville, 35 miles distant, received less than half its normal amount. On September 1, 1922, one of the heaviest downpours ever received at Cannonville did not reach Butler Valley, about 10 miles to the southeast, and on September 16, 1924, a hailstorm that destroyed fruit trees

The mean monthly precipitation at stations in the Kaiparowits region and vicinity is shown in Figure 4. This diagram also shows the maximum and minimum recorded monthly rainfall and the distribution of rain during the wettest and driest years. At some stations the rainfall for certain months in the driest years far exceeds that for the same months of the wettest years. At Escalante the greatest measured precipitation for May occurred in the driest year on record.

CHARACTER OF RAINSTORMS

The characteristic rainstorm of the Kaiparowits region is a violent local shower. Gentle rains that last more than 24 hours are very rare, but showers of 20 to 30 minutes' duration may result in a heavy and covered the ground with white ice marbles had a radius of less than 5 miles.

Showers on the Kaiparowits Plateau and along the rim of the High Plateaus are usually accompanied by hail, and during their progress and for some time afterward the air is uncomfortably chilly, but at altitudes below 6,000 feet the intense heat that precedes the spring and summer showers is reestablished within an hour or two after the rain has ceased. The ground soon loses its wetness, and so quickly is clothing and camp equipment dried that it has been found unnecessary to carry tents, even during August. The only serious hindrance to field work is the lightning, which almost invariably accompanies showers in August and September. It is disturbing to see lightning strike near-by trees and rocks and frighten the pack horses, for it seems as if each bolt was directed toward the men at work in the field. In September, 1922, two men were killed in Grass Valley, south of Widtsoe.

TEMPERATURE

The elements of most significance in the temperature of southeastern Utah are given in the following tables, which are compiled from records obtained through the United States Weather Bureau. All the stations listed are in charge of voluntary observers, and many of the records are incomplete and some may be inaccurate. The information available, however, is considered sufficient to indicate the value to be given to the temperature element in the climate of the Kaiparowits region. The figures are for the period ending December 31, 1923.

Records of temperature in southern Utah (°F.)

Alton

[Altitude, 7,000 feet. Station in high, narrow valley, and about 500 feet from base of foothills. At Ranch, in Long Valley, about 6 miles southwest, prior to 1915]

	Years	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Mean	16	24.7	27.7	33.0	41.9	48.0	56.6	62.1	61.6	54.7	45.8	36.2	26.5	43.2
Highest monthly mean	16	38.8	41.5	46.6	57.5	64.4	75.2	73.2	78.1	71.7	62.3	51.4	40.7	58.4
Lowest monthly mean	16	10.7	13.8	19.4	26.4	31.6	38.0	45.0	45.0	37.7	29.4	21.0	12.3	27.5
Highest temperature	18	64	62	67	78	87	94	93	93	88	81	70	68	94
Lowest temperature	18	−20	−20	−10	−2	5	25	25	31	18	3	−9	−19	−20

Cannonville

[Altitude, 6,000 feet. Station located in small valley; cliffs and plateau lands several hundred feet in height a few miles to the west and north; low hills to the south and east]

	Years	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Mean	20	27.6	30.6	33.4	44.9	52.1	61.4	67.1	64.9	57.9	48.1	38.1	28.3	46.6
Highest monthly mean	20	41.5	44.7	52.0	60.2	69.5	80.5	85.0	82.0	75.9	65.9	53.9	42.6	62.8
Lowest monthly mean	20	13.6	16.7	24.0	29.5	34.7	42.8	49.3	47.8	39.9	30.4	22.2	14.1	30.4
Highest temperature	20	67	67	74	84	96	100	101	101	100	84	72	76	101
Lowest temperature	20	−20	−32	0	6	13	20	32	30	11	10	−9	−15	−32

Escalante

[Altitude, 5,700 feet. Station in small town in hilly country with numerous rocky bluffs, on edge of flat, barren plain]

	Years	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Mean	13	26.7	32.6	41.0	48.2	54.8	65.0	69.2	67.7	59.9	49.9	39.1	28.3	48.5
Highest monthly mean	13	40.3	45.8	54.9	64.1	71.2	83.2	86.0	83.6	77.0	65.6	54.3	42.3	64.0
Lowest monthly mean	13	13.2	19.2	27.1	32.3	38.5	46.9	52.5	51.7	42.9	34.3	24.0	14.3	33.0
Highest temperature	15	61	84	80	83	92	98	98	97	90	87	72	62	98
Lowest temperature	15	−17	−11	8	11	25	31	38	32	22	15	1	−15	−17

Giles

[Altitude, 4,000 feet. Station in valley of small river in generally rolling country]

	Years	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Mean	12	25.1	31.2	42.5	52.2	61.8	69.7	77.2	74.6	64.6	50.9	38.0	24.9	51.1
Highest monthly mean	12	38.8	45.8	57.9	69.0	79.3	91.0	96.5	93.8	84.6	68.4	53.9	39.5	68.2
Lowest monthly mean	12	11.5	16.6	27.1	34.6	43.2	50.5	57.9	56.3	44.8	33.1	22.1	10.4	34.0
Highest temperature	12	59	70	84	95	100	110	111	106	99	89	73	64	111
Lowest temperature	12	−21	−18	5	8	26	32	39	39	25	11	−5	−11	−21

Hite

[Altitude, 3,500 feet. Station in the canyon of Colorado River, whose walls are 1,500 to 2,000 feet high; station 500 feet from river]

	Years	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Mean	14	35.7	42.4	51.1	59.2	68.2	77.7	84.2	82.8	72.5	59.7	47.5	35.2	59.7
Highest monthly mean	14	46.8	54.7	65.1	74.2	83.4	94.2	99.5	97.7	88.5	75.4	60.9	46.1	73.9
Lowest monthly mean	14	24.7	30.0	37.3	44.3	52.9	61.3	68.8	67.9	56.4	43.9	34.1	24.3	45.5
Highest temperature	14	66	81	86	94	104	111	115	110	104	91	76	76	115
Lowest temperature	14	1	6	18	28	35	40	44	51	39	29	19	−1	−1

Kanab

[Altitude, 4,925 feet. Country is generally level and open to the south, with high abrupt hills to the north]

	Years	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Mean	9	30.5	35.1	41.6	48.5	54.7	64.0	70.5	70.4	61.2	52.3	42.6	30.3	50.1
Highest monthly mean	9	44.4	49.6	57.3	66.3	74.6	84.2	89.1	89.2	80.1	69.6	57.6	44.3	67.2
Lowest monthly mean	9	17.1	21.2	26.7	30.2	36.7	44.0	51.8	51.9	42.4	35.0	27.7	16.7	33.4
Highest temperature	11	62	70	85	87	101	101	105	101	95	89	79	66	105
Lowest temperature	11	−15	−8	1	8	16	23	39	35	24	9	10	−11	−15

Records of temperature in southern Utah (°F.)—Continued

Widtsoe

[Altitude, about 7,500 feet]

Mean	3	2.11	24.3	31.6	36.5	48.4	58.1	64.7	61.0	54.6	44.7	34.2	27.1	42.2
Highest monthly mean	3	24.6	26.9	36.6	39.1	50.2	60.8	65.8	63.0	57.8	49.4	37.4	29.9	45.1
Lowest monthly mean	3	17.0	22.7	29.0	33.2	47.2	55.6	64.1	59.4	51.0	40.4	31.5	24.3	39.5
Highest temperature	3													92
Lowest temperature	3													−17

The influence of altitude and topographic position on temperature is shown by a comparison of the tables for Alton, Giles, Hite, and Kanab. Decreasing altitudes are accompanied by increasing mean annual temperatures. At Alton (altitude 7,000 feet) the thermometer rarely goes above 90°, and the highest temperatures recorded for 18 years are June, 94°; July, 93°; August, 93°; and for four or five months in a year the thermometer falls below 20°, and −20° has been recorded. At Hite (altitude 3,500 feet) zero temperatures are rarely recorded. The range between the highest and the lowest monthly means is least for Widtsoe, 5.6°, followed in order by Hite, 28.4°; Alton, 30.9°; Escalante, 31°; Cannonville, 32.4°; Kanab, 33.8°; and Giles, 34.2°. These figures of mean annual temperature and the range between the lowest and the highest average monthly means are not unlike those prevailing in temperate latitudes and therefore give little indication of the temperatures experienced in this region.

The annual and daily ranges of temperature are of greater significance. The maximum annual range recorded for Alton is 114° (94° to −20°); for Escalante, 115° (98° to −17°); for Giles, 132° (111° to −21°); for Hite, 116° (115° to −1°); for Kanab, 120° (105° to −15°); and for Widtsoe, 109° (92° to −17°). The greatest range (133°) is at Cannonville, where a July and August temperature of 101° is offset by the low February record of 32° below zero. At all points within the Kaiparowits region below 7,000 feet, temperatures that exceed 100° normally occur for 10 to 20 days each year. At such times the temperature in the sun is almost intolerable. In the Fiftymile Desert and the Wahweap country the surface soil reaches 140°, and bridle buckles and camp utensils exposed to the sun almost scorch the fingers. Except within the deeper major valleys and to a less extent in other canyons, temperatures below zero are normal in December, January, and February, and at points on the higher plateaus zero weather for five or six days in succession has been experienced. Reservoirs are coated with ice, and the soil is frozen to depths of 2 to 6 feet. Nearly every year the Colorado River in Glen Canyon freezes over in places; in 1878 the ice was 2 feet thick at Lees Ferry; and during the winter of 1924–25 horses were taken across on the ice at the mouth of Halls Creek—a feat many times performed by the Navajos at the Crossing of the Fathers.

High ranges in annual temperature are accompanied by great daily range. A daily range of about 40° is probably common to the whole area; ranges of 50° have frequently been experienced. A worker in this region soon learns that however hot the day may be an ample supply of blankets may be required at night. In June, 1918, along the south rim of the Kaiparowits Plateau the heat of the day interfered with field work, but on three mornings frost covered the ground. At altitudes above 5,000 feet several days with temperatures of 70° to 80° were followed by nights in which ice formed in the camp buckets. Sudden changes during the day are infrequent, except when thundershowers cool the air for a few hours. On hot summer days a hailstorm may lower the temperature within an hour to a point where handling instruments and writing in notebooks is painful.

Fortunately, however, in the Kaiparowits region high temperatures and great daily range are accompanied by dry air. Instrumental measurements have not been made, but for the region as a whole the humidity is probably less than at Flagstaff, Ariz., where the mean relative humidity is 62 per cent, being lowest (39 per cent) during June, the driest and, during some years, the hottest month.[29] High humidity and high temperature are not contemporaneous, with the result that heat, though distressing, is not enervating and oppressive. Here, as in the Navajo country, " a hot-air bath, not a steam bath, is part of the daily routine."

The average date of the first killing frost of autumn ranges from September 12 at Alton and Cannonville to November 3 at Hite; and the average date of the last killing frost of spring ranges from March 24 at Hite to June 20 at Alton. The stations under observation (see p. 21) have normally a growing season as follows: Alton, 84 days; Cannonville, 98 days; Widtsoe, 99 days; Kanab, 128 days; Escalante, 128 days; Giles, 140 days; and Hite, 224 days. No frost records are available for Paria. Where water has been made available this long growing season, coupled with high temperature, is favorable for alfalfa, corn,

[29] U. S. Weather Bur. Bull. W, vol. 1, 1912.

and fruit raising. However, when a period of several years is considered, it appears that the normal length of the growing season may be much shortened. Thus the growing season may be shortened by six weeks at Hite and reduced to 95 days at Giles, 50 days at Kanab, 75 days at Widtsoe, 51 days at Escalante, and 22 days at Cannonville; and Alton may have killing frost any month of the year. These records are charted in Figure 5.

The bearing of these figures on agriculture may be seen from the fact that corn requires, on the average, 90 to 150 days and fruit an even longer time to reach maturity.

up and down canyon walls the air seems continuously in motion and at times is difficult to face, but during the course of field work no widely sweeping sandstorm was encountered. The most disagreeable experiences are associated with the huge clouds of whirling dust which roll across the ground to meet the oncoming thundershowers. As compared with the winds in adjacent areas, those of the Kaiparowits region are neither intense nor continuous. In the minds of the Navajo who live south of the Colorado River the Wind People were sent to dry up the earth, and "Wind and Night" (sandstorm) is a dreaded expression of powers for evil. To the Piutes of southern Utah the winds and storms over the plateau top and among the winding canyons are not unfriendly; chiefly the lightning is dreadful and sublime. Mooney [80] has thus translated one of their folk songs:

The wind stirs the willows,
The wind stirs the willows,
The wind stirs the willows,
The wind stirs the grasses,
The wind stirs the grasses,

The rocks are ringing,
The rocks are ringing,
The rocks are ringing,
They are ringing in the mountains,
They are ringing in the mountains,
They are ringing in the mountains.

An interesting phase of wind activity was observed in canyons, where, with seeming disregard to regional direction, winds on summer days travel up the valley and reach the surface above by going up the hot cliffs at the canyon head or dividing to follow tributaries. At night they return down the valley, and the explorer soon learns to place his camp fires with this knowledge in mind. At many junctions of canyons small ridges of sand are alternately moved and replaced.

[80] Mooney, James, Bur. Am. Ethnology Fourteenth Ann. Rept., pp. 1054–1055, 1896.

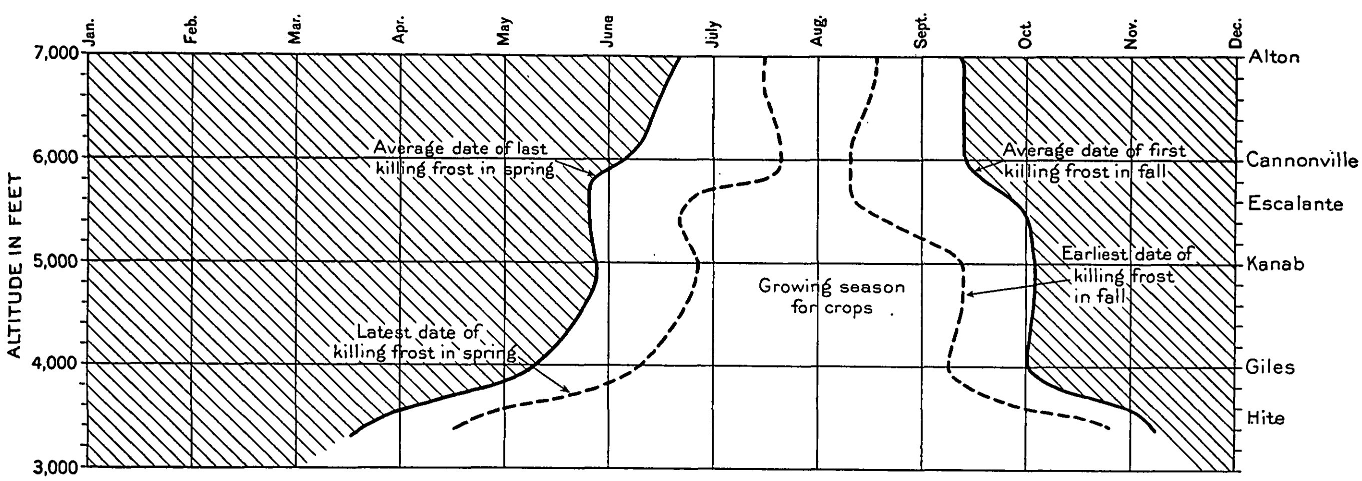


FIGURE 5.—Relation of time of killing frost to altitude in southeastern Utah. Based on records at meteorologic stations

WIND

Small areas of dunes and rippled flats of eolian sand, widely spread over the Kaiparowits region, bear witness to the presence of winds. In places rocks are being polished and etched by wind-blown sand and vegetation is successively buried and uncovered.

For the two stations where records have been kept the prevailing direction of wind is west at Alton and northwest at Cannonville. As it crosses the grass-covered or forest-covered High Plateaus its force is diminished and it reaches the settlements at the plateau base strained almost clear of dust. As the wind proceeds eastward down the Escalante Valley it gathers force enough to sweep the ground clear of dust, which it carries to Glen Canyon and to the uninhabited regions beyond. The wind along the southwest base of the Kaiparowits Plateau likewise has no collecting ground for dust and is hindered in its course by rock masses that rise from the surface and project from the plateau. It must start and stop, pick up, and deposit sand at relatively short intervals. The absence of extensive flats and the presence of innumerable cliffs, mesas, and canyons provide conditions unfavorable for uninterrupted sweeps. Whirling columns of dust are in evidence, and around bases of rock buttresses and

SOIL

In the Kaiparowits region soil is rare; if defined as deeply decomposed or disintegrated rock mixed with humus and water it is almost absent. On flat-topped mesas and plateaus the soil, weathered directly from the underlying rock, forms a mantle a few inches thick, but even here the soil cover is not continuous. On the plateau edges (the " breaks ") the areas of disintegrated shale and sandstone, though technically classed as soil, have no agricultural value. In general the conditions are unfavorable for making and retaining soils. The scanty vegetation, the absence of sod, the sudden showers, and the rapid run-off favor removal of the soil as rapidly as it is formed. Soil does not remain on the steep slopes that are characteristic of this region, nor on flatter areas where the surface is thoroughly washed by tumultuous waters from cloudbursts and swept clean by winds. Over hundreds of square miles the surface consists of clean, bare rock.

Most of the soil in this region is transported soil. It has been brought to its present position by streams and wind. Many depressions on the surface have been filled by débris washed from their edges, and into many rock cracks surface material from near-by places has been dumped. Some former canyons and innumerable tributary valleys have been partly filled with stream-borne débris, and a few flat-floored valleys are flanked with soil deposited at highwater stages. Similar soil is displayed in alluvial cones along valley sides and in fragmentary terraces that cling to canyon walls. Eolian soils in the form of dunes are displayed here and there at the bases of cliffs, on open flats, and within canyons. At one place in the Escalante Valley dunes have completely obliterated the canyon wall and replaced bare rock with soil that supports a cover of vegetation. In the Wahweap country wind-blown soil coats large areas, and fine dust settling from the air probably forms part of most soils in this region. In fact, some of the best grazing areas in valleys owe their value to annual grasses that find uncertain foothold in the shifting sands.

Such soil as the region affords is derived from rocks that are deficient in the mineral matter needed by plants. The sandstone and sandy shale of the Paria Valley, Glen Canyon, Waterpocket Fold, and Escalante Valleys are prevailingly quartzose and therefore poorly supplied with plant foods. The sandstone and shale that constitute the upper half of the Kaiparowits Plateau contain a higher proportion of desirable minerals, and the limestone and basaltic lava along the face and top of the Paunsaugunt, Table Cliff, and Aquarius Plateaus furnish soil of good quality. But, although about 90 per cent of the soil is derived from rocks that furnish little or no lime, potash, and phosphoric and sulphuric acid, the soil is not infertile, owing largely to the arid climate. Because the scant supply of water in the ground is not sufficient to leach out the soluble constituents, the bits of plant food sparingly distributed in the rocks are accumulated in the soils and stored for long periods. That the soil has fertility is shown by the vigorous natural growth of perennials and annuals where sufficient water is present and by the crops harvested at Lees Ferry, Paria, Cannonville, and Escalante. The one substance lacking is water. The dry air and open-textured soil permits the moisture to escape at the surface, thus depressing the water table to a depth that makes natural farming unprofitable and dry farming speculative, but irrigation farming brings satisfactory returns. Unfortunately there is not enough water available in the Kaiparowits region to supply more than a few square miles, except at prohibitive cost. The most favorably situated lands are already under irrigation, and the land that might be irrigated is more than offset by the amount destroyed by the down cutting of alluvium in the washes. (See p. 30.)

VEGETATION

Members of the Powell and Wheeler surveys were impressed by the general scantiness of the plant cover of southern Utah. Powell [31] remarks:

> Many portions of the elevated district are devoid of timber; * * * the forests of these upper regions are monotonous, as the variety of tree life is very small; * * * the coniferous trees * * * are ragged and gnarled, and the lumber they afford is not of the finest quality.

Powell lists 5 species of pines, 6 of fir, 2 of juniper, 3 of poplar, a maple, a box elder, an oak, a birch, a hackberry, and 2 species of ash—these last seven rare—as

> a nearly complete list of forest trees. * * * Nearly all the grasses on the highlands are bunch grass. The spaces by which they are separated are bare or occupied by weeds and shrubs. * * * A continuous turf is never seen. * * * The regions south and east of the High Plateaus are exceedingly desolate; naked rocks are found, refusing footing even for dwarfed cedars and piñon pines; the springs are infrequent and yield no bountiful supply; its patches of grass are widely scattered, and it has but little value for agricultural purposes.

Dutton [32] saw in sharp contrast the vegetation of the rim of the Aquarius Plateau and of the canyon lands that stretch eastward to the Colorado. He says:

> Yesterday [in upper Fremont Valley] we were toiling over a burning soil, where nothing grows save the ashy-colored sage, the prickly pear, and a few cedars that writhe and contort their stunted limbs under a scorching sun. To-day we are among forests of rare beauty and luxuriance; the air is moist

[31] Powell, J. W., Report on the lands of the arid region of the United States, with a more detailed account of the lands of Utah, pp. 98–110, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1879.

[32] Dutton, C. E., Report on the geology of the High Plateaus of Utah, pp. 284–291, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

and cool; the grasses are green and rank, and hosts of flowers deck the turf like the hues of a Persian carpet.

Eastward from the plateau rim he saw

burning plains, barren even of sage—all glowing with bright color and flooded with blazing sunlight. * * * It is the extreme of desolation, the blankest solitude, a superlative desert; * * * the plain is barren, treeless, and waterless.

If Dutton had descended from the High Plateaus to the "desolate" Escalante Basin, where "the air boils like a pot," or had visited the Paria and Glen Canyon districts, some harsh lines would be absent from his picture. Traverses of these regions bring to view a remarkably distributed and widely varied flora, above which, along the plateau rims and tops, trees and brush are as abundant as in most parts of the Colorado plateaus. It is true, however, that vegetation in the Kaiparowits region has an unfriendly environment. Nowhere is it luxuriant, and at few places do the plants crowd one another in their search for water and favorable soil. As a rule, the grass is in bunches, the shrubs in clumps, and the trees in small groves with considerable spaces separating them. Many plants have no near neighbors; they stand as individuals in tracts of several acres or are present by twos or threes in areas of several square miles. Except on the Kaiparowits Plateau and about the headwaters of the Paria and Escalante Rivers, patches of green are a small part of the landscape. Large areas are devoid of vegetation.

The high walls of hundreds of canyons are in general without plant cover on their faces and on their tops. It is possible to follow the rim of Glen Canyon from the Paria to Halls Creek and to continue the journey along the crest of the Waterpocket Fold to the Circle Cliffs without stepping on grass or passing beneath trees. (See pl. 21, *C*.) Similar conditions would be found in a traverse along the Escalante River from its mouth to Sand Creek. For the region as a whole, including the plateau tops, cliffs, and canyon walls, it is estimated that vegetation in the sense that that term is used in the Colorado plateau province covers 20 per cent of the surface; for the lower Escalante Valley, the southeast end of the Kaiparowits Plateau, and the south half of the Waterpocket Fold it covers probably less than 5 per cent.

The distribution of plant life in the Kaiparowits region corresponds roughly with the zonal arrangement outlined for northeastern Arizona,[33] but the boundaries of the zones are more irregular and broader, and overlapping of zones is common. In this region topography, with its attendant control of rainfall, temperature, evaporation, insolation, and wind, determines the character of plant life and the boundaries of ecologic provinces. The unusually complex vertical and horizontal arrangement of canyons, stream flats, slopes, cliffs, mesa tops, plateau tops, areas of soil, and areas of bare rock naturally provides local environment with little regard to contour lines.

Cottonwoods grow within the lowest canyons at 3,125 feet and also in dry washes above 6,000 feet. In places yellow pine constitutes forests between 7,000 and 9,000 feet but is absent from large areas between 7,000 and 8,000 feet and appears here and there below 5,000 feet. Piñon and juniper range from about 3,500 feet to the edge of the High Plateaus at 10,000 feet. Sagebrush, willow, and water-loving grasses, reeds, and ferns seem to be distributed almost regardless of altitude.

Although it is difficult to establish boundaries, it has been found convenient in field work to recognize three plant zones in the Kaiparowits region, as follows:

1. Zone of cottonwood, cactus, and yucca. This zone includes the Colorado and tributary valleys to an altitude of about 5,000 feet. Within this zone vegetation is everywhere scanty. In Glen Canyon yucca and cactus occupy the few talus slopes and cling to the walls; willow grows profusely on exposed sand bars, reappearing after each flood; cottonwoods stand on high level terraces at the mouths of tributary streams, where scrub cedar, oak, box elder, Brigham tea, rabbit brush, hackberry, and greasewood are also found. The vines and bushes within and adjoining Glen Canyon are duplicated in the Paria, Escalante, and Halls Valleys and along streamways draining south from the Kaiparowits Plateau. Cottonwoods are particularly abundant in the Paria Valley. The vines present include poison oak, Virginia creeper, clematis, and grape. Grass of several varieties appears as detached tufts among boulders, in rock cracks, and on quiescent sand dunes. Moss and ferns watered from seeps form green spots on red sandstone walls. Tamarisks and Lombardy poplar that were planted at Paria about 1875 have made good growths; fruit trees, corn, and sorghum give satisfactory yields at Paria, Halls Ranch, Lees Ferry, and Hite.

2. Zone of piñon, juniper, and sage; altitude, 5,000 to 8,000 feet. The dominant vegetation for a larger part of the Kaiparowits region consists of continuous forests, scattered patches, and individual trees of piñon and juniper, together with vigorously growing sagebrush. (See pls. 8, *B*; 22, *B*.) This type prevails on the top and flanks of the Kaiparowits Plateau, along both sides of the Waterpocket Fold, and on the slopes of the Paunsaugunt, Table Cliff, and Aquarius Plateaus. The relative amounts of piñon and juniper differ widely from place to place, and the sage grows under the trees, in "parks" between them, or in uninterrupted fields covering hundreds of acres.

[33] Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, p. 72, 1916.

With these dominant forms are found nearly all the plants represented at lower altitudes, and within this zone are many individual trees and some groves of yellow pine and aspen, characteristic of higher altitudes. Bullberries, service berries, and mountain mahogany are fairly common, and at Pleasant Spring (altitude about 6,000 feet) occurs an unusual association of piñon, juniper, aspen, willow, oak, birch, alders, luxuriant wild cherries, and rosebushes. Fruit trees, corn, wheat, and grapes flourish at Cannonville, Tropic, Henrieville, and Escalante. Potatoes, which were found growing wild in the Potato Valley (Escalante), produce excellent crops.

3. Zone of yellow pine, spruce, and fir; altitude, 8,000 to 11,000 feet. On the upper slopes and top of the Aquarius, Table Cliff, and Paunsaugunt Plateaus and round about Canaan Peak yellow pine predominates at altitudes under 9,000 feet and is followed upward in turn by spruce and fir. The trees are interspersed with beautiful groves of aspen and undergrown with oak, willow, manzanita, sage, and many grasses. In places the pines grow singly or in widely spaced groups, and grass-floored parks are common. Nearly all the lands in zone 3 are within the Powell National Forest—the source of lumber and of summer grazing for Kane, Garfield, Wayne, and Piute Counties. The following list of plants growing in the forest has been furnished by Mr. Wallace M. Riddle, forest supervisor:

Valeriana ceratophylla.
Kunzia tridentata, bitter or deer brush.
Pseudocymopterus tidestromii, angelica.
Astragalus thompsonae, loco.
Astragalus decumbens, small loco.
Sericotheca dumosa, bearberry.
Hedysarum pabulare, beeweed.
Apocynum scopulorum.
Koeleria cristata, early grass.
Carex misandra, mountain broadleaf.
Carex festiva.
Juncus badius, meadow grass.
Hymenoxys richardsonii, yellowweed.
Lithospermum multiflorum, yellow honeysuckle.
Eriogonum croceum, small yellowweed.
Eriogonum corymbosum, apple brush.
Eriogonum racemosum.
Thalictrum sparsiflorum, waterweed.
Madronella odoratissima, horsemint.
Tithymalus luridus, smarting milkweed.
Ligusticum porteri, wild carrot
Dasystephana affinis, meadow bluebell.
Dasystephana parryii.
Dugaldea hoopesii, sneezeweed.
Dasiphora fruticosa, elk brush.
Arnica rhizomata, dwarf sunflower.
Arnica cordifolia.
Muhlenbergia trifida, no eatem grass.
Delphinium barbeyi, larkspur.
Symphoricarpos oreophilus, trip brush.
Mertensia sampsonii, water bluebell.
Amarella scopulorum, blue flower.
Amarella plebeja.
Chamaenerion angustifolium, fireweed.
Geum oregonense, crane's-bill.
Asclepiodora decumbens, poison willow.
Festuca calligera.
Festuca viridula.
Bromus polyanthus.
Agrostis hiemalis.
Poa (scabrella?).
Aconitum columbianum.
Lupinus (sp.).
Conioselinum scopulorum.
Cirsium (near C. drummondii and C. eatonii).
Antennaria rosea.
Geranium richardsonii.
Castilleja linariaefolia.
Achillea lanulosa.
Erigeron macranthus.
Potentilla filipes.
Chaenactis douglasii.
Zygadenus elegans.
Anemone globosa.
Wahlbergella drummondii.
Arabis drummondii.

With regard to the utilization of the land the vegetation of Garfield, Kane, and San Juan Counties, Utah, has been studied by Depue Falck,[34] of the United States Geological Survey. He recognizes five zones, which he describes as follows:

1. The transition desert brush type occupies the lower altitudes of the region and is a mixture of various small brush species which differ in dominance and density according to local conditions. The more common of these plants are species of saltbush, such as shadscale (*Atriplex confertifolia*), common saltbush (*Atriplex canescens*), two small suffrutescent species (*Atriplex nuttallii* and *Atriplex corrugata*), as well as little rabbit brush, black brush (*Coleogyne ramosissima*), Mormon or Brigham tea (*Ephedra*), greasewood (*Sarcobatus vermiculatus*), yucca, and pricklypear. Grama, galleta, and Indian rice are the principal grasses.

2. The shadscale type occupies only a few of the lower valleys, where shadscale (*Atriplex confertifolia*) is the dominant shrub and is usually associated with little rabbit brush, saltbush, and either grama or galleta grass.

3. The juniper-piñon type is found throughout the area under discussion between altitudes of 5,000 and 7,000 feet. Within this type as mapped are many small open patches where pure or mixed stands of small brush dominate. At the higher altitudes these stands consist almost entirely of sagebrush; in the lower areas there is in many places only a scrubby growth of juniper with a short brush and grass association composed principally of shadscale, saltbush (*Atriplex canescens*), galleta grass, Indian rice (*Oryzopsis hymenoides*), and grama grass (*Bouteloua gracilis*). In addition mountain mahogany, oak brush, crab apple (*Crataegus*), and cliff rose are abundant brush species included with this type.

4. The oak type occurs in only a few relatively small areas at the higher altitudes, generally adjoining the timbered forest areas. This type as mapped west of Monticello represents an almost pure stand of oak brush (*Quercus utahensis*) supplemented by a few scattering yellow pine and in places small sage patches. On the slopes of the Henry Mountains the type includes a number of other species and is in reality a high brush type, with oak the dominant species. The ridge of this range is extremely rocky and barren, supporting only a sparse growth of purple loco weed, whereas the upper portion of the north slopes contains patches of spruce, fir, and aspen, and yellow pine grows lower down and in the canyons. Some of this timber would have commercial value if it were accessible. Sagebrush, buck brush (*Symphoricarpos*), and cliff rose (*Cowania stansburiana*) are associated with the oak brush on these mountains. At Alton a scattered yellow pine is associated with the oak brush.

5. The sage type designates areas where sage (*Artemisia tridentata*) presents a dominant appearance to the eye and makes up practically 75 per cent of the ground cover. Bunch grass (*Agropyron spicatum*) is the principal secondary species at the higher altitudes but is replaced by galleta grass (*Hilaria jamesii*) on the lower mesas. Scattering plants of big rabbit

[34] Personal communication transmitted in a letter from John D. Northrop, Jan. 16, 1926.

brush and little rabbit brush (*Chrysothamnus stenophyllus*) and a periodical growth of several annual grass and weed species occur throughout this type. In general, this type is not found below an altitude of 5,000 feet.

ANIMALS

Among the indigenous animals of the Kaiparowits region field mice, cliff mice, chipmunks, ground squirrels, cottontails, and coyotes were frequently seen, and the nocturnal desert rat ("trade rat") is much in evidence. Porcupines, badgers, and woodchucks live in forested areas. Snakes and lizards appear on the lower dryer lands, but reptiles are here much less common than in regions south of Glen Canyon. Prairie dogs likewise are not abundant. Bears and wild cats were seen on several occasions, also tracks of the mountain lion. Colonies of Sonoran beavers are at work on Boulder Creek and Sand Creek, and the name Paunsaugunt (place of beavers) for the southernmost of the High Plateaus suggests much wider distribution. It is reported that otter, deer, and mountain sheep were plentiful during pioneering days and that wild horses were occasionally seen. The Piutes tell of once abundant antelopes. East of the Kaibab Plateau deer are now rare, and the only mountain sheep noted during the course of field work was a flock of six near the southeast base of the Kaiparowits Plateau. Here, as in other parts of the Southwest, centipedes and scorpions are found, but though they are occasionally unwelcome visitors about camp, they are not abundant. Crickets and spiders are plentiful, but mosquitoes give little trouble. Deer flies are a troublesome pest in some of the upland marshy valleys. Grasshoppers are found in sufficient abundance to serve the Piutes as an article of food. In 1871 they destroyed the crops at Kanab. An interesting variety of aquatic insects live in spring-fed basins, small streams, and rainwater "tanks." Among those studied by Moore and Hungerford, the most common are back swimmers (*Notonecta*), water boatmen (*Arctocorixa*), striders (*Gerris*, *Trepobates*, *Microvelia*), and dytiscid beetles (*Rhantus*, *Thermonectes*).[35]

INHABITANTS

INDIAN TRIBES

The Kaiparowits region has always been sparsely settled. To the cliff dwellers and the Pueblo tribes it was an unfriendly, isolated country. The few small cliff houses in Glen Canyon, in the Paria Valley, and along the rim of the Kaiparowits Plateau are in striking contrast with the numerous well-designed structures found in surrounding regions. They are poorly built and suggest temporary dwellings, pioneer outposts, or refuges for scattered bands driven out from better places. They seem to be wayside camps, not permanent settlements.

[35] Moore, R. C., and Hungerford, H. B., Water insects from a portion of the southern Utah desert: Kansas Univ. Sci. Bull., vol. 14, pp. 409–422, 1922.

The Hopis say that their ancestors came to Tusayan from regions north and west. They also speak of an edict of the "old people," forbidding travel or dwelling beyond the "great water chasm." Although in Hopi tradition this prohibition is given a religious significance, it seems not unlikely that reports of pioneer scouts formed its basis.

From a center, probably at Chinle, the Navajos extended their settlements west, east, and south but crossed the Colorado only for hunting and barter. Likewise the Piutes, who appear to have been forced by hostile tribes to occupy undesirable lands, chose the San Juan and Virgin Valleys and the plateau lands farther west and east in preference to the Paria and Escalante Valleys and the Kaiparowits Plateau. Arrowheads found here and there show that the region below the rim of the High Plateaus was a hunting ground, but the springs and canyon bottoms show no signs of long-time occupancy. Thompson in 1872 met one band of Piutes at the northeast base of the Aquarius Plateau, and the pioneer Mormon band found four or five Piute families living in the Potato Valley. Several times the Navajos entered the Paria Valley by the Crossing of the Fathers and raided the pioneer outposts, and they still visit the Kaiparowits region to sell blankets and buy buckskin. The Piutes likewise come occasionally to sell baskets and to gather piñon nuts and medicinal herbs. The 1920 census lists four Indians in Garfield County and none in Kane County. During the course of geologic field work in 1900, 1915, 1918, 1921, 1922, and 1924 the only human beings seen outside of settlements were a family in camp at Paria, cattlemen engaged in a round-up on Halls Creek, and a few sheep herders within the national forest and on the Kaiparowits Plateau.

THE MORMON PIONEERS

The Mormon immigrants to Utah lost little time in spying out land suitable for settlement. Within 10 years after their arrival at Salt Lake, in 1847, pioneer colonies had been established at Lehi, Provo, Nephi, Fillmore, Beaver, Parowan, and other places along the foot of the Wasatch Mountains and in the San Pete Valley. The Virgin Valley also had been visited by missionaries and agricultural prospectors. In 1854 scouts were sent out in all directions from Santa Clara as a center. Four expeditions made their way eastward across the Uinkaret, Kanab, and Kaibab Plateaus and crossed the Colorado, extending their explorations into the "lands of the Navajos and Moqui" (1858–1860). As a result of these investigations, "many Saints were called from the north to form settlements in southern Utah." The city of St. George was founded in 1861, fertile spots in the Virgin, Santa Clara, Ashe, and Muddy Valleys were occupied, and the way was opened for extending settlements eastward along the base of the High Plateaus to the Paria River and to regions south of the Colorado.

For this work of colonization the adherents of the Mormon Church were peculiarly adapted. Unlike the Spanish explorers, intent on conquest and conversion, the scouts of the church were men interested primarily in agriculture and stock raising. It was their business to find lands, water, and grass—to select spots suitable for villages and farms. The pioneer colonists were looking for homes, not for places to exploit and abandon. Out of this attitude grew their policy of dealing with the Indians—a watchful friendliness, which has saved southern Utah from the disastrous experiences of most other parts of the country. To the Mormons the Piutes, Navajos, and Hopi are Lamanites, one of the lost tribes of Israel, who may gradually be reclaimed, and they are also neighbors, with whom friendly relations are essential.

Regarding the Piutes of southern Utah, Brigham Young wrote to Jacob Hamblin [36] on March 5, 1858:

> The hour of their redemption draws nigh, and the time is not far distant when they will receive knowledge and begin to rise and increase in the land and become a people whom the Lord will bless.
>
> The Indians should be encouraged in keeping and taking care of stock. I highly approve of your designs in doing your farming through the natives; it teaches them to obtain a subsistence by their own industry and leaves you more liberty to visit others and extend your missionary labors among them. A few missionaries to show and instruct them how to raise stock and grains, and then not eat it up for them, is most judicious. You should always be careful to impress upon them that they should not infringe upon their rights in any particular, thus cultivating honor and good principles in their midst by example as well as precept.

In a public address in October, 1852, 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.

From the day of its founding St. George became the commercial, administrative, and ecclesiastic capital of southern Utah. With friends and supplies assured, outlying settlements could be established with some confidence. Pipe Springs was colonized in 1863; Moccasin Springs, Kanab, and Mount Carmel in 1864, and Paria in 1865. Kane County, with 16 settlements, was organized in 1865. This hopeful progress came to an end with the beginning of the Navajo raids in 1866, and for the next five years the population of the whole county probably averaged less than 25 whites. For the two years preceding the first attacks the Indians had been restless. The coming of a few peaceful whites to live among them was not disagreeable, but the uninvited occupation of lands by an increasing number of families, with flocks and herds, was alarming. In the minds of the Indian all land and forage and hunting in southern Utah belonged to the Piutes or to the Navajos, and all food supplies were the common property of the clans. To him possession of land did not imply continuous occupancy. It was not only his privilege to ask for food; it was his right to demand it. Even before the coming of the Mormon pioneers and the possession of firearms and horses, the profitable trade in furs and skins had made it less necessary to depend for support on the cultivation of small tracts of land, supplemented by hunting, and the possession of horses and firearms made the Indian still more a nomad. A particular grievance of the Piutes was the destruction by sheep and cattle of the "ak" and other grasses, the seeds of which were a valuable source of food. As Jacob Hamblin [37] 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.

Piute and Navajo alike resented the facts that deer and elk and mountain sheep were driven from their accustomed feeding grounds and that the domestic livestock which took their place were treated as private property.

The troubles began by a Navajo raid on Paria, the most distant outpost, and the theft of cattle from Kanab, and this raid was followed by Piute attacks on emigrant trains that were going from Salt Lake to California and by the murder of settlers at Short Creek, Pipe Springs, Upper Valley, and Averett Creek. In 1869 three members of Powell's exploring party were killed while asleep. That these murders of Indians by whites and whites by Indians did not develop into a disastrous war with its consequent devastation of all white settlements in southern Utah is largely owing to the faith, skill, and daring of Jacob Hamblin, who discouraged reprisals and took upon himself the task of visiting hostile bands with a view to establishing peaceful relations. Late in 1865 he attempted to visit the Navajo chiefs, going by the Lees Ferry-Tuba

[36] Little, J. A., Jacob Hamblin, a narrative of his personal experience, 2d ed., Salt Lake City, Deseret News, 1909.

[37] Idem, pp. 94–95.

route, but upon reaching Oraibi he learned that the Navajos were in a revengeful mood and that "it would be useless and perhaps dangerous to go into their country." Returning to St. George, he began a series of visits to the clans north of the Colorado River, with the hope that the Piutes would throw in their lot with the Mormon pioneers. The prospects were not bright, for the white man's way of doing things did not appeal to the redskins. Hamblin was told in 1856:

> We can not be good; we must be Piutes. We want you to be kind to us. It may be that some of our children will be good, but we want to follow our old customs.[38]

But tact, combined with the previous fair treatment and the hereditary feud between Piutes and Navajos, finally led to an alliance, and during the years 1867 to 1871 Piutes and Mormons sympathetically combined in watching passes and water holes on the Arizona-Utah trails and in warding off attacks of marauding Navajo bands.

The misunderstanding between the Piutes and whites came to an end with that remarkable conference of September 19, 1870, on the bleak summit of Shivwits Plateau, when in replying to Hamblin and Major Powell the chief of the Shivwits said:[39]

> Your talk is good, and we believe what you say. We believe in Jacob and look upon you as a father. 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 the springs, and you may drink; the water is good. We will be friends, and when you come we will be glad. We will tell the Indians who live on the other side of the great river that we have seen Ka-pu-rats (one arm off, referring to Major Powell), and he is the Indians' friend. We will tell them he is Jacob's friend. 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 moons come 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 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 love our country; we know not other lands. We hear that other lands are better; we do not know. The pines sing, and we are glad. Our children play in the warm sand; we hear them sing and are glad. The seeds ripen and we have to eat, and we are glad. We do not want their good lands; we want our rocks and the great mountains where our fathers lived. 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 1871 peace was concluded with the Navajos, and the long succession of thefts, parleys, murders, and punishments came to an end. In the fall of that year Hamblin and Powell proceeded to Fort Defiance, using the newly found crossing at Lees Ferry, and in a council attended by some 6,000 Navajos considered for three days the hoped-for peaceful relations to be established among the Navajos, Piutes, and whites. The council was continued at Oraibi, where an agreement was reached that in the settlement of future misunderstandings Hastele should represent the Navajos and Hamblin the Mormons of southern Utah. The peace talk closed with the words of the Navajo spokesman: "We hope we may be able to eat at one table, warm by one fire, smoke one pipe, and sleep under one blanket." This unwritten arbitration treaty was faithfully kept; even the treacherous killing of three Navajos in 1875 by a resident of Grass Valley, which roused the revengeful feelings of the whole Navajo tribe, did not result in further bloodshed.

Confidence in the word of the Navajos led the pioneers to reoccupy their abandoned fields and villages and to search for new locations in the region east of the High Plateaus. The ruined homes at Paria (winter, 1871) and at Lees Ferry (1873) were restored. Cannonville (1875), Henrieville (1878), and Escalante (1875) were colonized, and permanent settlers came to the Fremont Valley (1883).

But the reclamation of lands and the building of homes in the Kaiparowits region presented difficulties not experienced by the settlements farther west. The climate is unfavorable, and the approach to cities that serve as sources of supply is long and difficult. In corresponding latitudes the oases at the west base of the Wasatch are warmer, receive 30 per cent more rainfall, and are traversed by streams of greater and more regular flow. Escalante is 80 miles from the railroad; Cannonville 90 miles; and Paria, by way of Kanab, more than 150 miles. Escalante, Henrieville, and Paria are at the very ends of little-traveled roads; very few people pass through them except to visit the score of families on upper Boulder Creek.

From the borders of these settlements unoccupied land extends for 120 miles; eastern Kane and Garfield Counties and two-thirds of San Juan County constitute an area of about 10,600 square miles within which there are no permanent habitations. The ranch buildings at Hite, at Halls Creek, and in the Henry Mountains are intermittently occupied, and prospectors come and go from their cabins in upper Glen Canyon, but neither white men nor Indians have chosen this region for more than temporary use. Furthermore, the settlements themselves are separated from one another by natural barriers.

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[38] Little, J. A., op. cit., p. 47.

[39] Quoted in Powell, J. W., Exploration of the Colorado River of the West, pp. 129–130, 1875.

To reach Tropic, Cannonville, and Henrieville, three settlements whose borders nearly overlap, a traveler by wagon or automobile from Escalante must climb the High Plateaus, circle Table Cliff, and descend the steep slopes into the Paria Valley. From Paria to Cannonville the road is the rough bed of a stream. It was found during the course of field work that the people dwelling in the Paria Valley know little of the Escalante Valley and of the Waterpocket Fold and that the Glen Canyon region is unfamiliar ground to residents of Escalante.

Within the Kaiparowits region there are six settlements—Lees Ferry, Cannonville, Henrieville, Tropic (the last three included within a radius of 6 miles), Escalante, and Boulder. Lees Ferry is the home of one family; Boulder includes about 20 families, who live on scattered ranches; the other four settlements are small villages. All of them are oases—isolated areas of watered, tillable land bordered by barren lands of wide extent.[40]

LEES FERRY

Lees Ferry, Ariz., was chosen as a refuge by John D. Lee in his attempt to escape the consequences of participation in the Mountain Meadows massacre (1857). A tract of a few hundred acres near the mouth of the Paria is favorably situated for irrigation, and alfalfa, corn, and fruit trees have been intermittently planted since about 1870. In a boat built of lumber brought from the Kaibab Plateau Hamblin and Powell crossed the Colorado at this point, demonstrating its value as a ferry site. In 1873 a ferry boat was constructed by men from Paria, and in 1874 it was protected by a stone fortification. Since that date Lees Ferry has been an essential station on the route from Utah to Arizona. It is convenient headquarters for Government surveying and exploring parties. During the "gold boom" of 1910–1913 Lees Ferry was the headquarters for parties of men who were working at Warm Creek and along the Paria. For some years past it has consisted of a dwelling house, a few acres of cultivated land, and a ferry boat kept in operation by Coconino County, Ariz. With the completion in 1929 of the bridge across the Colorado at the head of Marble Gorge, Lees Ferry is 5 miles distant from the Flagstaff-Kanab highway. Its historic ferry boat and picturesque approaches are no longer of use.

PARIA

Paria (pah, water; reah, deer), on the Paria River, 50 miles above its mouth, is the oldest settlement in southeast Utah. Situated on the established trail leading to the Ute ford (Crossing of the Fathers) and at the only feasible crossing of lower Paria Canyon, the region about Paria was a temporary stopping place for the Piutes and Navajos and perhaps for the cliff dwellers before them. Hamblin several times visited this place during his explorations, and Powell (1871), Marshall (1872), and A. H. Thompson (1875) camped here. It is possible that Escalante (1777) also passed this spot.

As a site for a small agricultural community the vicinity of Paria appeared attractive to the pioneers. Paria Canyon is here crossed by a hogback (East Kaibab monocline), above which the valley floor broadens and below which for a distance of about 8 miles the canyon walls stand back from the stream, leaving alluvial flats in a favorable position for irrigation. Grazing lands extend on both sides of the stream. From records kept by the historian of the Mormon Church it appears that in 1865 Peter Schurtz settled at Rock House, 2 miles below the hogback, only to be driven away the following year by Navajos, who utilized his place as a center for raids on settlements farther west. In 1871 Rock House was relocated by six families, and houses, corrals, a fort, and 1½ miles of ditch were constructed. The next year there were 11 families, and the place produced "plenty of corn, sorghum, and garden truck." In 1873 Adairville, farther downstream, was established, and it soon became a prosperous community of cattlemen and farmers. But Rock House and Adairville were destined to short lives. In 1874 "trouble with the ditches" caused the 15 families at Rock House to relocate above the hogback, at the present site of Paria, and in 1878 the eight families at Adairville joined in the exodus, for "the water in dry years did not reach their farms." In 1877 there were people enough to form a ward of the Kanab "stake." For several years the new village of Paria prospered, the field and garden crops returned good yields, and the cattle increased in number and quality. By 1884 the population included 107 resident members of the Mormon Church, in addition to nonresident cattlemen and about 20 Piute men and women who worked intermittently on the basis of half rations. But prosperity came to a sudden end in 1885.

Floods in 1883 were followed by the unusually severe winter of 1883–84 and by more floods in the summer of 1884, which washed away farmhouses and fields and converted the narrow stream channel into a wash that extended in places from rock wall to rock wall. (See pl. 27.) Except for a few acres protected downstream by rock buttresses all the arable lands disappeared. In the spring of 1884 Paria had its maximum population. In September of that year 48 people remained, and in 1885 the Paria ward was disorganized. For the last 40 years the removal of

[40] For descriptions of the oasis-like settlements in the Plateau province see Gregory, H. E., Keller, A. G., and Bishop, A. L., Physical and commercial geography, p. 47, 1910; Gregory, H. E., The oasis of Tuba: Assoc. Am. Geographers Annals, vol. 5, pp. 107–119, 1915; Jefferson, M. W., Utah, The oasis at the foot of the Wasatch: Geog. Review, vol. 1, pp. 346–358, 1916.

soil and alluvial banks has continued, until the amount of usable land probably does not exceed 60 acres. This area supports in part the two or three families who live at Paria during the planting and harvesting seasons. The ambitious plans of the nonresident Aziutah Land & Cattle Co. for the construction of a dam and 10 miles of ditch for carrying water from the Paria to the 50,000 acres of land on its banks remain in a speculative stage. Likewise the exploitation by the American Placer Corporation of the assumed gold resources of the region, which in 1910 resulted in recording 108 mining claims, affords no promise of a repopulated district. (See p. 148.)

CANNONVILLE, HENRIEVILLE, AND TROPIC

With Cannonville as a center, five settlements have been established in the upper Paria Valley—all of them within a radius of about 6 miles. Three of these—Cannonville, Henrieville, and Tropic—have grown into villages; the other two—Clifton, 2 miles east of Tropic, and Georgetown, 3 miles southwest of Cannonville, on Yellow Creek—were abandoned because of the scarcity of water and the destruction of the fields by floods. The site of these villages has advantages not found elsewhere in the Paria Valley. It is well watered and has good soil; firewood, coal, and lumber are near at hand; extensive tracts for grazing surround it; and the climate is suitable for field crops and during most years for fruits. That the settlement of this region was delayed 10 years after the establishment of Kanab and Paria is due largely to its isolation. To reach it from the west involved building expensive roads down the cliffs of the High Plateaus, and from the south the only feasible approach is along the bed of the Paria River. The first settlers came to Cannonville in 1875, to Clifton in 1876, to Henrieville in 1878, to Georgetown in 1886, and to Tropic in 1891. With some fluctuations, the combined population of the three existing villages has shown a small, consistent increase. All the settlements in the upper Paria Valley have experienced great difficulty in controlling the intakes of irrigation ditches and in maintaining the canals across the alluvial flats. Beginning about 1890, the Paria River and many tributary streams have cut deeply into their floors, replacing fertile fields with a network of canyons walled with sand and gravel. At Henrieville and Cannonville about a third of the arable acreage of 1880 has been destroyed, and each year sees more fertile soil carried away as stream-borne silt. At Georgetown land sufficient for the support of one family remains. Tropic has forestalled future difficulties by developing an irrigation supply high on the Paunsaugunt Plateau, where a dam on the Sevier River and a ditch 4 miles long directs water over the plateau rim to lands along the Paria. Since this ditch was completed in 1894 the village has more than doubled its population.

ESCALANTE

In 1871 the Escalante Valley was visited by Hamblin. In 1872 Dellenbaugh and Thompson, of Powell's exploring expedition, "saw Mormons from Panguitch who talked of making a settlement here and advised them to call the place Escalante." (See p. 8.) The first settlers came in 1875, and a town site was selected in 1876 in the Potato Valley, near the junction of Pine Creek and the Escalante River—the present village of Escalante. The reports of arable land, of abundant water for irrigation and power, and of favorable grazing lands that extended far in all directions induced many families to leave the less congenial plateau tops to the west, even though for the first two years some of them were forced to find shelter under overhanging rocks, in caves dug in banks, and in makeshift wickiups, tents, and shacks. Five years after its establishment the Escalante ward enrolled 441 names, and its consistent growth has made the village the largest compact settlement in southeastern Utah. As a typical record of pioneering in the Kaiparowits region the following account of the settlement of Escalante is given by permission of the historian of the Church of Latter-day Saints:

In February, 1875, William J. Flake, Isaac Riddle, Isaac J. Riddle, Charles D. White, Isaac Turley, and William Hutchings, all of Beaver, Utah, crossed the Escalante Mountains from Sweetwater and explored the region of country lying along the Escalante Creek and its tributaries with a view to finding a place suitable for the location of a settlement. These brethren, being favorably impressed with the country, measured some of the land where Escalante now stands and estimated that there were 1,000 acres of arable land or more which could be used for agricultural purposes. They also found a great plaster of Paris bed on the hills on the southwest. These brethren gave a good report of the country, which led to the settlement of Escalante being founded the same year.

A number of brethren from Panguitch, who desired to change their place of residence to a country where the climate was more moderate than on the upper Sevier, decided to settle in Potato Valley or on the Escalante Creek, having been impressed by the report of the explorers already mentioned. Consequently Andrew Peter Schow (who was appointed by Bishop George W. Sevy, of Panguitch, to take charge of the proposed colony), Thomas Heaps, David Stevenson, Don Carlos Shirts, William Alvey (all of Panguitch), and Isaac Turnbow, of Panacca, Nev., crossed the rim of the basin at what is called the Saddle of the Escalante Mountains June 28, 1875, with two wagons. These were the first wagons ever brought into Potato Valley. The brethren succeeded in descending the mountain on the east side after roughlocking the wheels and a man riding with each hind wheel. Thus they made the dangerous descent and arrived on the present site of Escalante June 29, 1875. The six men mentioned had no families with them. They held a council at the mouth of the canyon and decided to locate a town site on the north side of the creek, opposite the place where the town of

Escalante now stands. They made a temporary survey and prepared to build a house, each man claiming a quarter section, in order to secure the land for other settlers, with a view to building up a town. On this visit these pioneer brethren, while living in their wagons, spent considerable time working on the road over the mountain, most of them returning home for Christmas. The settlers mentioned represented other men, who also came over during the season and assisted in the work on the road. The understanding was that each man should have 20 acres of farming land, 2½ acres of lucern land, and a city lot. In case a man had two wives or more than one family he was to have two or more city lots. Only for a short time during the winter of 1875–76 was the infant settlement entirely vacated.

In February, 1876, some of the brethren who had visited Escalante and worked on the road the previous year returned to their chosen location and commenced work on an irrigation ditch on the north side of the Escalante Creek, in order to bring water onto the town site, but in April, 1876, the brethren agreed to move the town site and build their houses on the south side of the stream for farming purposes. Josiah Barker was the first man who brought in his family; he arrived in March, 1876, and had a terrible experience in crossing the East Fork Valley in the snow. About a dozen other families arrived later in the spring. William Alvey, the first to locate his family on the present town site, found shelter in a cellar which he built. In that same cellar all the first women of the settlement found temporary shelter against storms, which were not infrequent in the beginning. The shelter there was found to be better than in the shanties which the brethren hastily had constructed of willows. In that same cellar, 10 by 12 feet, the first choir practices in the settlement were held, while meetings were commenced in a bower built of brush and willows in June, 1876. On the 23d of July, 1876, a lumber shanty was hastily built in which a public dinner was served on pioneer day, July 24. All the people participated in this feast, including a number of Piute Indians, altogether 140 souls, not counting canines. Previous to this, on the centennial day of the United States, July 4, 1876, the people showed their loyalty as best they could. In the absence of a better flag they hoisted a striped Navajo blanket to the breeze. They, however, sent for a genuine flag, which was raised on the 24th. At this time there was only a very little water in the Escalante Creek—scarcely sufficient for the people to irrigate their garden spots, to say nothing of their farms—but in a most marvelous way the water commenced to increase, though there was considerable scarcity of water until 1882.

The unsatisfactory feature of Escalante's situation is its inaccessibility. The village stands at the base of slopes and cliffs that necessitate a climb of 2,700 feet to reach the "saddle" between the Aquarius and Table Cliff Plateaus, and the sharp descent beyond is only the beginning of a road that stretches 52 miles to the railroad at Marysvale. Before the present expensive, skillfully planned road was constructed to Widtsoe, mail and wagons traveled the rough, roundabout route through Henrieville, Tropic, and Panguitch, which made the distance to the railroad about 125 miles. When snow lay deep on the mountains even this route was barred. In the winter of 1886 an outfit was forced to go by way of the Waterpocket Fold, Hall Creek, Fremont Valley, and Salina—a distance of more than 200 miles. Before the railroad was constructed to Marysvale (1900) salable produce, chiefly butter and cheese, was carted to Salt Lake City, 250 miles.

POPULATION

The distribution and growth of the population of the Kaiparowits region is shown in the following table. The figures for 1900, 1910, and 1920 are those given by the Bureau of the Census; the other figures represent the membership of the Church of Jesus Christ of Latter-day Saints, which is estimated by the church historian to comprise 92 per cent of the population.

Population of the Kaiparowits region, 1882–1930

Settlement	1882	1883	1884	1890	1894	1895	1896	1900	1910	1920	1923	1924	1925	1926	1927	1930
Paria	85	83	[a] 130 [b] 48	10?	(?)	7	-----	31?	7?	8?	6	5?	-----	-----	-----	-----
Escalante	441	417	435	692	948	896	952	723	846	1,032	1,006	1,040	1,033	1,046	1,064	1,016
Cannonville	137	86	128	242	130	120	171	211	219	311	283	277	216	216	207	227
Henrieville	-----	-----	-----	145	136	142	99	181	158	170	158	153	147	157	159	207
Georgetown	-----	-----	-----	22	85	61	12	4	-----	-----	-----	-----	-----	-----	-----	-----
Tropic	-----	-----	-----	-----	194	222	281	379	404	474	542	461	480	458	424	447
Boulder	-----	-----	-----	-----	-----	-----	-----	104	91	177	175	150	130	144	144	192
	663	586	611	1,111	1,493	1,448	1,515	1,602	1,718	2,172	2,170	2,086	2,006	2,021	1,998	2,089

[a] April. [b] September.

The census records for 1930 give the population of Garfield County, which includes not only the settlements of Escalante, Boulder, Cannonville, Tropic, and Henrieville east of the High Plateaus but also the villages of Panguitch (1,661, or about one-third of the population of the county), Widtsoe, Hatch, Spry, Antimony, and the farms and ranches of the Sevier Valley, as 4,642. For Kane County, which includes Georgetown and Paria, also Kanab (1,195, more than one-half the population of the county), Alton, Glendale, Johnson, Mount Carmel, and Orderville, the total is 2,235.

During the period 1900–1920 the total increase in the population of Kane County was 243, and for that part of the county east of Kanab the population decreased to a point where only 12 persons remained.

During the same period the population of Garfield County increased by 1,368, of whom 802 were added to the settlements on the High Plateaus and 566 to those in the Kaiparowits region. The population of Kane County, 2,054 (0.5 to the square mile), and of Garfield County, 4,768 (0.9 to the square mile), seems very small for regions settled 50 years ago, but it adequately represents the "carrying capacity" of southeastern Utah. The number of new settlers coming in is offset by the number moving out. The small annual increase shown—about 68 for Garfield County, 12 for Kane County, and 27 for the Kaiparowits region—is largely the excess of births over deaths. The families of rural Utah are large. In 1920 the population of Garfield County included 2,198 children (about 47 per cent) under 14 years of age and 1,216 children (25 per cent) under 7 years. Escalante claims the largest proportion of children under 5 years of age of all American communities. The population is remarkably homogeneous. It is almost wholly Nordic—the absence of dark eyes and hair is very conspicuous. Of the combined populations of Garfield and Kane Counties native-born whites constitute 97.1 per cent and foreign-born whites 2.8 per cent, of whom 99.6 per cent are from northern Europe. Colored races, including Indians, are represented by four Chinese and one Negro.

In the decade from 1920 to 1930 the population of Garfield County decreased from 4,768 to 4,642, and that of Kane County increased from 2,054 to 2,235.

AGRICULTURE

Powell recognized the fact that the Kaiparowits region had "but little value for agriculture," and Thompson's traverse across the Paria and Escalante Valleys led him to the conviction that

> In this portion of Utah irrigation is essential to agriculture. If all the single acres it is possible to cultivate without artificial irrigation were aggregated, I do not believe the sum would reach one-fourth of 1 square mile.

The experience of the settlers is quite in accord with these conclusions.

Without artificial irrigation the food crops of the Kaiparowits region would be those of the cliff dweller and Piute—piñon nuts, cactus fruits, the seeds of the "ak," "waiva" (wild millet), sunflower, goldenrod, some squash, and rarely corn, and when Pongonits, the wind god, dried up the springs and withered the grasses, reliance would be placed on deer, rabbits, badgers, porcupines, rats, mice, and lizards. The area of land that originally possessed the essential agricultural features of suitable climate, level surface, fertile soil, and sufficient water for irrigation furnished at reasonable cost is estimated as 8,000 acres for the Escalante Valley, 5,000 acres for the upper Paria Valley, and 3,000 acres for the lower Paria Valley. In practice it has been found unprofitable to supply water to as much as half the otherwise available acreage, and since the region has been settled much choice land near Cannonville and at Paria has been destroyed by flood channeling. (See p. 30.)

After 40 years' experience it has been possible to place under ditch about 4,000 acres of land that immediately adjoins the village of Escalante, about 1,000 acres on Boulder Creek, Sand Creek, and other tributaries to the Escalante River, and about 3,000 acres in the vicinity of Tropic, Cannonville, and Henrieville. Of these areas, which cover about 8,100 acres, it has been found practicable actually to irrigate about half. This discrepancy is accounted for in part by the variation in water supply from year to year and the difficulty of maintaining ditches, and in part by the lack of near-by market for crops that could readily be raised. The small increase in population has been accompanied by a corresponding increase in the acreage cultivated.

La Rue[41] suggests the possibility of obtaining water at Escalante for 13,500 acres but at a cost not justified by prospective value of lands. He also thinks it "probable that by utilizing storage reservoirs the Paria may furnish sufficient water to reclaim approximately 10,000 acres of additional land." But attempts to use such waters within Paria Canyon have resulted only in hastening the destruction of lands by periodic floods, and plans for conveying water from the Paria or its tributaries to the small acreage above the canyon walls offer little promise. After a survey and estimate of cost, a scheme for reclaiming 25,000 acres along the lower Paria was abandoned.

The principal crops raised on irrigated land in this region are alfalfa, wheat, oats, barley, and potatoes. Garden vegetables are grown in abundance, and in favorable seasons orchards produce satisfactory yields.

The annual wheat crop at Escalante is about 3,000 bushels—more than enough to supply the community with flour. In 1917 it was 6,000 bushels. Likewise Cannonville, Tropic, and Henrieville raise food enough to meet most of their wants and could profitably produce more if the cost of hauling to market were not so great.

The pioneers of the Kaiparowits region rejoiced to find that the stream flow increased soon after permanent settlements were established. The church historian writes:

> In direct answer to prayers and supplications on the part of some of the apostles who visited the settlement in 1882, the water in the Escalante has increased in a most marvelous manner. To say that there is at present five times the amount of water that served the first settlers would hardly do justice to the facts.

[41] La Rue, E. C., Colorado River and its utilization: U. S. Geol. Survey Water-Supply Paper 395, pp. 118–124, 1916.

This phenomenon, which is widespread within the Colorado Plateaus, was noted by Powell:[42]

The increase is abundantly proved; it is a matter of universal experience. The observations of the writer thereon have been widely extended. Having examined as far as possible all the facts seeming to bear on the subject, the theory of the increase of rainfall was rejected, and another explanation more flattering to the future of agriculture accepted.

The amount of water flowing in the streams is but a very small part of that which falls from the heavens. The greater part of the rainfall evaporates from the surfaces which immediately receive it. The exceedingly dry atmosphere quickly reabsorbs the moisture occasionally thrown down by a conjunction of favoring conditions. Any changes in the surfaces which receive the precipitation favorable to the rapid gathering of the rain into rills and brooks and creeks, while taking to the streams but a small amount of that precipitated, will greatly increase the volume of the streams themselves, because the water in the streams bears so small a proportion to the amount discharged from the clouds. The artificial changes wrought by man on the surface of the earth appear to be adequate to the production of the observed effects. The destruction of forests, which has been immense in this country for the past 15 years; the cropping of the grasses and the treading of the soil by cattle; the destruction of the beaver dams, causing a drainage of the ponds; the clearing of driftwood from stream channels; the draining of upland meadows, and many other slight modifications all conspire to increase the accumulation of water in the streams, and all this is added to the supply of water to be used in irrigation.

Students of geology and physical geography have long been aware of these facts. It is well known that, under the modifying influences of man, the streams of any region redeemed from the wilderness are changed in many important characteristics. In flood times their volumes are excessively increased and their powers of destruction multiplied. In seasons of drought some streams that were perennial before man modified the surface of the country become entirely dry; the smaller navigable streams have their periods of navigation shortened, and the great rivers run so low at times that navigation becomes more and more difficult during dry seasons; in multiplied ways these effects are demonstrated. While in the main the artificial changes wrought by man on the surface are productive of bad results in humid regions, the changes are chiefly advantageous to man in arid regious where agriculture is dependent upon irrigation, for here the result is to increase the supply of water.

Unfortunately increase in surface flow is accompanied by decrease in the amount of ground water and by sudden fluctuations in the volume of water in the streams. Much arable land is destroyed, and that which remains is more difficult to irrigate. The water has been obtained at a ruinous price. The experiments by Sampson and Weyl[43] in the Manti National Forest of central Utah show conclusively that artificial interference with natural run-off is detrimental.

STOCK RAISING

The Kaiparowits region is essentially a grazing district, perhaps the largest "free range" in the United States. The villages and adjoining farms serve as headquarters for sheepmen and cattlemen, without whose interests the population of Escalante, Cannonville, Tropic, and Henrieville probably would be numbered by a few tens and Boulder might not exist at all.

During the summer about one-third of the population is absent from the villages, caring for stock and raising feed on outlying ranches. The prosperity of these communities depends upon the amount, availability, and value of pasturage, and, as in Indian communities, the outstanding citizens are those who have a knowledge of water holes, trails, grass, and browse shrubs.

The amount of unappropriated and unreserved land is enormous—in Kane County about 2,300,000 acres and in Garfield County 2,500,000 acres. But these figures have little value as a guide to prospective settlers. Land is plentiful, but stock feed, though nutritious, is scarce. Cattle and sheep must range widely in search of scant grasses. The stock owned at Henrieville, Cannonville, and Tropic roams over the Paria Valley and the Wahweap country and along Glen Canyon, and that owned by residents of Escalante and Boulder uses the broad Escalante Basin, the Kaiparowits Plateau, and lands east of the Waterpocket Fold. As Powell[44] long ago pointed out, for all southern Utah the conditions are such that fixed division lines for pasture lands, fencing, and individual ownership of watering places is impracticable. Powell's estimate of 4 square miles as the minimum amount necessary for a "pasturage farm" for the region that includes all of Kane and Garfield Counties was considered by the pioneer settlers too low, even for the best locations, and has proved to be entirely inapplicable for areas south and east of the High Plateaus. For large parts of this region it is estimated that under average climatic conditions 1 square mile is none too much to allot to each beef steer. In 1925 the number of cattle owned by residents of Escalante, Boulder, Tropic, Cannonville, and Henrieville was approximately 12,000 and the number of sheep about 35,000.[45] Of these animals 8,000 cattle and 23,000 sheep were accommodated in the Powell National Forest—the cattle for 5½ months (May 15 to October 31) and the sheep for 3½ months (June 15 to September 30). Without the forest the stock industry would necessarily dwindle to small proportions.

The pioneer settlers, with small herds and flocks, before the native vegetation had been disturbed, were surrounded by conditions usual for stock ranges. "Good years" of the period ending in 1893 were followed by bad years, culminating in 1896, when "about 50 per cent of the range stock died of drought and starvation." Increased rainfall combined with the

[42] Powell, J. W., Report on the lands of the arid region of the United States, 2d ed., pp. 91–92, 1879.

[43] Sampson, A. W., and Weyl, L. H., Range preservation and its relation to erosion control of western grazing land: U. S. Dept. Agr. Bull. 675. 1918.

[44] Powell, J. W., op. cit., pp. 22–23.

[45] Estimates by Wallace Riddle, forest supervisor, in a communication dated Jan. 27, 1926.

extension of the grazing area to include the Kaiparowits Plateau brought more favorable conditions. Overstocking of the range in response to the increased value of cattle during the World War appears to have been the first step toward the present unfortunate state.

In crossing the Kaiparowits in 1915 grass for horses was abundant along Wahweap, Warm, and Last Chance Creeks and the mesas and dune-covered areas east of the Paria. On top of the Kaiparowits also grass was plentiful. In 1918 many flocks of sheep found good pasturage on the plateau, but during three days' travel about Warm and Wahweap Creeks the pack horses lived on oats, leaves of cottonwood, and tops of brush, and lack of feed prohibited travel along the rim of Glen Canyon. In 1922 there was insufficient forage for pack trains at all places except sand-dune areas in the Escalante Valley. In September, 1924, no grass or browse of any kind was found in unfenced areas of the Butler Valley and about Canaan Peak. There is no doubt that the Escalante and Paria Valleys and the Kaiparowits Plateau have deteriorated as pasture lands during the last decade, and it seems unlikely that they can be restored to the state existing during the period 1875–1890. Some system of reservation seems most likely to bring improvement.

It is interesting to note that in the Kaiparowits region the lack of water is not a serious hindrance to the cattle industry. Though water is scarce, the available sources are so situated that only a few small areas of grazing lands are unutilized because of distance from water holes. Many starving cattle were seen, but none that were seriously suffering from thirst.

MINING

Gold has been taken from gravel bars in Glen Canyon, and more can doubtless be recovered; but amounts justifying large outlays are unlikely to be found. (See p. 148.) The "oil fields" at Circle Cliffs and in Glen Canyon above the mouth of the Escalante have so far yielded no returns. The one known mineral resource of potential value is the coal of the Kaiparowits Plateau. (See pp. 148–153.)

GENERAL STRATIGRAPHIC RELATIONS

The sedimentary rocks of the Kaiparowits region are chiefly of Mesozoic age—Triassic, Jurassic, and Cretaceous. The highest plateaus of the region—the Paunsaugunt, Table Cliff, and Aquarius—are capped by Eocene strata, and in the upwarps, where erosion has planed deepest, Permian limestones and sandstones appear. In their lithologic features these rocks, particularly those assigned to the Triassic and Jurassic, resemble closely the corresponding series in other parts of the Colorado Plateau province.

Except for variations in thickness, there is little difference between the formations exposed at the Circle Cliffs or the Paria Valley and those in the Navajo country, 150 miles to the south, in the Virgin Valley, 80 miles to the southwest, and along upper White Canyon, 100 miles to the east. The Navajo sandstone can be traced almost continuously from western Colorado to southeastern Nevada and from northern New Mexico to central Utah, and throughout this great region the formation is characterized by essentially similar lithology, peculiarities of weathering, and topographic expression. The variegated marl, limestone conglomerate, and silicified trees of the Chinle formation distinguish this division in practically all parts of the plateau country, and even the thin Shinarump conglomerate shows little change over thousands of square miles.

The strongly predominant rock type of the region is sandstone. Hard, massive sandstone forms most of the plateau benches and vertical canyon walls; weak, shaly sandstone makes up a large part of the slopes and valley flats. Limestone is rare, except in the Kaibab Plateau. Lenses and thin beds of conglomerate appear at certain horizons. Clay shale is widespread in parts of the Cretaceous and Triassic, but where traversed it is quantitatively much less than sandstone. The stratigraphic features of the formations in the Kaiparowits region are summarized in the accompanying table. (See also pl. 5.)

Generalized section of the rock formations in the Kaiparowits region, Utah

System	Series	Group and formation	Character	Thickness (feet)
Tertiary.	Eocene.	Wasatch formation.	Calcareous sandstone, shale, and limestone; pink, white, and varicolored, soft; underlies highest plateaus; crops out in cliffs and forms slopes.	2,000
		—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; a fresh or brackish water deposit.	2,200
		Wahweap sandstone.	Yellowish-gray massive sandstone with some sandy shale, the upper 200 feet very massive and hard; grades downward into alternating hard and soft beds; a prominent cliff-forming division.	1,100–1,300
		Straight Cliffs sandstone.	Yellowish to brown irregularly bedded medium to massive sandstone; contains coal beds as much as 20 feet in thickness; forms prominent escarpments.	900–1,200
		Tropic shale.	Bluish-drab argillaceous to sandy shale; very uniform in color and texture; grades to fossiliferous sandstone at base; shale contains abundant *Gryphaea newberryi* and other fossils; forms slopes and badlands.	550–1,450
		Dakota (?) sandstone.	Yellow to nearly white sandstone; conglomeratic in part; irregularly bedded; contains thin beds of coal and large silicified trees in places.	0–100
		—Unconformity—		
Cretaceous (?).	Lower Cretaceous (?).	Morrison formation.	Maroon to light bluish-gray sandy banded shale, very massive, hard conglomerate, and coarse gritty maroon, yellow, and gray irregularly bedded sandstone; forms escarpments.	0–565
		—Unconformity—		

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

System	Series	Group and formation		Character	Thickness (feet)
Jurassic.	Upper Jurassic.	San Rafael group.	Summerville formation.	Thin-bedded red-brown to gray friable sandstone; shale-like beds, alternating red and white, form banded cliffs; contains much gypsum.	100–500
			Entrada sandstone.	Yellow, tan, light-red, brown and gray fine, even-grained sandstone; in places one massive cross-bedded stratum; some poorly bedded sandstone and red shale.	200–800
			Carmel formation.	Pink to red and bluish sandy shale; white and buff sandstone; gypsum in beds and as cement; dense siliceous and earthy dark-maroon and light bluish-green limestone; weathers in badlands and forms bench on top of Navajo sandstone.	90–450
			—Unconformity—		
Jurassic (?).	Lower 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.	1,200–1,800
			Local unconformity.		
			Todilto (?) formation.	Maroon coarse-grained cross-bedded sandstone, conglomerate, blue-gray hard, dense limestone; and maroon and brown shale; all in thin irregular beds.	125–249
			Wingate sandstone.	Reddish-brown, very massive sandstone; prominently jointed; crops out commonly in a single vertical cliff that resembles a palisade; cross-bedded but not so prominently as Navajo sandstone.	250–400
		—Unconformity—			
Triassic.	Upper Triassic.	Chinle formation.		Thick variegated calcareous shale or "marl," fine-grained sandstone, cherty limestone, and conglomeratic limestone; sandstone most abundant in the middle part; contains large silicified trees.	475–800
	Upper (?) Triassic.	Shinarump conglomerate.		Light-gray to yellow coarse-grained to conglomeratic sandstone, very irregularly bedded and variable in thickness; grades locally into bluish sandy shale; contains silicified wood; forms prominent bench.	0–125
		—Unconformity—			
	Lower Triassic.	Moenkopi formation.		Chocolate-brown to yellowish shale and sandstone, containing locally in upper portion very thin hard limestones; shale very sandy and grades into shaly sandstone; the sandstone ranges from thin-bedded platy to thick massive beds; ripple marked.	304–500
		—Unconformity—			
Carboniferous.	Permian.	Kaibab limestone.		White to yellowish massive, more or less dolomitic limestone, in part cherty; lower part increasingly sandy and grades downward into sandstone without sharp change; fossiliferous in part.	164
		Coconino sandstone.		Light creamy-white calcareous cross-bedded medium-grained sandstone.	0–93

PERMIAN FORMATIONS

LOCATION AND EXTENT

Beds of Permian age form the surface of the Kaibab Plateau, which extends from north-central Arizona northeastward nearly to the Paria River, in Utah. These exposures lie on the western border of the Kaiparowits region, and as they are but prolongations of the Permian beds that are well displayed on both sides of the Grand Canyon, a discussion of them properly belongs with reports on that region. In this paper they are briefly described for comparison and correlation with corresponding beds in the Kaiparowits region.

In the Circle Cliffs several canyons have cut into Permian limestone and sandstone, exposing in some places more than 200 feet of strata, and a deep well drilled near the top of the Circle Cliffs dome gives information concerning the rocks beneath. In addition to the broad exposures on the Kaibab Plateau and the outcrops in the Circle Cliffs, Paleozoic rocks appear at the surface in several other parts of southern Utah. Permian and Pennsylvanian rocks are well displayed on the San Juan River at Goodridge, on the Colorado River in Cataract Canyon, along the lower Green River, and in the canyons that head in Elk Ridge. Permian rocks are exposed in the San Rafael Swell, in White Canyon, and in Grand Gulch. Permian and older rocks are extensively developed also in the Virgin River region in southwestern Utah. It is therefore very probable that upper Paleozoic formations underlie all of the plateau country in southern Utah.

In the Kaiparowits region the exposed strata of Permian age are assigned to the Kaibab limestone and the Coconino sandstone.

KAIBAB LIMESTONE AND COCONINO SANDSTONE

HISTORICAL SKETCH

Descriptions of the beds now called Kaibab limestone and Coconino sandstone appear in all the geologic reports that relate to the Grand Canyon region. These formations could scarcely escape observation, for they are cut by innumerable canyons. The limestone forms the surface over wide areas and presents persistent features of lithology and fossil content. The sandstone is a distinctive stratigraphic unit, marked especially by its prominent cross-bedding. They were noted by Marcou in 1856 and by Newberry in 1861 and were later discussed and represented in sections published by Powell, Marvine, Howell, Gilbert, Dutton, and Walcott. Studies of the "carboniferous" by geologists of the Wheeler and the Powell surveys resulted in the well-known threefold division called Aubrey limestone, Aubrey sandstone, and Redwall limestone. In addition to the "Aubrey" limestone and the "Aubrey" sandstone—spoken of also as "Upper Aubrey" and as "cherty limestone" and "cross-bedded sandstone"—the Aubrey group included at its base a series of sandstones and shales which were either classed with the "Lower Aubrey" sandstones or treated as a minor subdivision as "Lower Aubrey" sandstone and shale. Darton[1] simplified this nomenclature by the substitution of the terms Kaibab limestone for "Aubrey" limestone, Coconino sandstone for "Upper Aubrey" sandstone, and Supai formation for "Lower Aubrey" sandstone and shale.

As a result of the extensive studies of Noble[2] the generalized descriptions of previous writers were replaced by an analysis that is based on detailed examination of carefully measured sections.

Reeside and Bassler[3] separated the Kaibab of the Kanab and Virgin River Valleys into five topographic and lithologic divisions.

Correlation of the Kaibab on the basis of lithology and paleontology presents little difficulty, but in spite of the abundant fossils present the exact age of the formation remained long in doubt. Marcou[4] classed it as Permian—the equivalent of the Magnesian limestone of England. Newberry[5] regarded it as "an integral part of the Carboniferous." Geologists of the Wheeler and the Powell surveys referred the "Aubrey" sandstone and "Aubrey" limestone to the upper Carboniferous and a few feet at the top to the "Permo-Carboniferous." Darton[6] and Robinson[7] placed the Kaibab and Coconino in the Pennsylvanian. Noble[8] correlated them with the Manzano group of New Mexico, then considered Pennsylvanian. In discussing the geology of the Little Colorado Valley, Gregory[9] states that "fuller investigation may result in placing all or part of the Kaibab among Permian formations." Evidence from many sources increasingly favors the correlation of the Kaibab and Coconino with part of the Manzano group of New Mexico, which is now classified as Permian.

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

[2] Noble, L. F., The Shinumo quadrangle: 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, 1923.

[3] Reeside, J. B., jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 54–76, 1922.

[4] Marcou, Jules, Résumé and field notes: U. S. Pacific R. R. Expl., vol. 3, pt. 4, p. 153, 1856.

[5] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 3, p. 73, 1861.

[6] Darton, N. H., op cit., pp. 28, 30.

[7] Robinson, H. H., The San Franciscan volcanic field: U. S. Geol. Survey Prof. Paper 76, pp. 24–25, 1913.

[8] Op. cit.

[9] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 18–22, 1917.

The usual section of the Kaibab formation is incomplete; either the bottom is concealed or the top is removed by erosion. The search by Gregory and Noble[10] for a place where unquestionably all the Kaibab is displayed was rewarded by finding in Kaibab Gulch a complete section with the Hermit shale below and the Moenkopi above, a section which may serve as the type of the Kaibab limestone.

The Coconino sandstone maintains a uniform character throughout the Grand Canyon district, although there are marked variations in thickness. The sandstone called Coconino in southern Utah,[11] part of which is described in this paper, occupies a stratigraphic position that corresponds to the Coconino of the Grand Canyon but probably is not precisely equivalent to it.

NORTHERN KAIBAB PLATEAU

Except for a small outcrop of Hermit shale in Kaibab Gulch the exposed Permian rocks at the north end of the Kaibab Plateau consist entirely of the Kaibab limestone. As seen here, the Kaibab is a somewhat magnesian gray arenaceous limestone, which commonly weathers very light drab-gray or buff. It is medium to massively bedded, and the thickness of individual beds ranges from a few inches to several feet. As indicated by resistance to erosion, the rock is harder than that of the formations above and below. Jointing is common, though somewhat irregular, and has guided the weathering of cliffs and canyon walls. Most of the Kaibab limestone is siliceous and arenaceous. In places it consists of about equal amounts of calcite or dolomite and quartz; elsewhere it is a sandstone with lime and magnesian cement. Gradation in the amount of sand grains is scarcely noticeable in many layers, but in some there is a distinct alternation of sandstone and slightly sandy or quite pure limestone. Besides the sand grains in the body of the rock silica occurs as small nodules and as quartz geodes. Locally chert nodules and lenses are abundant. In parts of the formation many fossil marine invertebrates are well preserved.

In other parts careful search revealed only fragmentary shells—no recognizable fossil remains. The Kaibab is evidently of marine origin, but the fossils and the abundance of sandy material that it contains indicate that the water in which it was deposited was not deep nor in this area probably at a great distance from land.

Because of its great resistance to erosion, as compared with the overlying Moenkopi and Chinle formations, which have been stripped from its surface, the Kaibab formation in House Rock Valley presents a rather smoothly rounded surface, which marks out accurately the structure of the rocks along the east flank of the Kaibab fold. In the steep slopes of the fold short consequent streams have carved deep, narrow canyons, in the walls of which the broken edges of the Kaibab strata are sharp and angular. The rock-strewn bottom of these canyons consists generally of a series of short steps over the edges of successive hard beds.

At Kaibab Gulch, about 8 miles south of the settlement of Paria, the canyon walls consist of Hermit shale succeeded upward by Kaibab limestones and sandstones that are unconformably overlain by Moenkopi sandstones and shale. At the base of the section calcareous sandstone immediately overlies red shale; no beds referable to the Coconino sandstone are present.

The strata exposed in Kaibab Gulch may appropriately be considered the type section of the Kaibab limestone. (See pl. 4, *A*, *B*.) As described by Noble,[12] the strata of Kaibab limestone in Kaibab Gulch comprise five major divisions.

Section in Kaibab Gulch, Utah

	Feet
(At top.) Very irregular beds of coarse breccia-conglomerate, interstratified with buff shale and calcareous sandstone and capped by massive beds of buff limestone; the limestone forms a strong cliff; the shale and sandstone form a slope broken by irregular cliffs of breccia	77
Massive gray crystalline limestone, cherty and fossiliferous, containing a bed of sandstone in the middle and passing at top into alternating beds of chert and buff earthy limestone; the beds of gray crystalline limestone form strong cliffs; the alternating beds of chert and buff limestone above the gray limestone form a steep, ledgy slope	326
Buff and reddish fine-grained sandstone, poorly consolidated and irregularly bedded, interstratified with beds of sandy breccia and travertine; forms slope	150
Massive buff siliceous limestone, cherty and somewhat fossiliferous, containing some calcareous sandstone near the middle and a well-defined bed of hard fine-grained buff cross-bedded sandstone near the base; all beds except the calcareous sandstone in the middle of the member form strong cliffs	119
Alternating beds of arenaceous limestone and irregularly bedded fine-grained buff sandstone; one thin bed of limestone, in the middle of the member, is very fossiliferous; the member forms a steep, ledgy slope, broken by small cliffs	45
	717

[10] Gregory, H. E., and Noble, L. F., Notes on a geological traverse: Am. Jour. Sci., 5th ser., vol. 5, pp. 229–238, 1923.

[11] 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, p. 8, 1923. Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 121–122, 1924. Gilluly, James, and Reeside, J. B., jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 63, 1928.

[12] Noble, L. F., A section of the Kaibab limestone in Kaibab Gulch, Utah: U. S. Geol. Survey Prof. Paper 150, pp. 41–60, 1928.

The detailed sections of Kaibab limestone at the Bass trail (Grand Canyon) in the Kanab Valley, in the Virgin Valley, and near Lees Ferry, as given by Noble, show a remarkable correspondence in lithologic detail and sequence of strata with the section at Kaibab Gulch. Even the Kaibab of the Muddy Mountains, Nev., as analyzed by Longwell,[13] may be readily correlated. But the beds that are assigned to the Kaibab at the Circle Cliffs and at the San Rafael Swell differ much from those at Kaibab Gulch in composition, arrangement, and thickness. Though the fossils indicate approximately equivalent age, they can not be correlated with assurance. Evidently the vicinity of the Paria River marks the position of a significant change in the Kaibab limestone. Immediately west of the river, in Kaibab Gulch, are the easternmost outcrops of typical Kaibab limestone. East of the river the formation thins, becomes more sandy, and loses some features characteristic of sections measured in the Grand Canyon region. East of Glen Canyon no strata assignable to the Kaibab have been recorded.

CIRCLE CLIFFS

PHYSICAL FEATURES

Several canyons in the central part of the Circle Cliffs afford excellent exposures of Permian limestone and limy sandstone that are without doubt referable to the Kaibab limestone. (See pl. 6, *B*.) Beneath the limestone lies light-colored cross-bedded sandstone that is classed as Coconino. As on the Kaibab Plateau, the limestone occurs beneath dark-red sandy shale of the Moenkopi formation, and the lithologic character and contained fauna of the limy beds are essentially the same as those seen in typical exposures of the Kaibab throughout the Colorado Plateau province. In fresh exposures the Kaibab limestone of the Circle Cliffs is very light gray to almost white and weathers to creamy gray or buff. It is fairly evenly bedded, and the thickness of the individual beds ranges from a few inches to 15 feet or more. Locally very thin-bedded, almost shaly strata appear. Some of the beds are very hard, even textured, and fine grained, weather with a characteristic finely pitted surface, and are marked by fine mosslike dendrites of manganese dioxide on fracture planes. Other beds are medium grained and subcrystalline and contain disseminated rounded grains of quartz sand. Alternating with the purer limestones are beds in which the proportion of sand is so great that the rock is properly termed a limy sandstone, but it is common to find an almost imperceptible gradation from limestone with scattering grains of sand to sandstone with abundant lime cement. The amount of sand is considerably greater than that in the Kaibab of the Kaibab Plateau or the Grand Canyon district. One peculiar light-yellow soft, massive ledge, which weathers in well-rounded surfaces and contains abundant angular fragments of chert, was observed at several places in the Circle Cliffs. This chert-bearing bed is in part a residual deposit, and the chert is clearly of secondary origin, but its position within the formation beneath massive, evenly stratified limestone shows that it does not represent exposure and disintegration of a part of the Kaibab rocks in post-Kaibab time.

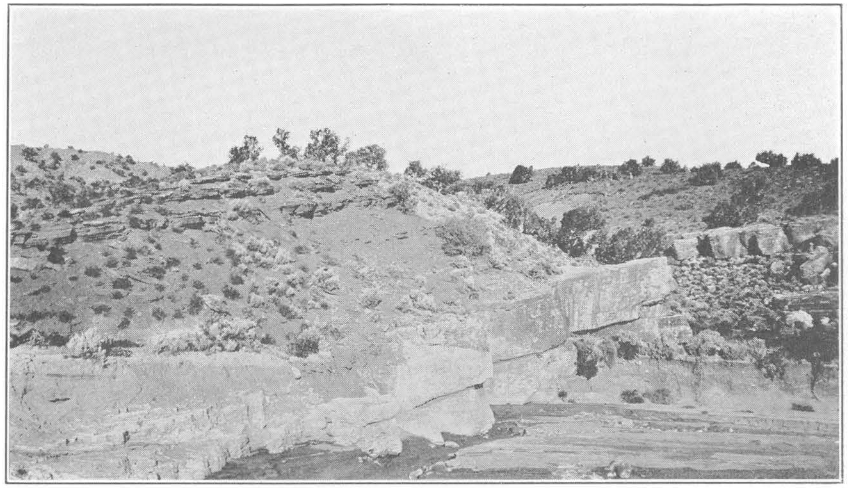
[13] Longwell, C. R., Geology of the Muddy Mountains, Nev.: Am. Jour. Sci., 5th ser., vol. 1, p. 48, 1921; U. S. Geol. Survey Bull. 798, pp. 38–43, 1928.

As exposed in the Circle Cliffs the Kaibab forms steep canyon walls that are made up of a series of massive benches and intervening slopes. In places the cliffs are sheer, but in general weak materials at certain horizons produce slopes composed of a series of minor benches.

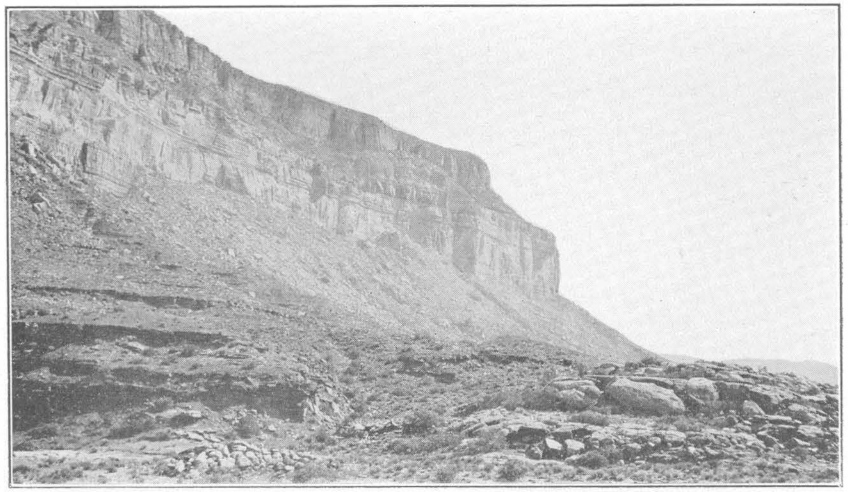
The Coconino sandstone, as defined in the Circle Cliffs, includes the light creamy-white, more or less cross-bedded sandstone that underlies the lowest observed limestone. It differs in no essential respect from the sandstone in the lower part of the Kaibab and is undoubtedly conformable with the beds above; indeed, the definition of the formations is somewhat arbitrary. The only basis for regarding the sandstone as a stratigraphic unit distinct from the Kaibab is the great thickness of the sandstone, as revealed by boring, and its correlation with the thick, widespread sandstone that in other parts of Utah has been called Coconino. This sandstone is very calcareous; as observed in some thin sections, the calcite filling between the sand grains is approximately equal in quantity to the sand. The quartz grains are medium in size and fairly well rounded. A few of the rounded grains consist of limestone. The cross-bedding is neither so prominent nor so uniform as that in the Coconino of the Grand Canyon; the individual cross-bedded lenses are much thinner; and the platy weathering of the cross laminae is much less striking. In general, the rock appears less resistant to weathering than the type Coconino and forms rounded "bouldery" surfaces between irregularly disposed joint planes.

STRATIGRAPHY

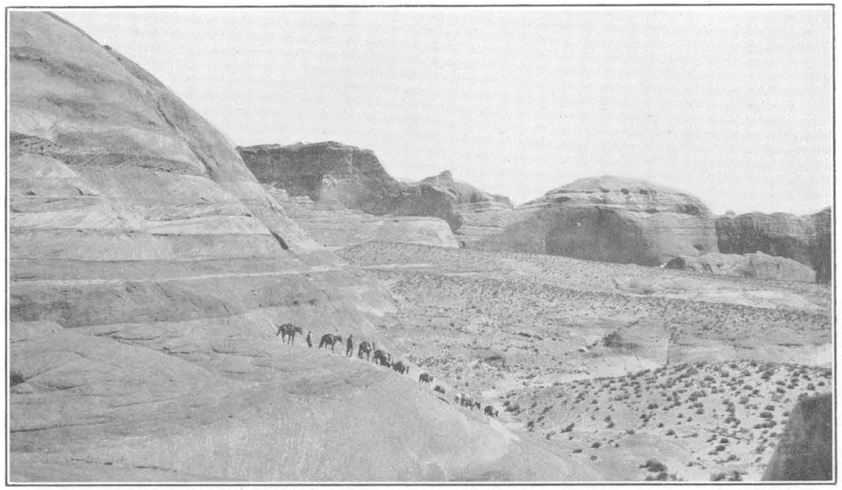
The stratigraphic sequence and the composition of the Permian beds in the Circle Cliffs are shown in the following measured sections. The maximum exposed thickness is 236 feet.



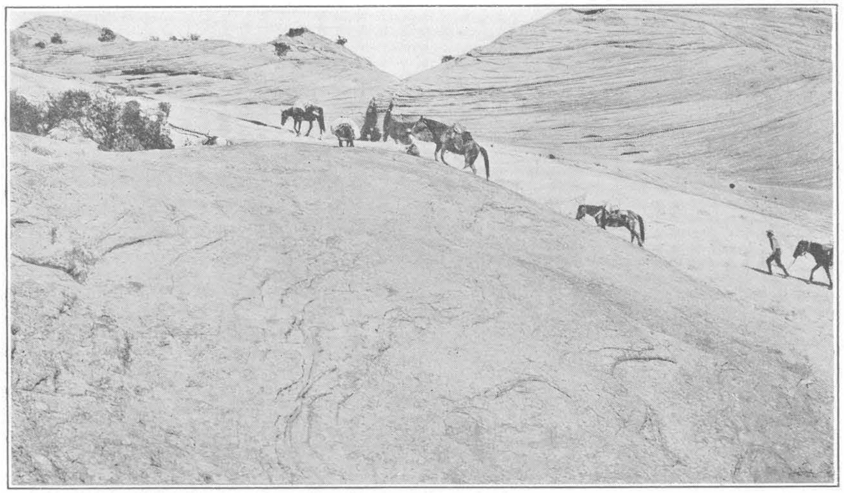
A. CONTACT OF MOENKOPI FORMATION AND KAIBAB LIMESTONE AT MOUTH OF KAIBAB GULCH



B. CONTACT OF KAIBAB LIMESTONE AND HERMIT SHALE IN KAIBAB GULCH



C. VIEW ALONG OLD UTE TRAIL LEADING TO THE CROSSING OF THE FATHERS



D. "TRAIL" OVER NAVAJO SANDSTONE, WATERPOCKET FOLD, NEAR BAKER RANCH

1 Generalized section of the rocks of southwestern Utah. By J. B. Reeside, Jr., and H. Bassler U. S. Geol. Survey Prof. Paper 129, 1922.

2 Section of the Paleozoic rocks in the Grand Canyon at Bass Trail. By L. F. Noble, U. S. Geol. Survey Prof. Paper 131, pl. 19, 1924.

3 Generalized section from southwestern part of Kaiparowits Plateau to upper part of Marble Gorge. This report.

4 Generalized section of south-eastern and north-central parts of Kaiparowits Plateau along Last Chance Creek to Table Cliff Plateau. This report.

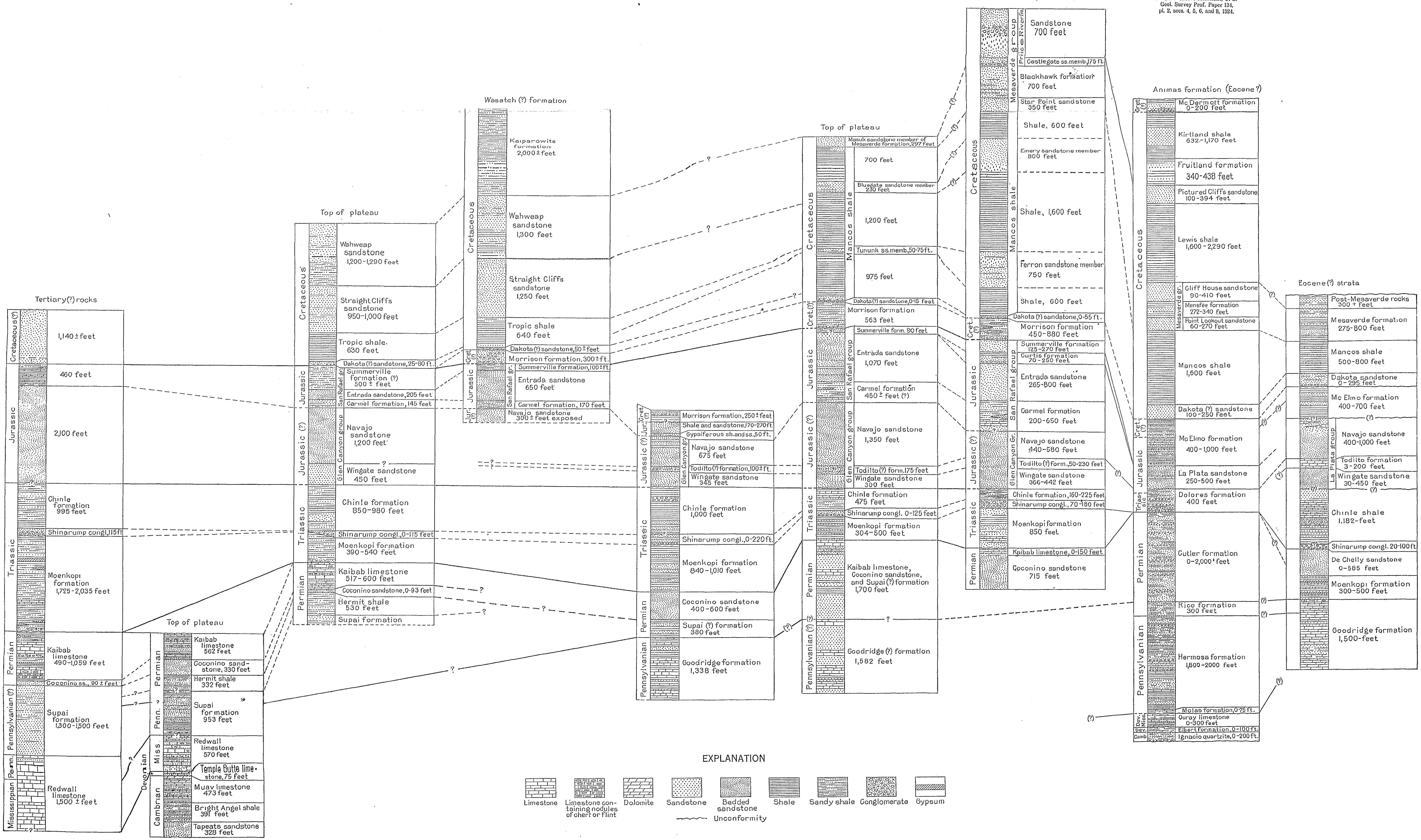
5 Generalized section of lower San Juan River Canyon. Compiled from measurements by H. D. Miser, U. S. Geol. Survey Prof. Paper 132, pl. 1, secs. 6, 7, 8, and 9, 1924.

6 Generalized section of Circle Cliffs, Waterpocket Fold, and Henry Mountains. This report.

7 Generalized section of San Rafael Swell and southern Wasatch Plateau. Compiled from measurements by James Gilluly (below Dakota?), and E. M. Spieker (above Morrison). Unpublished notes.

8 Generalized section of rocks in southwestern Colorado. Compiled from measurements by Whitman Cross (below Dakota?), U. S. Geol. Survey Geol. Atlas, Folio 130, 1905, and J. B. Reeside, Jr. (above Morrison), U. S. Geol. Survey Prof. Paper 134, pl. 2, secs. 4, 5, 6, and 8, 1924.

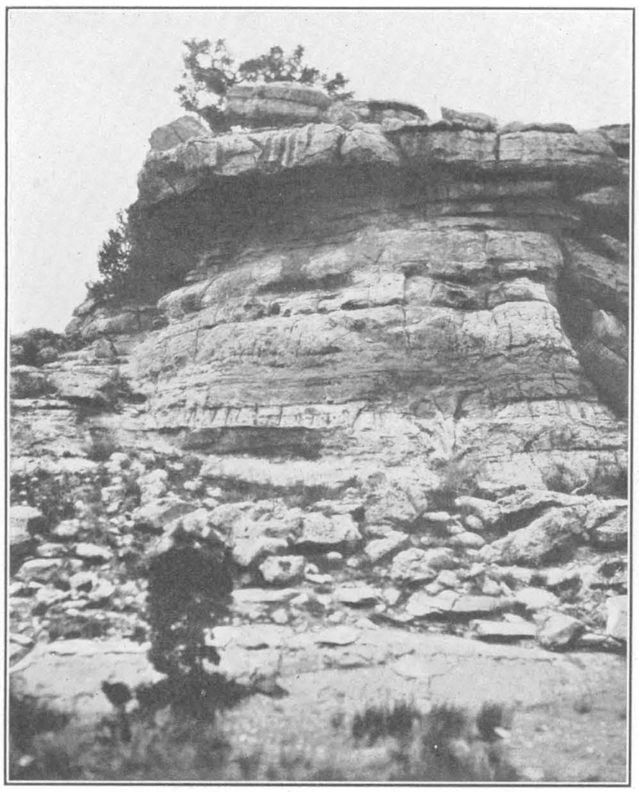
9 Generalized section of the Navajo country. By H. E. Gregory, U. S. Geol. Survey Prof. Paper 93, pl. 3, 1916.



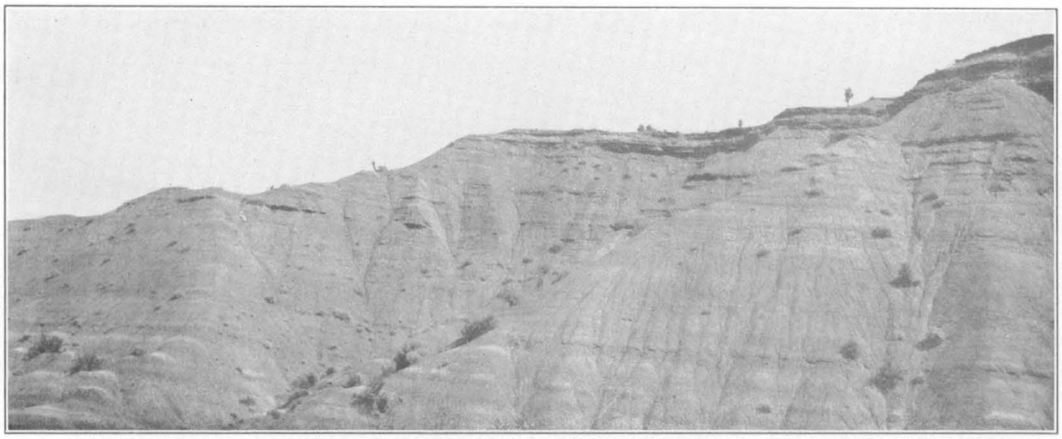
CORRELATION CHART SHOWING RELATIONS OF THE PALEOZOIC AND MESOZOIC ROCKS OF THE KAIPAROWITS REGION TO THOSE OF ADJACENT REGIONS

A. MARBLE GORGE

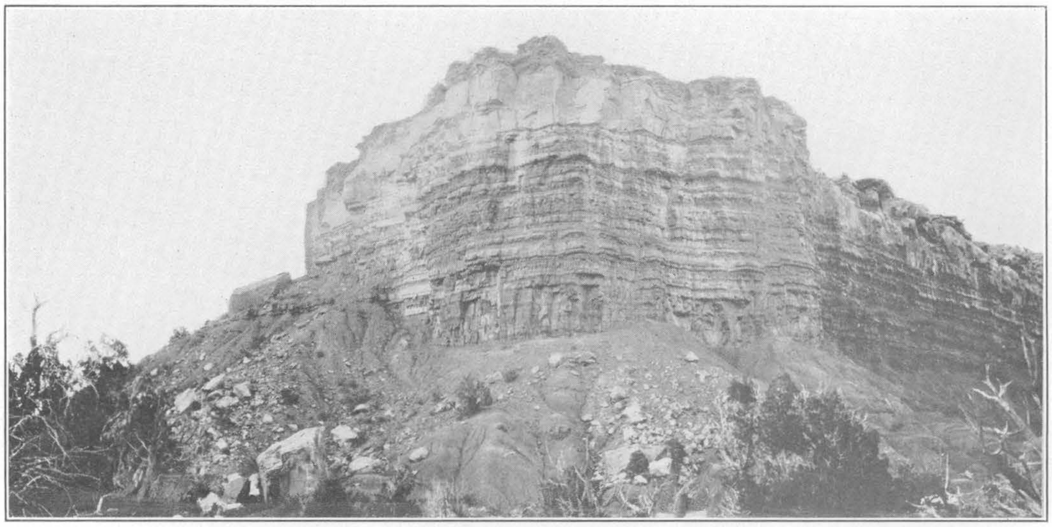
View looking downstream 12 miles south of Lees Ferry. Photograph by E. C. La Rue.



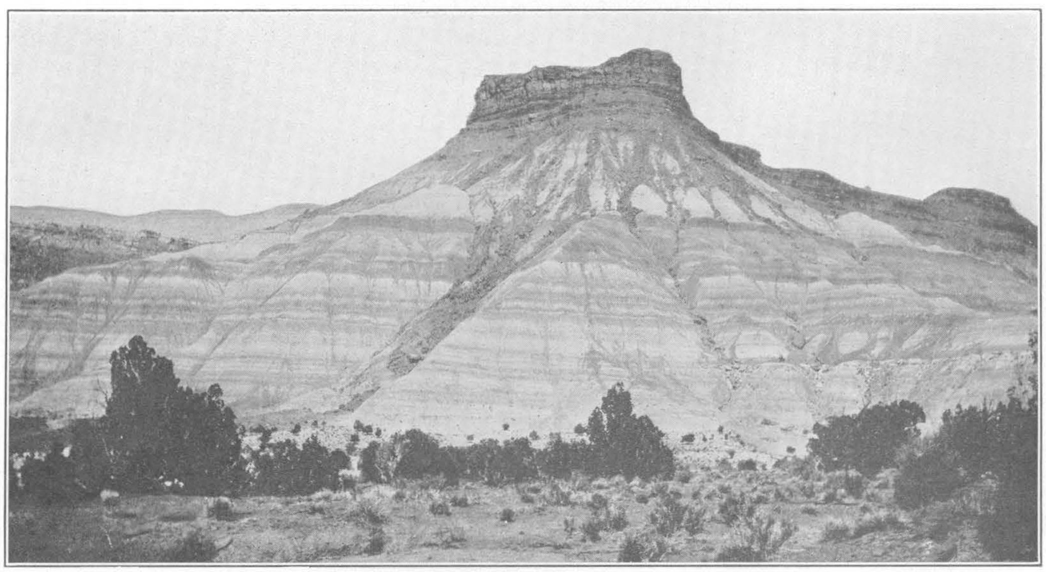
B. KAIBAB LIMESTONE NEAR JUNCTION OF SILVER FALLS AND MULEY TWIST ROADS, CIRCLE CLIFFS DISTRICT



A. SHNABKAIB SHALE MEMBER OF MOENKOPI FORMATION ABOUT 3 MILES SOUTHWEST OF PARIA



B. MOENKOPI STRATA UNCONFORMABLY OVERLAIN BY SHINARUMP CONGLOMERATE IN NORTHERN PART OF CIRCLE CLIFFS



C. BUTTE 1 MILE SOUTHWEST OF PARIA

Chinle formation capped by a remnant of Wingate sandstone. The foreground shows a dip slope formed by sandstone at the top of the Moenkopi; the Shinarump conglomerate is represented by a thin white sand at the base of the slope, but it disappears locally in this area, the Chinle resting directly on Moenkopi. The entire thickness of the Chinle, about 500 feet, is shown in this view.

Section of Kaibab limestone and Coconino sandstone west of The Peaks, Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Triassic (Moenkopi formation) at top.	
Permian:	
Kaibab limestone—	
6. Limestone, yellow, dolomitic, in massive, evenly bedded ledges, that weathers in large angular blocks pitted by solution; in places contains numerous dendrites of manganese dioxide and concretions resembling wad; contains fossils; forms resistant cap of prominent bench	37
5. Limestone, light yellow, soft, dolomitic, massive, filled with angular fragments of white chert; weathers in smooth slope; exposed	15
4. Limestone, soft, light creamy yellow, thin to medium bedded; weathers in slope; partly concealed	37
3. Limestone, white, very sandy; rounded sand grains scattered rather evenly through the limestone but more lime than sand; weathers in thick ledges	34
2. Sandstone, white, medium to coarse grained, rounded quartz grains in a lime matrix, more sand than lime; massive	19
Total Kaibab limestone	163
Coconino sandstone—	
1. Sandstone, white, medium to coarse grained, rounded quartz grains in a lime matrix, moderately soft, massive; breaks into irregular blocks on weathering; exposed	73
Total Permian	236

Section of Kaibab limestone north of The Peaks, Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Triassic (Moenkopi formation) at top	107
Permian:	
Kaibab limestone—	
4. Limestone, light creamy to rich yellow, dolomitic, massive, in rather even beds 2 to 5 feet thick; weathers in large angular solution-pitted blocks; lower part coarse grained, upper part fine grained and dense; caps bench	17
3. Limestone, light yellowish gray, dolomitic, fine grained, very massive but rather soft; weathers white in smooth, rounded surfaces and slopes; contains abundant chert and hard splintery white flint in nodules, lenses, and angular fragments; in places the rock resembles a breccia composed of angular chert fragments held in a matrix of limestone; exposed	18
Permian—Continued.	
Kaibab limestone—Continued.	
2. Limestone, yellowish gray, soft, thin to medium bedded, poorly exposed; this zone characteristically weathers as a slope; partly covered	43
1. Limestone, light creamy yellow, dolomitic, dense, fine-grained, very massive, and in beds 1 to 2 feet thick with very fine cavities; weathers in large blocks and irregular rounded slopes; upper part more evenly bedded and weathers to slightly lighter color than lower part	56
Total Kaibab limestone	135

The uppermost portion of the Kaibab (bed 4) at this locality has less than half the thickness of the corresponding stratum (bed 7) at The Peaks. This decrease appears to be due to pre-Moenkopi erosion.

Section of Kaibab limestone northeast of Wagonbox Mesa, below Yellow Cone, 2 miles west of point where Burr trail crosses the Navajo sandstone, Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Triassic (Moenkopi formation) at top	258
Permian:	
Kaibab limestone—	
5. Limestone, brown and yellowish, soft; contains much chert; weathers in ledge irregularly pitted; locally somewhat shaly	18
4. Limestone, tan to gray, in part sandy; contains numerous calcite concretions and chert nodules	32
3. Sandstone, white to buff, medium to fine grained, calcareous; upper part grades to very sandy limestone	30
2. Limestone, dark gray and brown, very sandy; weathers in angular blocks with pitted surfaces; forms a prominent ledge; contains pelecypods	5
1. Sandstone, white to buff brown, fine to medium grained, massive, calcareous; weathers gray; crops out in rounded surfaces; exposed	42
Total Kaibab limestone	127

The top bed of the Yellow Cone section apparently corresponds to the soft cherty zone which on the north and west side of The Peaks is overlain by very massive, hard, thick limestone. The pelecypods (*Pleurophorus ?* n. sp.) obtained in the 5-foot bed of limestone are the same as those found more abundantly in the sandy beds in the central part of the Circle Cliffs, near the point where the Muley Twist road to Green River joins the road from Silver Falls Canyon to the Ohio Oil Co.'s well, near Wagonbox Mesa.

Section of Kaibab limestone at junction of Muley Twist and Silver Falls Canyon roads, south of Ohio Oil Co.'s well, Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore. (See pl. 6, *B*)]

	Feet
Triassic (Moenkopi formation) at top	30
Permian:	
Kaibab limestone—	
4. Limestone, light yellowish gray, very cherty; the chert in irregular nodules, lenses, and layers; the limestone soft, rather thin bedded, and weathering in slopes that are strewn with weathered fragments of chert	10–25
3. Limestone, yellow and light tan, dolomitic; lower part very sandy, grading without sharp change from underlying sandstone; upper part fine grained, hard, dense, cherty, weathering in angular pitted blocks; the limestone contains numerous small, greenish grains, apparently glauconite; fossiliferous	47
2. Sandstone, light gray to almost white, fine grained, very calcareous, massive; weathers yellowish, in rounded shoulders and large blocks, in part soft, in part hard; grades locally to very sandy limestone in which percentage of sand and lime is about equal; fossiliferous	63
1. Limestone, dark gray, very sandy, hard; exposed	1
Total Kaibab limestone	136

FAUNAL CHARACTER

Careful search for fossils in a number of sections of the Kaibab in the Circle Cliffs revealed a scarcity of organic remains. Fossils were collected, however, both from the zone of limestone beneath the very cherty zone and in the lower sandy beds. Though faunal lists show a predominance of molluscan forms, the molluscoids, including both bryozoans and brachiopods, are numerically most abundant in the limestones. Two or three types of productids are very common. The limy sandstone contains large numbers of a single type of pelecypod, the remains of which, though generally not well preserved, cover completely the surface of many slabs.

G. H. Girty's identifications of the fauna, accompanied by brief comment concerning the collections, are presented below:

Lot 4379. At the Yellow Cone, northeast of Wagonbox Mesa, about 1½ miles west of Burr Flat; east side of Circle Cliffs, Garfield County, Utah. From limestone, bed 2, Yellow Cone section:

Marginifera aff. M. cristobalensis.
Acanthopecten coloradoensis.
Astartella sp.
Pleurophorus? n. sp.

Lot 4380. About 1 mile southwest of Ohio Oil Co.'s well, near center of Circle Cl ffs swell, Garfield County, Utah. From limestone about 10 to 15 feet higher stratigraphically than collection 4379.

Sponge.
Chonetes hillanus?
Productus aff. P. popei.
Productus ivesi.
Pustula aff. P. montpelierensis.
Pustula sp.
Composita sp.
Edmondia aff. E. ovata.
Nucula? sp.
Parallelodon? sp.
Aviculipecten, 2 sp.
Pseudomonotis aff. P. hawni.
Pseudomonotis sp.
Myalina aff. M. swallowi.
Astartella aff. A. concentrica.
Myoconcha? n. sp.
Pleurophorus aff. P. occidentalis.
Pleurophorella? sp.
Euphemus? sp.
Nautilus sp.

Lot 4381. Junction of Silver Falls and Green River roads, about 3 miles south of Ohio Oil Co.'s well, Garfield County, Utah. From calcareous sandstone, bed 2 of measured section at this point:

Pleurophorus? n. sp.

Lot 4382. About 3 miles south of Oh o test well and about 1 mile east of junction of Silver Falls and Green River roads, center of Circle Cliffs swell, Garfield County, Utah. From upper part of Kaibab limestone, bed 3 of measured section:

Septopora? sp.
Chonetes hillanus?
Pustula aff. P. montpelierensis.
Pustula sp.
Composita sp.
Edmondia aff. E. gibbosa.
Pernipecten? sp.
Lima n. sp.
Myalina sp.
Myoconcha? n. sp.
Astartella? n. sp.
Pleurophorus aff. P. occidentalis.
Pleurophorus? sp.
Plagioglypta canna?
Pleurotomaria sp.
Aclisina sp.

Lot 4382. One mile east of junction of Green River and Silver Falls Canyon roads, 3 miles south of Ohio Oil Co.'s well, Garfield County, Utah. Kaibab limestone, from horizon 50 feet below that of lot 4382:

Sponge undet.
Septopora sp.
Phyllopora sp.
Schizophoria n. sp.
Chonetes hillanus?
Pustula montpelierensis var.
Composita sp.
Parallelodon aff. P. politus.
Parallelodon aff. P. sangamonensis.
Acanthopecten coloradoensis.
Pernipecten n. sp.
Deltopecten aff. D. occidentalis.
Aviculipecten indet. (several sp.).
Pseudomonotis indet. (several sp.?).
Myalina aff. M. swallowi.
Schizodus n. sp.
Schizodus sp.
Schizodus?, 3 sp.
Astartella aff. A. concentrica.
Astartella aff. A. varica.
Myoconcha? n. sp.
Myoconcha? n. sp. var.
Pleurophorus aff. P. occidentalis.
Pleurophorus sp.
Pleurophorus? sp.
Bucanopsis aff. B. modesta.
Euphemus sp.
Pleurotomaria indet. (several sp.).
Orthoceras?
Goniatites?
Griffithides sp.

Lot 4381–a. At west side of junction of Green River and Silver Falls Canyon roads, about 3 miles south of Ohio Oil Co.'s well, Garfield County, Utah. From upper part of calcareous sandstone, bed 2 of section:

Solenomya? sp.	Schizodus? sp.
Nucula sp.	Pleurophorus? n. sp.
Parallelodon? sp.	Bellerophon sp.
Myalina aff. M. permiana?	Pleurotomaria sp.

Lot 4381. Bluff on west side of creek, at junction of Green River and Silver Falls Canyon roads, 3 miles south of Ohio Oil Co.'s test well, Garfield County, Utah. From lower part of Kaibab limestone:

Sponge indet.	Cliothyridina? sp.
Fenestella sp.	Deltopecten aff. D. occidentalis.
Septopora? sp.	Aviculipecten indet. (several sp.).
Chonetés hillanus?	Pseudomonotis? sp.
Pustula aff. P. montpelierensis.	Pleurophorus? n. sp.
Girtyella? n. sp.	Griffithides? sp.
Spiriferina sp.	
Squamularia? sp.	

The faunas represented by the collections have been described only in small part and contain many new species and some new genera. Furthermore, the preservation of all this material is unfavorable for close identification. Both these circumstances have contributed to make it necessary to leave many forms with only generic references or with the species only approximately identified. In spite of this fact, the faunal relations stand forth with considerable clearness and corroborate the correlations suggested on the field labels. All the lots are Permian and show more or less close faunal affinities to the Kaibab limestone.

CLASSIFICATION AND CORRELATION

Although the lithologic character and stratigraphic position ally the beds beneath the Moenkopi in the Circle Cliffs with the Kaibab limestone and although the contained fossils indicate clearly the Permian age of these rocks and substantiate the correlation with the Kaibab, there remain several uncertainties concerning their classification.

In the Grand Canyon the stratigraphic divisions of the Permian are clearly defined and persist, with few changes throughout a very large area. Noble's section at the Bass trail, which may be taken to represent the average conditions, shows 562 feet of Kaibab limestone, subdivided into three zones—(1) cliff-forming, fossiliferous, and somewhat cherty gray crystalline limestone, 292 feet thick, at the top; (2) an irregularly bedded buff and reddish friable sandstone 136 feet thick, tending to form slopes, in the middle; and (3) sandstone and limestone, grading upward into massive siliceous limestone, 134 feet thick, at the base. The average thickness of the Kaibab in the Grand Canyon district is a little less than 600 feet. An abundant marine Permian fauna is found in the limestone; a distinctive assemblage of fossils occurs in the so-called "*Bellerophon* beds" at the summit of the formation; and what may be termed the normal Kaibab fauna, represented by lists given by Girty,[14] in lower beds.

At the Bass trail the Coconino sandstone, next below the Kaibab, is 330 feet thick. It is a buff, uniformly fine-grained sandstone, characterized by cross-bedding on a huge scale, and presents the appearance of a single bed. It forms the strongest, highest cliffs in the upper part of the canyon wall. The quartz sand grains of the formation are bound together by siliceous cement, and the rock does not effervesce with acid. In the lower part of the Coconino are abundant tracks of small reptiles and amphibians.[15] Southeastward, toward the mouth of the Little Colorado River, the thickness of the Coconino increases, but northeastward, in the Marble Gorge, it diminishes progressively. In the upper part of the Marble Gorge the Kaibab and Coconino retain their characteristic features, but the thickness of the Coconino is less than 100 feet. (See pl. 6, *A*.) These formations are analyzed in the following section:

Section of the wall of Marble Gorge opposite the mouth of Badger Creek, 7½ miles below Paria River

[Measured by Raymond C. Moore]

Permian:		
Kaibab limestone—		Feet
11. Limestone, gray, weathering light buff, with interbedded shaly limestone, cherty; some of the beds massive, 2 or 3 feet thick, forming weak benches; this division characteristically forms broken slopes		100
10. Limestone, gray, weathering brown; very massive and hard, beds 3 to 10 feet thick, stratification even; forms sheer cliffs; beds break in angular joint faces		226
9. Limestone, gray to buff; medium to massive beds form benches that alternate with thin-bedded soft shaly to sandy beds, and the whole forms a steep slope; this weaker zone forms a persistent break between the sheer cliffs above and below in the canyon walls		108
8. Limestone, gray to buff, and sandstone; this division commonly forms a steep cliff that is continuous with the underlying sandstone cliff; made up as follows:	Feet	
Limestone, gray to buff, thin	5	
Limestone, buff, a hard massive layer; forms sheer cliff	7	
Limestone, buff, softer than adjacent beds	6	
Sandstone, brown, cross-bedded, hard, a single massive ledge	5	
Sandstone, reddish, soft, shaly; makes recess in cliff or in places a slope	2	

[14] Girty, G. H., in Darton, N. H., A reconnaissance of parts of northern New Mexico and Arizona: U. S. Geol. Survey Bull. 435, 1910, and elsewhere.

[15] Gilmore, C. W., Fossil footprints from the Grand Canyon: Smithsonian Misc. Coll., vol. 77, No. 9, 1926.

	Feet	Feet
Permian—Continued.		
Kaibab limestone—Continued.		
8. Limestone, gray to buff, and sandstone—Continued.		
Sandstone, reddish brown, moderately hard; forms rounded slope or weak cliff	7	
Sandstone, brown, calcareous, soft and rather shaly, forms slight slope	1½	
Limestone, bluish gray; weathers buff; hard; forms projecting ledge	2	
Sandstone, reddish brown, soft, calcareous, crumbles to loose sand	1	
Limestone, light yellow to cream, very soft, thin bedded, shaly, impure; contains small spots and nodules of manganese dioxide	3½	
Limestone, bluish drab, dark, hard; breaks with a ringing sound; very fine grained and earthy in appearance; weathers in single massive ledges with surface finely pitted	1½	
		41½
Total Kaibab limestone		481
Coconino sandstone—		
7. Sandstone, reddish brown, generally hard but locally soft; crumbles in the hand; the lower 2 feet a massive layer, irregularly bedded; the next 3 feet evenly laminated horizontally; the upper 10 feet irregularly bedded, rather massive; weathers in rounded surfaces, nodules at top		15
6. Sandstone, yellowish brown, hard, thin bedded, each stratum cross-bedded; weathers in platy fragments, stained black on surface		6
5. Sandstone, light red, soft, somewhat irregularly stratified; the layers cut across inclined laminae of subjacent bed		15
4. Sandstone, light yellow, a single hard massive ledge, cross-bedded; breaks in large blocks, prominently stained with desert varnish		5
3. Sandstone, yellowish, highly cross-bedded; weathers in slabs that break oblique to the bedding; massive		18
2. Sandstone, very light yellow, sugary, prominently cross-bedded, the inclined laminae dipping southwest; siliceous cement; very massive		34
Total Coconino sandstone		93
Hermit shale—		
1. Sandstone, chocolate-brown to reddish brown, fine-grained, dense; some beds moderately hard and form weak cliffs; mostly rather soft, interbedded with sandy shale of similar color; the sandstones are characterized by concretionary structure; exposed		296

At places in the Marble Gorge the Coconino sandstone is apparently divided into two subequal ledges. In its stratigraphic position, its very massive noncalcareous character, the large scale of its southward-dipping cross-bedding, and its light color, this sandstone seems clearly to belong to the Coconino formation, as represented in the Grand Canyon. However, the line of division between the Coconino and the Kaibab is not prominent, partly because distinctions in color and weathering are less marked in this area than in the Grand Canyon district. In the generalized section at Lees Ferry reported by Bryan [16] the total thickness assigned to the Kaibab and Coconino agrees approximately with the measurements in the Marble Gorge, but, as given by Bryan, the thickness of the Kaibab appears too small and that of the Coconino correspondingly too large, unless much limestone of typical Kaibab lithology is included in the Coconino.

The Permian section at the upper end of the Marble Gorge differs little from the sections in the Grand Canyon except in the lesser thickness of the Coconino sandstone and the greater thickness of the underlying Hermit shale, which measures 531 feet at a point 3 miles below Badger Creek. Even the softer zone in the middle part of the Kaibab and the sandy beds correspond to features observed many miles to the south. The Permian beds of the Grand Canyon persist with surprisingly slight change for a distance northeastward of at least 65 miles from the Bass trail, but in Kaibab Gulch, about 30 miles northwest of the upper Marble Gorge, the Coconino sandstone is absent; and there typical Kaibab, 717 feet in thickness, rests directly on Hermit shale. Seemingly the northward-diminishing Coconino sandstone disappears before it reaches the north end of the Kaibab Plateau. Conceivably, however, the sandy beds in the lower part of the Kaibab at this place are equivalent to a portion of the sandstone called Coconino in Utah.

The top of the Kaibab dips beneath the surface 10 miles north of Kaibab Gulch, but where it reappears in the Circle Cliffs its lithologic features resemble those of the typical Kaibab in Arizona. However, the formation as a whole appears sandier, and the amount of fairly pure limestone is much less. The deep boring of the Ohio Oil Co. in the central part of the Circle Cliffs begins in the Kaibab and shows that the very calcareous sandstone, which is stratigraphically the lowest rock exposed, continues beneath the surface for several hundred feet (p. 157). Cuttings from the upper part of the well reveal no essential differences from the adjacent surface rocks, and there is every reason to conclude that these unexposed strata are a continuation of the Carboniferous capped by the Kaibab beds in the Circle Cliffs.

[16] Bryan, Kirk, in Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah: U. S. Geol. Survey Prof. Paper 132, pl. 1, section 3, 1925.

Is the decrease in thickness of the limestone in the Circle Cliffs due to erosion preceding Moenkopi deposition, which removed the upper part of the beds once laid down in the Circle Cliffs region? That some part of the northward and eastward thinning in the Circle Cliffs is due to pre-Triassic erosion is suggested by the absence of the so-called *Bellerophon* fauna, which indicates that the youngest part of the Kaibab preserved here is older than the top of the formation in the Grand Canyon country. At the San Rafael Swell, where the Kaibab limestone ranges in thickness from 85 feet down to a mere film, Gilluly and Reeside[17] found a widespread erosional unconformity below the Moenkopi formation and reached the conclusion that " some of the Kaibab limestone has been removed and that in some part the eastward thinning of the Kaibab is due to pre-Triassic erosion."

Sandstone that is evidently equivalent to that below the Kaibab in the Circle Cliffs is found in the Cataract Canyon, along the San Juan River, in the Henry Mountains, and elsewhere in eastern and southern Utah. This is the "Aubrey" sandstone of earlier writers, and has been called Coconino sandstone in recent reports.[18] Does this sandstone really correspond to the type Coconino sandstone? The complete gradation between the fossiliferous limestone of typical Kaibab aspect and the underlying sandstone, which is likewise fossiliferous, seems to indicate that they are only slightly different parts of a single widespread deposit. Limestone occurs in and underlies the sandstone, as shown by surface exposures and by well records. The occurrence of marine shells in the sandstone of the Circle Cliffs and its calcareous character contrast with the vertebrate footprints and siliceous character of the typical Coconino and, together with stratigraphic evidence, suggest that the formations are not exactly equivalent. This conclusion is supported by the observations of Gregory and Noble[19] that typical Coconino thins northward to the vanishing point in Kanab Canyon, is 25 feet thick at Ryan, on the west side of the Kaibab Plateau, and is entirely lacking in Kaibab Gulch—observations which led to the suggestion " that sandstone assigned to the Coconino in the northeastern, eastern, and southeastern parts of the plateau province may form part of the Kaibab." Differences in lithologic peculiarities supply additional evidence.

It seems probable that the lesser thickness of the limestone in the Circle Cliffs and the San Rafael Swell, as compared with areas to the southwest, its alternation with limy sandstone, and the considerable increase in thickness of the calcareous sandy beds represent a gradual but marked change in the lithologic character of Kaibab sedimentation indicative of approach toward an old land mass. Studies of the Carboniferous and early Mesozoic rocks in areas east and north of the Colorado River indicate that there was persistent or recurrent elevation in a region bordering southern Utah. Red clay and sand, coarse conglomerate, and gritty arkose (Molas, Hermosa, and Cutler formations), which are certainly in part of subaerial origin, indicate land conditions, and so do notable unconformities that do not persist southwestward. In passing from northern Arizona to southern and southeastern Utah the Carboniferous beds below the Kaibab change so greatly in character that equivalents of the formations of the Grand Canyon can not be certainly identified. It is perhaps not possible to determine definitely whether the sandstone termed " Coconino " in southeastern Utah is actually equivalent to the Coconino of the Grand Canyon or whether, as is true in part, it is a facies of Kaibab deposition. By definition the name Kaibab is here applied to the limestone facies of these widespread Permian deposits, and the name Coconino is employed for the partly subjacent and partly intergrading and intertonguing sandstone facies that occurs in eastern and southern Utah. This usage is followed in the designation of the Permian strata of the Circle Cliffs. However, the thinning of the type Coconino toward the north, the more or less pronounced differences in lithologic character of the type Coconino and the Utah Coconino, and stratigraphic uncertainties of different sorts suggest that extension of the name Coconino to Utah is of doubtful propriety.

KAIBAB-MOENKOPI EROSION INTERVAL

At none of the exposures in the Circle Cliffs where the contact between the Kaibab limestone and the Moenkopi formation was examined is there any marked discordance in bedding or any very noticeable irregularity of the upper surface of the Kaibab. However, an unconformity at the top of the Permian is indicated by a marked variation in thickness of the hard yellowish-brown noncherty member that caps the Kaibab in the northern part of the Circle Cliffs and the gradual disappearance of that member to the east and south. The maximum observed thickness of this ledge-forming member is 37 feet, as measured a short distance west of The Peaks. In the southern and eastern part of the Circle Cliffs the Moenkopi rests directly on the very cherty zone that underlies the massive hard limestone just mentioned, and in places not much of the cherty member remains. Where the upper part of the Kaibab appears to have been removed by erosion, the lower limy sandstones occur proportionally nearer the top of the formation.

[17] Gilluly, James, and Reeside, J. B., jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 64, 1928.

[18] Longwell, C. R., and others, op. cit., p. 8. Miser, H. D., op. cit., p. 35.

[19] Gregory, H. E., and Noble, L. F., op. cit., pp. 236–237, 1923.

Where the uppermost Kaibab is missing a light-colored sandstone of uneven thickness commonly occurs at the base of the Moenkopi.

That the Moenkopi formation rests unconformably on the Kaibab or its equivalent has been generally recognized by students of the Colorado Plateau stratigraphy. The extent and significance of this erosion interval has been discussed by Dake[20] and more recently by Longwell[21] and others.[22] The described exposures indicate an extent of the pre-Moenkopi erosion surface of more than 80,000 square miles. At most places the relief of the eroded Kaibab is small; it was channeled but not deeply incised, and the lowest Moenkopi beds maintain the dip and strike of the highest strata of the Kaibab. At Spring Mountain, Nev., however, the entire thickness of the Kaibab and part of the Supai was cut through, and in the Moab region the Moenkopi rests with sharp discordance on the Cutler. For the plateau province as a whole the evidence suggests a fairly uniform emergence, followed by a general widespread submergence with little change in the attitude of the Kaibab beds. As pointed out by Gilluly and Reeside,[23] "if it is true, as has been suggested, that the Coconino and Kaibab grade laterally one into the other, the unconformity is not necessarily of much importance structurally over the plateau province as a whole—that is, it does not indicate a period of orogenic activity."

TRIASSIC FORMATIONS

HISTORICAL SKETCH

Although the great Triassic formations of the plateau province are boldly outlined by color and manner of erosion, the precise limits and age of the formations are difficult to establish. Most of the many unconformities are local; the strata, especially the thinner sandstones, limestones, and shales, change in character within short distances along the strike, and fossils are extremely scarce. Naturally, therefore, the published descriptions and classifications of the Triassic sediments of southern Utah are very dissimilar.

Howell,[24] in the section of the Mesozoic that he measured in the Paria Valley, assigned to the Triassic 2,250 feet of strata. In them he included all or part of the Wingate and Navajo, the Chinle, the Shinarump conglomerate, and the Moenkopi, as these formations are now defined. Dutton[25] applied the term "Shinarump shales" to the group of strata now recognized as Moenkopi, Shinarump, and Chinle formations (in part). He has much to say regarding their constant character, their color, and their erosion features and adds:

> With the exception of the dark iron-gray shales of the Cretaceous, the tones of other formations are usually bright, lively, and often extremely delicate. In the Shinarump they are mostly strong, deep, and so rich as to become cloying. Maroon, slate, chocolate, purple, and especially a dark brownish red (nitrous acid color) are the prevailing hues. * * * The age of the Shinarump is either Permian or Lower Triassic, identity with the lower red beds of Colorado and Wyoming is unquestionable, [and] the formation therefore covers an area probably exceeding 250,000 square miles.

The top of the Shinarump was not determined by Dutton,

> owing to the gradual transition into the Vermilion Cliff series above. * * * Within these (Shinarump) shales there often occurs a singular conglomerate. It consists of fragments of silicified wood embedded by a matrix of sand and gravel. Sometimes trunks of trees of considerable size, thoroughly silicified, are found.

In the Henry Mountain region Gilbert[26] placed the "Shinarump group" at the base of the "Jura-Trias" and subdivided it into

> (*a*) Variegated clay shale, purple and white above and chocolate below, and silicified wood, 300 feet; (*b*) gray conglomerate with silicified wood, the "Shinarump conglomerate," 30 feet; (*c*) chocolate-colored shale, in part sandy, 400 feet.

In these descriptions the Chinle formation, the Shinarump conglomerate, and the Moenkopi formation are recognizable. All the geologists of the Powell and Wheeler surveys recognized this threefold division of the so-called "Shinarump group" and tentatively assigned it to the Triassic, basing their conclusions on the Triassic age of saurian bones and fossil plants from the Shinarump conglomerate, determined by Cope and Newberry. To these workers the Shinarump conglomerate was merely a marker in the midst of a great thickness of shale resting on a widespread platform of Carboniferous limestone. No doubt has been cast on the Triassic age of the "upper Shinarump" (Chinle), but the early prevailing opinion that the "lower Shinarump" (Moenkopi) is also Triassic was abandoned after Walcott had described Permian fossils from shale underlying the Shinarump conglomerate. This discovery led to the conclusion that the Shinarump conglomerate marked the division between the Triassic and the Permian. However, fuller knowledge of the relation of the Moenkopi to

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

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

[22] Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., jr., Notes on the stratigraphy of the Moab region Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, p. 796, 1927.

[23] Gilluly, James, and Reeside, J. B., jr., op. cit., p. 65.

[24] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 270–272, 1875.

[25] Dutton, C. E., Report on the geology of the High Plateaus of Utah, pp. 144–147, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[26] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 6, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

the Shinarump above and the Kaibab below and a reconsideration by Girty of the evidence derived from fossils cast doubt on the accepted correlation. As subdivided by Gregory [27] the Triassic included the Chinle formation and the Shinarump conglomerate, and the Moenkopi was classed as doubtful Permian. Later studies by Girty, however, proved the equivalence of the Moenkopi of southern Utah and known lower Triassic beds of Idaho.

The Triassic, then, as now defined, embraces three subdivisions—the Moenkopi formation, the Shinarump conglomerate, and the Chinle formation. The beds assigned to the Moenkopi contain fossils of Lower Triassic age; the Chinle formation and probably also the Shinarump conglomerate are Upper Triassic.

MOENKOPI FORMATION

AREAL DISTRIBUTION AND THICKNESS

In the Kaiparowits region the Moenkopi formation is exposed at Lees Ferry; at Sand Wash, near the abandoned settlement of Paria; in the House Rock Valley; and at the Circle Cliffs and in adjoining areas on the west flank of the Waterpocket Fold. At Lees Ferry, where erosion of the folded strata in the Echo monocline brings all the Triassic formations into view, the Moenkopi rests on an uneven surface of the Kaibab limestone and is capped by Shinarump conglomerate, which forms a sharply outlined basal step that may be traced for miles southward along the Echo Cliffs and southwestward along the base of the Paria Plateau. (See pl. 8, *A*.) At Sand Wash, the northern terminus of the Kaibab Plateau, the Moenkopi forms the base of the Vermilion Cliffs and is well exposed along the Paria-Kanab road. Southward it extends up the House Rock Valley as a much eroded and faulted series of beds that coat the flanks of the eastward-dipping Kaibab monocline. (See pl. 4, *A*.) Westward it may be continuously traced to points beyond the Virgin River. In the Circle Cliffs depression erosion of the overlying formations has exposed Moenkopi beds as an almost continuous floor in an oval area about 30 miles long and 10 miles wide. From this area extensions of the Moenkopi reach outward radially along the stream valleys that cut through the encircling Jurassic cliffs. (See fig. 9.)

The thickness of the Moenkopi differs widely in different places. At Lees Ferry it is about 500 feet, and sections measured at near-by localities include 390 and 420 feet of strata. At Kaibab Gulch and Sand Wash nearly complete sections measured, respectively, 490 and 540 feet. In the Circle Cliffs region the average thickness of the Moenkopi is 475 feet, the maximum being slightly more than 500 feet and the minimum 304 feet—a variation ascribed mainly to erosional unconformities at the top and bottom of the formation. Beyond the borders of the Kaiparowits region the variation is greater. The type section in the Little Colorado Valley measures 389 feet, but Miser [28] found 920 feet on the San Juan River, and as shown by Reeside and Bassler [29] the thickness of the Moenkopi increases westward, reaching its maximum in the Virgin River Valley, where two sections include 1,775 and 2,035 feet of strata. At least locally in the Moab region the Moenkopi is cut out entirely by the unconformity at the base of the Chinle.[30]

LITHOLOGIC FEATURES

The Moenkopi formation at Lees Ferry consists of beds that differ little in composition, structure, and arrangement from those in the Navajo country, to the south and east. The predominant lithologic features are thin brown sandy gypsiferous shale and red and brown sandstone with white bands near the top. (See p. 48.) At Sand Wash likewise reddish-brown shale and brown sandstone make up most of the section, but the lowermost 400 feet is banded with zones and individual beds of alternating red and green shale which give to the outcrops a strikingly beautiful appearance. This assemblage of beds resembles the Moenkopi of the Kanab and Virgin Valleys more closely than those of regions south and east of the Paria Valley.

In the Circle Cliffs the Moenkopi formation consists dominantly of interlaminated mudstone, sandy micaceous shale, and thin-bedded platy or shaly sandstone that splits readily along laminae, covering the weathered slopes with flaky sandstone chips. With the mudstone and thin sandstone occur lenses of massive fine to medium-grained sandstone, but grit and conglomerate, as well as true clay shale, are lacking.

As a whole the rocks of the Moenkopi formation are distinctly weak and tend to form slopes broken by weak benches, some of which are barely discernible. In some places harder and thicker sandstones that are massive locally and weather in large slabs or in thick angular blocks form pronounced but generally not very high cliffs. Beneath the protecting cap of hard Shinarump conglomerate the upper beds of the Moenkopi form a cliff that ranges from a few feet to more than 100 feet in height. Commonly this cliff is re-

[27] Gregory, H. E., Geology of the Navajo country, a reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Prof. Paper 93, pp. 30–31, 1917. See also Shimer, H. W., Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., vol. 30, pp. 493–496, 1919.

[28] Longwell, C. R., and others, op. cit., p. 17.

[29] Reeside, J. B., jr., and Bassler, Harvey, op. cit., p. 60.

[30] Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., jr., op. cit., p. 797.

cessed, the massive Shinarump projecting like a great cornice. (See pl. 8, *A*.) The brick-red color of the Moenkopi, in contrast to the light greenish gray of the Shinarump, and the etching out of fairly evenly spaced thin soft beds in the Moenkopi cliffs contribute to the striking resemblance of these cliffs to well-built brick houses. Limestone is not abundant, but on the south side of this area, near the very top of the formation, a few thin beds of very hard, dense, fine-grained unfossiliferous limestone are interbedded in the sandy shale, and one of these beds, a foot thick, which is light bluish gray on fresh fracture and weathers a tannish brown, continues with very even thickness for nearly a mile. At another point near the top of the formation on the west side of the Circle Cliffs the sandy beds are distinctly calcareous. Gypsum is also rare. No interstratified beds of gypsum and little secondary vein gypsum were observed, but small fragments of selenite and mineralized water indicate the presence of more or less disseminated calcium sulphate. In exposures of the Moenkopi near Capitol Wash and northward toward Fruita, in Wayne County, only a short distance north of the Circle Cliffs, the Moenkopi is strongly gypsiferous. In a few places casts of salt crystals were observed in the shaly sandstone. The oil-bearing beds of the Circle Cliffs and the Waterpocket Fold belong to the Moenkopi formation. (See p. 154 and pl. 31.)

A characteristic feature of the thin-bedded strata is the abundance of ripple marks. In many places each platy layer is marked with asymmetric ripples that measure on the average about an inch from crest to crest, and some of the thicker sandstone shows a very fine cross-bedding that is due to migration of the ripples. Mud cracks, which generally affect only one or two thin layers, appear in some places.

The dominant color tone of the Moenkopi in the Circle Cliffs is a shade of brownish maroon or reddish chocolate-brown, but a considerable part of the formation is a very light creamy tan or buff. In parts of the red divisions there are thin ash-gray zones. These colors are arranged in definite bands and zones that follow the bedding and evidently represent original differences in the character of the deposit, the ferric pigments being completely oxidized in some parts of the formation, whereas in others there is much less iron and this not so well oxidized. The wide distribution and evenness of the banding are rather striking features of any general view of the Moenkopi landscape. (See pl. 7.)

STRATIGRAPHY

Sections of the Moenkopi were measured at Lees Ferry, Kaibab Gulch, Sand Wash, and the Circle Cliffs.

Section of Moenkopi formation on south side of Colorado River at Lees Ferry

[Measured by Herbert E. Gregory]

	Feet
Shinarump conglomerate.	
Unconformity.	
Moenkopi formation:	
5. Shale, arenaceous, and thin fine-grained sandstone, banded dark red, brown, and white, in alternating beds; calcareous and iron cement; some beds of shale thin as cardboard, their foliation surfaces ripple marked, some cracked and coated with grains of mica; includes three thin beds of sandy, flaky limestone; thin veins of gypsum cross nearly every square inch of vertical cliff face; estimated	220
4. Shale, uniformly chocolate-colored, very sandy, in part imbricated and unevenly bedded; many foliation surfaces are sun dried and show ripple marks and glistening flakes of muscovite; seams of gypsum cross the beds, intersecting at different angles; unequal resistance of the strata causes weathering to produce a slope that rises by short-spaced steps	160
3. Conglomerate, brown, composed of mud pellets and fragments of calcareous shale and of sandstone	½
2. Shale, yellow, ripple marked, friable; some layers separated by thin sheets of gypsum	8
1. Conglomerate, buff and brown, composed chiefly of pebbles and chips of limestone, with which are embedded both worn and angular chunks of chert as much as 4 inches in length; the upper part in places shows nests of poorly rounded pebbles of chert, quartz, and quartzite less than half an inch in diameter; lenses of gray, cross-bedded sandstone and of yellow shale are included; weathers with very rough surface	½–8
Total Moenkopi formation	390+
Unconformity.	
Kaibab limestone.	

The Moenkopi formation at Kaibab Gulch is not well displayed for study; parts of it are covered, other parts are dissected into badland mounds, and the steeply dipping strata are locally faulted and in places coated with débris from landslides. The incomplete section is here included for comparison with sections measured to the south at Lees Ferry and 8 miles to the north at Sandy Wash.

Section of Moenkopi formation at Kaibab Gulch, Utah

[Measured by Herbert E. Gregory]

	Feet
Shinarump conglomerate.	
Unconformity.	
Moenkopi formation:	
15. Shale, brown, lumpy, sandy, gypsiferous, with five beds 1 to 3 feet thick of brown friable sandstone	60

Moenkopi formation—Continued.	Feet
14. Sandstone, red, flaky, imbricated; contains mud lumps and salt pseudomorphs	2
13. Shale, light red, interstratified with buff and white resistant beds and lenses of cross-bedded sandstone; forms steep slope	56
12. Shale, brown and drab, sandy; very gypsiferous near base; weathers to badland knolls streaked with remarkably regular bands of brown, green, and gray	183
11. Covered, probably red shale	50
10. Limestone, buff, arenaceous, in places shaly; contains undeterminable shell fragments	2
9. Shale, chocolate-brown and red	16
8. Shale, red and green; white gypsum in regular, even beds	1
7. Shale, brown, with much gypsum in seams and disseminated grains	38
6. Sandstone, brown, in beds less than 7 feet thick, and sandy shale, unevenly bedded, lenticular; contains thin beds of gypsum	40
5. Shale, brown, in regular beds	4
4. Shale, brown, with sandstone lenses, gypsum and lime cement	33
3. Sandstone, dark brown, in beds 1 to 4 feet thick, alternating with sandy shale. All beds highly irregular and uneven; cross-bedded, lumpy; surfaces of overlapping laminae abundantly marked with mud cracks, ripple marks, worm trails, and flakes of mica; forms slab talus	23
2. Shales, dark brown, glistening with mica; bed is wavy; breaks into hard, sharp-shaped flakes	4
1. Conglomerate, composed of flattened pellets of gray-buff limestone, red shale, sandstone, and quartz, arranged as lenses in shale and as cross-bedded coarse calcareous sandstone coated with chunks of quartz	1–4
Total Moenkopi formation	514

Unconformity.
Kaibab limestone.

At Sand Wash the upturned beds that form the base of the Moenkopi have been beveled by erosion and partly buried in débris; some of them have been disturbed by landslides. In general the exposure resembles the Moenkopi outcrops in the Kanab Valley. The lowest beds are brown thin sandstone and ripple-marked and sun-dried shale. These beds are followed upward by 4 to 6 feet of yellow earthy limestone and about 500 feet of sandy, very gypsiferous, very thinly laminated shale, strikingly banded by zones of red and green. Above this banded shale lies about 75 feet of reddish shale, sandy and slighly gypsiferous, and about 20 feet of reddish-brown shale interbedded with massive sandstones 1 to 3 feet thick.

In the west part of the Circle Cliffs, in the eastern part adjacent to the Waterpocket Fold, and in the central part near The Peaks exposures of the Moenkopi include all the beds from the top to the base of the formation. The following sections are typical of the Circle Cliffs region as a whole:

Section of Shinarump conglomerate and upper part of Moenkopi formation on west side of Circle Cliffs between Horse Creek and The Peaks, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Shinarump conglomerate	46–60
Moenkopi formation:	
19. Shale, chocolate-brown, very sandy, grading into shaly sandstone, more calcareous above	7
18. Sandstone, chocolate-brown, thin bedded, ripple marked, and cross laminated	3
17. Shale, chocolate-brown, very sandy; grades into thin shaly sandstone, micaceous	5
16. Sandstone, chocolate-brown, hard, shaly to platy; forms slight projecting ledge	1
15. Shale, brown, sandy, grading to thin shaly sandstone; weathers as slope	8
14. Sandstone, chocolate-brown, hard, platy; forms a ledge	1
13. Shale, chocolate-brown, sandy; grades to shaly sandstone	22
12. Sandstone, chocolate-brown, thin bedded; locally weathers massive and forms a prominent projecting ledge, ripple marked and laminated; contains shaly zones	5
11. Shale, chocolate-brown, sandy, micaceous, with thin seams and beds of soft sandstone; in upper part contains thin beds of shaly sandstone	46½
10. Sandstone, light greenish gray, platy, fine grained, micaceous, with large asymmetric ripple marks; produces a slight bench	½
9. Shale, chocolate-brown, sandy; contains abundant thin beds of shaly sandstone that weathers in thin chips and platy slabs; forms gentle rounded slope in which micaceous material is abundant	27
8. Sandstone, brown, with thin light-gray bands, platy, with thin beds of shale between harder layers, very micaceous, ripple marked; top layer very hard and slabby	2½
7. Shale, chocolate-brown, sandy, with thin yellow and brown beds of sandstone that make slight benches	56
6. Sandstone, light yellow, stained red on outcrop, very massive, hard; forms projecting wall	50
5. Sandstone, light yellow, massive; weathers in thin plates; grades to shaly sandstone; forms bench	12
4. Shale, chocolate-brown, sandy, micaceous	40
3. Sandstone, light yellow, locally stained red on outcrop, massive; grades locally into shaly or thin-bedded sandstone; forms prominent bench	160
2. Sandstone, yellow, very shaly; grades to sandy shale	5
1. Sandstone, yellow, calcareous, micaceous, massive but thinly laminated, with ripple bedding, grades to shaly sandstone; exposed	4
(Top of Kaibab limestone 35 feet more or less below.)	
Total Moenkopi formation measured	456
	492

Practically all the beds in the foregoing section thicken or thin along the strike, and some of them disappear within relatively short distances. The color divisions are persistent and appear to follow definite bedding planes. The uppermost 185 feet is chocolate-brown, whereas, with the exception of about 40 feet, the lower 270 feet is light creamy yellow. Some of the massive sandstones included in the lower division are pinkish red.

Section measured just west of point where Muley Twist (Green River) road enters canyon through cliffs on east side of Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Triassic:	
Shinarump conglomerate—	
7. Sandstone, bluish gray, in places black from contained bitumens, massive, medium to coarse grained	20–40
Moenkopi formation—	
6. Shale, maroon to chocolate-brown, very sandy, and thin platy sandstone; weathers in slope	150
5. Sandstone, gray, weathering brown, in beds 2 to 6 inches thick, separated by 8 to 12 inches of sandy shale	9
4. Shale, yellow and gray, sandy; forms slope; about 23 feet above base a bed of hard shaly, very calcareous fine grained gray-brown sandstone appears	50
3. Shale, light yellow, very sandy; grades into shaly sandstone and soft sandstone; weathers massive, especially upper 15 to 20 feet, which weathers as a rim rock; the sandstones are saturated with oil and are in part stained black	90
2. Sandstone, pink and brown; grades to sandy shale; bedding very irregular, fine grained; parts of the division rather massive, parts in very thin beds, variable	118
1. Sandstone; upper part brown, hard, limy; lower part gray, soft, and somewhat shaly	8
Total Moenkopi formation	425
Permian:	
Kaibab limestone.	

In general character the Moenkopi shown in this section is not essentially different from that in exposures farther west, except that the upper part of the formation seems to be somewhat less resistant to erosion and uniformly makes slopes, and that the lower part includes massive sandstones, some of which are strongly petroliferous.

Section of Moenkopi formation measured in canyon north of The Peaks, northwest of Wagonbox Mesa, Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Triassic:	
Shinarump conglomerate	50–150
Unconformity.	
Moenkopi formation—	
10. Shale, maroon, sandy; contains many paper-thin sandstone layers; grades to yellow in upper 15 feet	50
Triassic—Continued.	
Moenkopi formation—Continued.	
9. Sandstone, yellow, fine grained, soft; weathers rather shaly	3
8. Shale, maroon, with thin shaly sandstone	39
7. Sandstone, buff, brown, and gray; fine grained, thin bedded, in layers to 4 inches thick	8
6. Shale, yellowish brown, sandy	26
5. Sandstone, pink to maroon, thin bedded, with a few massive layers as much as 16 inches in thickness at intervals; interbedded with shale, very sandy; upper part yellow-brown	48
4. Sandstone, gray and light pink, fine grained, hard; weathers brown and light gray, in beds 2 inches to 1 foot thick, but in fresh exposures beds appear very massive, upper part more reddish than lower; ordinarily well exposed	42
3. Sandstone, red, with thin sandy shale interbedded, medium to massive bedding	31
2. Sandstone, light brown and yellow to pink, very thin bedded, platy, abundant ripple marks; grades locally to shale; weathers reddish brown; forms slopes	36
1. Shale, pink to red, sandy; contains thin beds of platy sandstone; weathers in slopes	21
Total Moekopi formation	304
Permian:	
Kaibab limestone.	

The diminished thickness of the Moenkopi in the region of The Peaks appears to be due to a decrease in thickness of the upper chocolate-colored zone. This decrease is accompanied by a corresponding increase in the thickness of the massive Shinarump conglomerate, to which the preservation of the outliers of the Shinarump called The Peaks is partly due.

AGE AND CORRELATION

In the absence of satisfactory faunal evidence the age of the Moenkopi formation in the Kaibab region can not be directly determined. Correlation with the type Moenkopi of the Little Colorado Valley, Ariz., is based on lithologic character and stratigraphic position. The formation lies between unmistakable Kaibab limestone and Shinarump conglomerate, from which it is separated by evident unconformities. There is no doubt that the Moenkopi of Lees Ferry, Kaibab Gulch, Sand Wash, and the Circle Cliffs is part of a widely extended formation that lies at the base of the Triassic.

In the older geologic literature of the plateau province a series of chocolate-colored shales was recognized as the lower division of the "Shinarump group," which was assigned to the Triassic. To equivalent strata in the Painted Desert Ward[31] applied the

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

term Moenkopi formation and described its constituent members in these general terms: "It is very probable that the lower portion of the Moenkopi beds belongs to the Permian." To permit comparison based on measured sections the Moenkopi was redefined by Gregory,[32] and its features as shown in the Little Colorado Valley, the San Juan Valley, and the Defiance Plateau were described in some detail. The Moenkopi of southwestern Utah is discussed by Reeside and Bassler,[33] who found that west of the Kaibab Plateau the Moenkopi attains a thickness much greater than at the type locality and is divisible into five persistent members, together with a discontinuous unit at the base of the formation, as follows:

Section of the Moenkopi formation west of the Kaibab Plateau

[From Reeside and Bassler]

		Feet
6.	Upper red beds; brick-red, deep red, and brown shale and sandstone; locally massive beds of yellow medium-grained sandstone	475±
5.	Shnabkaib shale member; gray to white sandy shale and soft sandstone with some pink layers and much gypsum	360–630
4.	Middle red beds similar to No. 2.	
3.	Virgin limestone member; earthy yellow limestone separated by yellow and red calcareous shale	11–160
2.	Lower red beds, red to brown gypsiferous shale	360±
	Sandstone	0–288
1.	Rock Canyon conglomerate member (absent at some localities); an assemblage of shale, limestone, gypsum, conglomerate of limestone and chert boulders, and a minor amount of sandstone.	

In the Virgin River Valley the Rock Canyon conglomerate and the Virgin limestone member are characterized by a marine fauna of Lower Triassic age. As measured by Lee,[34] shale and fossiliferous limestone equivalent to the Virgin member attain a thickness of 350 feet near Cedar City, and Longwell[35] described the lower half of 1,200 to 1,600 feet of Moenkopi in the Muddy Mountains as marine limestone. In the Spring Mountains of Nevada the marine portion of the Moenkopi is about 600 feet thick.

Of the subdivisions established by Reeside and Bassler the Rock Canyon conglomerate appears to be represented by the assemblage of miscellaneous materials that is immediately associated with the Kaibab-Moenkopi unconformity at most localities in Utah, Arizona, and Nevada. A basal conglomerate, composed largely of chert fragments derived from the Kaibab, marks the base of the Moenkopi at Lees Ferry. An attenuated representative of the Virgin limestone member which is included in a section measured at Sand Wash and a thin unfossiliferous limestone at Lees Ferry may be equivalents. The Shnabkaib member has been traced from the Kanab Valley to the Paria River. (See pl. 7, *A*.) East of the Paria and south of Glen Canyon detailed correlation with the beds characteristic of the Moenkopi of the Virgin River Valley is difficult; members that are prominent in that valley are absent or at least inconspicuous in this area. It is probable that the Moenkopi of the Kaiparowits region represents only a part of that preserved in areas farther west. Likewise detailed correlation of subdivisions in the Moenkopi at Lees Ferry, Sand Wash, and the Circle Cliffs with beds of equivalent age east of Glen Canyon can not be made with assurance.

In sections measured by Longwell and Paige along the Colorado River below Cataract Canyon the Moenkopi formation, which has a maximum thickness of 830 feet, includes three distinct subdivisions. The lower division, about 400 feet thick, consists of regularly bedded red and maroon sandstone and sandy shale with a layer of gray conglomerate at the base. The middle division is a coarse gray cross-bedded sandstone a few inches to 60 feet thick.

The upper division, which is limited at the top by an erosional unconformity, comprises 350 to 400 feet of chocolate-colored, red, and gray sandstone. Recent investigations of Reeside[36] and others indicate the probability that only this upper division is Moenkopi and that the underlying red shale and sandstone belong in the Permian. The Crescent Creek section includes a "few bands of dense gray limestone" 100 feet from the top, and calcareous shale is recorded at Trachyte Creek and Twomile Canyon. East of the Colorado River the massive cross-bedded sandstone exposed in the walls of upper Glen Canyon continues as a characteristic feature of the Moenkopi and gives to the formation an appearance quite unlike that in the Little Colorado, Paria, Kaibab, and Virgin Valleys.

The determination of the Virgin limestone member as of Lower Triassic age, corresponding to the *Meekoceras* zone of southeastern Idaho, and the correlation by Gilluly and Reeside[37] of the Moenkopi of the San Rafael Swell with the Woodside, Thaynes, and Ankareh formations of the Uinta Mountains—all recognized as Lower Triassic—make it reasonable to assume that all the beds mapped in the Kaiparowits region as Moenkopi are of that age. The beds that conformably underlie this fossiliferous zone appear to belong clearly to the same time interval, and they are separated by a well-marked unconformity from the under-

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

[33] Reeside, J. B., jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 59–62, 1922.

[34] Lee, W. T., The Iron County coal field, Utah: U. S. Geol. Survey Bull. 316, p. 362, 1907.

[35] Longwell, C. R., Geology of the Muddy Mountains, Nev.: Am. Jour. Sci., 5th ser., vol. 1, p. 48, 1921; U. S. Geol. Survey Bull. 798, pp. 43–52, 1928.

[36] Personal communication.

[37] Gilluly, James, and Reeside, J. B., jr., op. cit., p. 66.

lying Permian Kaibab limestone. In the Kaiparowits region, where the evenly bedded Moenkopi does not contain marine fossils but where very similar lithologic and stratigraphic relations are found, it seems very probable that these rocks correspond in age and should be referred accordingly to the Lower Triassic.

Near Fruita, Wayne County, Utah, fossils were collected from sandy limestone beds in the Moenkopi. These fossils were identified by G. H. Girty as follows:

Myalina n. sp.	Myalina sp.
Pseudomonotis? n. sp.	Bakewellia? sp.
Astartella? sp.	Pleurotomaria? sp.
Holopea? sp.	Naticopsis? sp.
Ostracoda?	

The lower portion at least of the Moenkopi exhibits a regularity of bedding and uniformity of texture that strongly suggest deposition in a large body of water. A withdrawal of the sea, accompanied by more or less erosion and the occurrence of more or less widespread continental deposition, is indicated by the hiatus in the Moenkopi and the character of the upper beds of the formation in different parts of southeastern Utah and the Navajo country. After Moenkopi time there was widespread erosion, which partly beveled the soft Moenkopi strata and in places carved distinct erosion channels in them. The subsequently deposited Shinarump constitutes a very widespread thin veneer, which covers this erosion surface and fills its depressions. It appears that in the Circle Cliffs the erosion preceding the Shinarump epoch cut deeply into the Moenkopi, removing all of the upper continental beds laid down here.

MOENKOPI-SHINARUMP EROSION INTERVAL

After the deposition of the Moenkopi red beds there was an interval of erosion that affected a very large part of the plateau country, as is indicated by the widespread evidence of removal of parts of the Moenkopi beds, the beveling of these beds, the carving of erosion channels, and the very marked change in the nature of the sedimentation that preceded and followed the erosion.

In several parts of the Circle Cliffs the study of the contact between the Moenkopi and Shinarump shows that the dip of the Moenkopi rocks is slightly different from that of the Shinarump. The conglomerate and coarse grit of the Shinarump extend more or less evenly across the slightly upturned and smoothly beveled lower strata. An erosional unconformity is easily demonstrated. In very many places erosion channels 50 to 100 yards in width and 20 to 100 feet in depth, carved in the Moenkopi beds, are filled with the massive grit of the Shinarump, and the abrupt change in the character of material along uneven surfaces is everywhere characteristic. The Shinarump may be considered a "basal conglomerate" for the overlying series of shale, sandstone, and limestone, which constitute the Chinle formation.

SHINARUMP CONGLOMERATE

The conglomerate that was originally described by Powell[38] as the middle member of his "Shinarump group" (Triassic) has been noted by nearly all workers in the plateau province. A special study of this unusual formation was made by Gregory.[39] In New Mexico, Arizona, Utah, and Nevada the exposures of the Shinarump conglomerate are remarkably alike; the beds exhibit the same range of thickness, texture, and composition, and at nearly all places form resistant benches between series of friable shales. The westernmost outcrop of the Shinarump is in the Spring Mountains, Nev.[40] From this area it may be traced eastward through the Muddy Mountains, along the Vermilion Cliffs, across the Waterpocket Fold and Glen Canyon to eastern Utah, where it forms the plateau summit of Elk Ridge. In the Kaiparowits region the Shinarump conglomerate is represented in sections measured at Lees Ferry, at places near Paria, and at the Circle Cliffs. (See pp. 49, 50.) At Lees Ferry the Shinarump consists of 45 feet of much cross-bedded, very lenticular gray conglomerate, and includes lenses of sandstone of different textures. The pebbles of quartz and quartzite, as much as 2 inches in diameter, are in contact with one another and also arranged as chains of pebbles embedded in sandstone. Fossil wood is abundant; three logs more than 50 feet in length, one of them 2½ feet in diameter, appear near the top of the formation. At Sand Wash and Kaibab Gulch, where the Shinarump conglomerate is 30 to 80 feet thick, large pebbles are rare and the formation consists essentially of coarse white, cross-bedded conglomerate and gnarly lenticular sandstone, together with much fossil wood. At the Circle Cliffs the Shinarump is present as gray, irregularly cross-bedded, massive sandstone, without prominent conglomerate lenses or abundant petrified wood, and it differs much from place to place in thickness, texture, bedding, composition, and color. West of the South Fork of Silver Falls Creek the rock is grayish-brown, irregularly bedded massive sandstone which shows thin cross lamination and contains bluish sandy shale in its middle part. Near The Peaks the body of the rock is fine-grained massive sandstone that contains beds and lenses of conglomerate. Most exposures of the Shinarump in the Circle Cliffs area include a lower soft, massive sandstone bed, a middle group of greenish-

[38] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains, pp. 53, 68–69, U. S. Geol. and Geog. Survey Terr., 2d div., 1876.

[39] Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, pp. 424–438, 1913; Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 37–41, 1917.

[40] Gregory, H. E., and Noble, L. F., op. cit.

gray shale, and an upper massive cross-bedded sandstone that forms a resistant ledge. "Desert varnish" is common. In addition to fossil wood some foliation surfaces display impressions of ferns. Within distances of less than a mile at the head of Halls Creek and along Capitol Reef Wash the Shinarump ranges in thickness from less than 30 feet to more than 100 feet and in texture grades from medium-grained to coarse sandstone. Locally near Paria and south of Fruita, in Wayne County, the Shinarump is wanting. In general the texture of the Shinarump along the Waterpocket Fold and northward is finer grained than at localities in northern Arizona. Pebbles that exceed 1 inch in diameter are rare. The same condition prevails in exposures about the Henry Mountains.

Section of Shinarump conglomerate northeast of Wagonbox Mesa in the Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Chinle formation:	
9. Brown, blue, and purple sandy shale; forms slope.	
Shinarump conglomerate:	
8. Brown massive hard ripple-marked cross-bedded sandstone; weathers dark brown in large angular blocks; disintegrates gradually along thin irregular cross laminae; contains cycad leaves, of which a collection was obtained	4½
7. Light greenish-blue sandy shale; weathers in slope	15
6. Yellowish-brown platy ripple-marked cross-bedded sandstone, in beds 3 inches to 2 feet thick, with alternating soft sandy shale and shaly sandstone	8
5. Light greenish-blue sandy shale; contains thin lenses and beds of shaly sandstone that grade locally to beds of ripple-marked cross-bedded platy sandstone 1½ feet thick; this division is cross-bedded also on larger scale, and thin beds of sandstone slope obliquely downward	19
4. Yellow soft massive sandstone, with hard yellowish-brown capping rim rock 1 foot thick, rather evenly bedded	7
3. Light greenish-blue sandy shale	5
2. Soft massive, irregularly bedded sandstone, light creamy yellow to nearly white, locally with brown patches on weathered surface	3–4
Total Shinarump conglomerate	62
Moenkopi formation:	
1. Chocolate-brown sandstone and sandy shale; forms slope.	

The age of the Shinarump conglomerate is determined chiefly by its stratigraphic position. It lies between the Lower Triassic Moenkopi formation and the Upper Triassic Chinle formation. Fossil coniferous wood of species characteristic of the Chinle is abundant. Fragments of fossil cycads from the area northeast of Wagonbox Mesa (bed 8 in section above) are described by Berry[41] as *Otozamites powelli*, "identical with what Fontaine called *Zamites powelli* from Abiquiu."

CHINLE FORMATION

DEFINITION, AREAL EXTENT, AND THICKNESS

As defined by Gregory,[42] the Chinle formation includes the group of shales, "marls," thin soft sandstones, and limestone conglomerates lying between the Shinarump conglomerate and the Wingate sandstone. This interesting assemblage of strata has been traced from the Dutton Plateau, N. Mex., across the Navajo country to Lees Ferry, and along the Vermilion Cliffs into southwestern Utah. It reappears in the Muddy Mountains and Spring Mountain, Nev., west of which no outcrops have been discovered. The formation is exposed in upper Glen Canyon, at the San Rafael Swell, and eastward to Grand Junction. Along the San Juan Valley it may be traced well into Colorado. The Bears Ears and Wooden Shoe Buttes, the culminating points of Elk Ridge in San Juan County, Utah, are erosion remnants of Chinle shales and sandstones.

Throughout most of the Kaiparowits region the formation is concealed by younger rocks, but deformation of the beds along the Echo Cliffs, the East Kaibab monocline, and the Waterpocket Fold has permitted streams to cut deeply into the overlying beds and to expose in some places part and in other places all of the Chinle. The Chinle is well displayed on both sides of the Colorado River at Lees Ferry; it forms the borders of the basin in which the old village of Paria is placed; it is exposed in Glen Canyon below the mouth of Halls Creek; and complete and partial sections are revealed in canyons cut into the western flank of the Waterpocket Fold between the Escalante River and the north rim of the Circle Cliffs.

Records show that the Chinle is thickest in northeastern Arizona and southwestern Utah. At its type locality, the Chinle Valley, 1,182 feet of strata are exposed. In the Lees Ferry region measurements of 400, 520, 980, and 1,000+ feet are reported, and at Virgin City a section includes 995 feet. In southeastern Utah measured sections give 592 feet in Paria Valley, 474 to 593 feet along the Waterpocket Fold, 320 to 393 feet in upper Glen Canyon, and 830 feet in the San Juan Canyon. Some of the variation in measurements, especially at Lees Ferry, results from differences of opinion regarding the division to be established between the Chinle and the Wingate, but the evidence shows that the formation is thinner in the Kaiparowits region than in areas to the southeast and west. How much this thinning is due to

[41] Berry, E. W., Cycads in the Shinarump conglomerate of southern Utah: Washington Acad. Sci. Jour., vol. 17, pp. 303–307, 1927.

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

smaller original thickness and how much to the erosion that preceded the deposition of the Glen Canyon group of sandstones remains to be determined.

TYPICAL SECTIONS

The stratigraphy of the Chinle formation in areas that border the Kaiparowits region is shown in sections measured by Longwell [43] in upper Glen Canyon, by Gregory [44] in the Navajo country, by Miser [43] in the San Juan Canyon, and by Reeside and Bassler [45] in the Virgin River Valley. For the Kaiparowits region Moore [43] has published sections measured at the head of Halls Creek and in the Circle Cliffs. The following additional sections are typical of the Chinle exposures between the Grand Canyon and the Waterpocket Fold:

Section of lower part of Chinle formation on east side of Paria River at Lees Ferry

[Measured by Herbert E. Gregory]

	Feet
Chinle formation:	
21. Sandstone, light red and buff, fine even grains, cross-bedded on minute scale, in beds 10 to 40 feet thick; extends upward as massive cross-bedded sandstone to the top of the canyon wall.	
20. Shale and sandstone, light red and gray, in alternating series of shale beds 6 inches to 6 feet thick and sandstone beds 1 to 5 feet thick; unevenly bedded; all more or less cross-bedded; contain short lenses of flattened clay balls; calcareous; few saurian bone fragments; some foliation surfaces ripple marked and sun baked	110
19. Shale, dark red, very thin, calcareous; some foliation surfaces ripple marked	1
18. Sandstone, light red, imbricated, calcareous; contains flakes of mica, small quartz pebbles, and crystals of gypsum	2
17. Shale, buff, sandy, calcareous	¾
16. Sandstone, green-white, massive, cross-bedded	1
15. Shale, red and gray; strata as thin as paper, wavy; ripple marked	½
14. Limestone and limestone conglomerate, pink, green; concretionary limestone pebbles in eight lenticular beds 4 inches to 3 feet thick: contains saurian bones weathered into pink spongy mounds	22
13. Sandstone, "banded," white and brown, lenticular, friable	4
12. Shale and "marls," pink, lavender, and ash-gray; contains lenses of limestone conglomerate and of fine-grained brown sandstone and some petrified wood	36
Chinle formation—Continued.	
11. Limestone conglomerate, brown; pebbles size of peas cemented by lime and iron	1
10. Shale, red and green, lenticular; weathers as "marl"	6
9. Limestone conglomerate, brown, nodular; contains saurian bones and some petrified wood	4
8. Shale, purple-green, sandy, calcareous; contains limestone pellets, quartz pebbles, and lenses of loosely cemented sandstone	6
7. Limestone conglomerate, brown; weathers into concretionary nodules	2
6. Shale and "marl" like No. 3	4
5. Sandstone, brown; fine grained; weakly cemented with lime and iron	1
4. Shale, brightly colored, yellow, green, lavender, purple, red, pink, gray, blue, and white; highly irregular in bedding, composition, and texture; a series of sandy calcareous shale, calcareous sandstone, and impure limestone; includes many lenses of limestone conglomerate, soft sandstone, and clay mud balls, also balls of quartz sand, pebbles of quartz, chalcedony, jasper, and ironstone, and veins and scattered crystals of gypsum; petrified wood occurs as chips, blocks, and logs; a few bones and teeth of saurians and broken *Unio* shells; weathers into rounded knolls with spongy powdery surface, locally called marl	56
3. Sandstone, dull gray-brown, irregularly banded with black streaks; lenticular; cross-bedded; fine grained; weakly cemented with lime	23
2. Shale, pink, purple, blue-green, red, calcareous; contains aggregates of sand, lumps of blue-green clay, and thin lenses of cross-bedded sandstone; gypsum present as thin short beds, veins, and detached crystals; weathers to "marl"	10
1. Shale, gray; very thin bedded, sandy and calcareous; some foliation surfaces hard baked, glistening, and ripple marked	8
	298+

Unconformity.
Shinarump conglomerate; contains logs that exceed 80 feet in length.

Generalized section of Chinle formation 3 miles west of Paria village

[Measured by Herbert E. Gregory]

	Feet
Sandstones of Glen Canyon group.	
Chinle formation:	
5. Sandstone and arenaceous shale, light red, green-white and yellow; strata 2 inches to 5 feet thick, very irregularly bedded; fine grained; all calcareous; contains many lenses of mud flakes and limestone conglomerate, also strings of small quartz pebbles; weathers into mesas and box-headed canyons	140
4. Shale and "marl," brightly colored, variegated, calcareous; includes many lenses of concretionary limestone conglomerate, some lenses of brown imbricated sandstone, and stringers of quartz grains; about 80 feet below the top occur thin beds of gypsum, and 50 feet from the bottom much petrified wood; weathers into rounded mounds	285

[43] 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. 17–23, 1925.

[44] Gregory, H. E., op. cit., pp. 43–45.

[45] Reeside, J. B., jr., and Bassler, Harvey, Stratigraphic sections in southeastern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, p. 73, 1922.

Chinle formation—Continued. Feet

3. Sandstone, white and buff; cross-bedded generally in two series of beds separated by shale layers; contains two lenses of dark-green firm sandstone and many lenses of quartzite pebbles ---- 42
2. Shale, variegated, widely variant in composition, texture, and stratification; weathers like No. 4 -- 65
1. Sandstone, brown, in beds 1 to 6 feet thick, separated by layers of argillaceous and sandy shale; contains some gypsum and concretionary limestone ---- 60

Total Chinle formation ---- 592

Shinarump conglomerate.

Section of Chinle formation on east side of Circle Cliffs, northeast of Wagonbox Mesa

[Measured by Raymond C. Moore]

Wingate sandstone: Feet

22. Sandstone, reddish brown, fine grained, cross-bedded, prominently jointed.

Chinle formation:

21. Shale, light bluish, calcareous, weathering in slope; upper part stained purple, especially along joint planes, probably on account of pre-Wingate weathering ---- 48
20. Limestone conglomerate, light greenish-blue massive layer, composed of pebbles of limestone, quartz, jasper, and sand in a lime matrix ---- 1–2
19. Shale, light bluish, calcareous; weathers in slope ---- 31
18. Limestone, hard, nodular, massive, light bluish green, mottled with light purple; forms projecting ledge ---- 5
17. Shale, light blue, calcareous; grades into limestone above and below; forms slope ---- 37
16. Limestone, hard, nodular, massive, light bluish green, mottled with light purple; forms ledge; upper part contains irregular nodules of agate-like flint ---- 6
15. Limestone, impure, light greenish blue, with streaks and mottling of light purple; hard but breaks readily into irregular fragments; crops out in slope but grades without marked change into ledge-forming beds ---- 15
14. Limestone, light blue, mottled with light purple; upper part is hard and massive ---- 5
13. Shale, light bluish, calcareous, weathers in slope ---- 47
12. Shale, light yellowish brown, calcareous; becomes sandy in upper part and grades into thinly laminated soft calcareous sandstone; upper part changes locally to hard massive cross-bedded sandstone 10 feet in greatest thickness ---- 26
11. Sandstone, light yellowish brown, medium to coarse grained, very hard, massive, tangentially cross-bedded; breaks down in large angular blocks and weathers in thin platy fragments; contains much coarse crystalline calcite between the grains; locally conglomeratic and contains irregular beds and lenses, as much as 1½ feet thick, of soft purplish shaly conglomerate with pebbles three-fourths inch or less in diameter, composed chiefly of fine limy sandstone; weathers as a ledge which thins locally to 5 feet ---- 22

Chinle formation—Continued. Feet

10. Shale, canary-yellow at base, grading upward to light creamy lavender, light red, and brown; argillaceous in lower portion; becomes increasingly calcareous upward; the middle and upper parts contain irregular nodules and layers of impure limestone, mottled light greenish blue and lavender; the upper 3 feet appears locally as a massive nodular impure limestone; this zone weathers as a slope -- 55
9. Sandstone, dark brown, medium to coarse grained, soft, crumbly, micaceous, calcareous, cross-bedded; weathers in rounded irregular surfaces or slumps to loose sand ---- 27
8. Sandstone, dark brown, medium grained, hard, cross-bedded, massive; contains thin streaks and lenses of conglomerate in which some of the pebbles are 1½ inches in diameter; weathers in large angular blocks, which disintegrate along the platy cross beds; forms a prominent ledge ---- 4–6
7. Shale, sandy, purplish to brown; weathers as slope ---- 24
6. Sandstone, dark brown, thinly laminated in irregular curved lines due to ripple marking; abundant mica along bedding planes; forms bench ---- 5
5. Shale, sandy, purple to brown; weathers in rounded slope ---- 29
4. Limestone, dark earthy brown, impure, dense; shows fine structure composed of minute radiating crystals on weathered surfaces; weathers in irregular and rounded blocks ---- 1–1½
3. Shale, blue to purple, sandy; weathers in slope -- 26
2. Limestone, brown, very ferruginous, hard; breaks into irregular fragments that resemble rough slag; contains invertebrate fossils and fragments of silicified wood ---- 1–2
1. Shale, dark brown at base; grades to olive-green in middle and to blue and light bluish gray in upper part, sandy; weathers in rounded slopes and badlands ---- 83

Total Chinle formation ---- 500

Shinarump conglomerate.

Section of Chinle formation in an eastern tributary of Silver Falls Creek southwest of Wagonbox Mesa

[Measured by Herbert E. Gregory]

Wingate sandstone.

Chinle formation: Feet

27. Sandstone conglomerate, lavender and greenish blue, mottled red; consists of aggregates of sand, mud balls, pellets of limestone, and short, thick lenses of dark-red shale; friable; upper part much oxidized ---- 8
26. Limestone conglomerate, gray-green and green-blue; consists of pebbles and aggregates of limestone (95 per cent), and quartz and ironstone (5 per cent) that range in size from that of peas to pebbles as much as 1 inch in diameter, cemented by lime; includes a few lenses of firm, dense gray-green limestone; forms resistant bench ---- 12
25. Shale and shaly sandstone, red and purple; contains a few stringers and thin lenses of limestone conglomerate; calcareous; weathers in sharp-cut miniature canyons ---- 60

Chinle formation—Continued.	Feet
24. Sandstone, light red, brown, and green-white; imbricated; essentially a series of lenses about 1 inch thick that overlap in a tightly irregular manner	22
23. Limestone conglomerate (80 per cent), bluish green, gray, and mottled, and shale (40 per cent), red and brown, irregularly interleaved; limestone consists of greenish flattened balls, and with it are lozenges of green mud; weathers into a rough knobby surface	40
22. Shale, mottled red, lavender, greenish blue; grades into No. 23	12
21. Limestone, green and gray, massive, dense; includes geodes of calcite crystals; resistant; forms bench	2
20. Shale, red and gray, mottled, calcareous; grades into Nos. 21 and 19	8
19. Limestone conglomerate, speckled green, red, lavender, and blue; includes calcareous mud balls and aggregates of calcite crystals	5
18. Shale, yellow-red, calcareous, lenticular, soft; weathers to rounded surface	25
17. Limestone conglomerate, green-gray, very hard and dense; includes pebbles of jasper and chert; forms bench	2
16. Shale and "marl," brightly colored, predominant tones yellow and light red, with streaks and patches of purple, green, blue, and ash-gray; arrangement, color, and composition of beds widely and abruptly variant; weathers to rounded knolls with spongy surface	60
15. Sandstone, green, white, red, yellow, and gray, cross-bedded, calcareous, highly lenticular; includes lenses of limestone conglomerate and of flattened mud lumps; some petrified wood and saurian bones; soft, crumples readily to sand	16
14. Limestone conglomerate, brown, blue-green, and lavender; limestone pellets and concretionary forms in size from that of birdshot to that of hen's eggs are arranged as strings and lenses resistant to weathering	4
13. Shale and "marl," brightly banded and mottled dark red, light red, yellow, blue-green, lavender, and ash-gray; series of overlapping lenses of calcareous sandstone, argillaceous, calcareous, and arenaceous shale, and limestone conglomerate; includes concretionary aggregates of limestone, clay, ironstone, and sand, also quartz pebbles and gypsum crystals; weathers to rounded knolls	70
12. Limestone conglomerate, lavender and pink, dense, resistant	1
11. Shale and marl, variegated like No. 13	45
10. Limestone conglomerate, brown; consists of balls, disks, and lozenges less than 1 inch in diameter; weak lime cement permits the rock to weather into a mass of resistant pebbles	3
9. Shale, ash-gray, purple, red, green, and white, very micaceous and calcareous, imbricated; 12-inch bed of green resistant sandstone near the top; contains disseminated gypsum, ironstone concretions, some saurian bones, and fragments of petrified wood	48
8. Limestone conglomerate, purple and brown; contains concretionary pellets of chert and ironstone; many limestone pebbles coated black with manganese, resistant	2
7. Shale, blue-gray, calcareous, hard; forms steep slope	8
6. Sandstone, buff, thinly and irregularly laminated and imbricated; includes mud lumps; some foliation surfaces ripple marked	2
5. Shale, red, brown, and yellow, calcareous, irregularly bedded, increasingly sandy toward the top; contains some limonite nodules and ironstone concretions	26
4. Sandstone, brown and yellow, in thin, even beds, calcareous and micaceous; forms firm protecting bench	2
3. Shale, banded yellow and brown, with mottling of lavender, white, and red, argillaceous near base, strongly calcareous above; includes nodules and lenses of sand, cemented by lime and flattened mud lumps; forms slope	55
2. Shale or thin-bedded, flaggy sandstone, buff and brown, very unevenly bedded; some layers cross-bedded; shows ripple marks and contains a few saurian bones and fragments of invertebrates; weathers into yellow clay hills and buttes with tilted caps	40
1. Shale, dark brown, gray, and earthy black, irregularly bedded, nodular; contains much iron as stain and concretionary masses	15
Total Chinle formation	593

Shinarump conglomerate.

GENERAL FEATURES OF STRATIGRAPHY AND LITHOLOGY

In essentials the Chinle of the Kaiparowits region is identical with that of the Navajo country, where this formation is thicker and more widespread and has been studied in greater detail. All types of rocks and of fossils are common to the two areas, and in a broad sense the arrangement of the strata is the same. During Upper Triassic time the conditions of sedimentation appear to have been uniform over most, if not all, of the plateau province. But although as a whole the beds that compose the Chinle constitute a stratigraphic unit of unmistakable individuality, a comparison of the 16 sections measured in the Kaiparowits region makes apparent the wide variation in the order of deposition, composition, texture, color, and structure of the Chinle beds. Within an area of a few square miles all sections may show the same range of color and include the same kinds of rock, but the colors of individual beds are not persistent, and one kind of rock may be replaced by another kind within short distances along the strike. The relative amounts of limestone, shale, and sandstone differ with each section, as does also the position of these strata in the series. Moreover, the gradation in composition of the strata and of their included lenses and accessory materials is such that no two workers are likely to describe the rock or to subdivide the beds in exactly the same manner. Variation is particularly noticeable in the Circle Cliffs, where with few interruptions outcrops of Chinle may be traced for several miles. (See pl. 8, *B*.) In this area the lower half or two-thirds of all the sections is dominantly sandy and relatively dark, and the remaining upper part is very calcareous and lighter colored. The sandstone and conglomerate appear and disappear within short distances and differ notably from place to place in thickness and lithologic character. The calcareous beds range by insensible gradations from hard, compact limestone to limy shale, which unlike typical shale breaks into irregular-shaped sharp-angled fragments without noticeable bedding or jointing. In accordance with the degree of oxidation of the iron in the rock, the color of the limestone ranges from light bluish green to light lavender, and some beds or portions of beds are all of one color, whereas others show mottling. At the south end of the Waterpocket Fold and at the Burr trail the calcareous beds are dominantly blue.

The outstanding features of the Chinle formation are fossil wood, the peculiar limestone conglomerate, and the series of variegated shales that weather after the manner of marls. Fossil wood is common in the lower half of the formation; near Sixteenmile Spring, west of Paria, and at places in the Circle Cliffs it constitutes a fossil forest. It appears as chips, as blocks, and as tree trunks as much as 80 feet long and 3 feet in diameter. No trees were found in place, with roots extending into the ground; the logs show worn surfaces and ends and have been stripped of branches. Twigs are scarce, and no cones or needles were found. The limestone conglomerate occurs as lenses that range in length from a few feet to a mile and in thickness from less than an inch to more than 5 feet. In places it is exceptionally resistant, forming prominent shelves on cliff faces; elsewhere it crumbles easily. Some ledges consist mostly of dense limestone that contains a few pellets; others are made up of balls firmly or weakly cemented. The conglomerate consists essentially of lime and manganese pebbles, most of them concretionary. Chert, rarely jasper, fragments of calcareous shale, and well-rounded quartz grains are also present. The conglomerate grades through loosely compacted sandstone with disseminated crystals of calcite and dolomite into sandstone with lime cement. The shale near the middle of the Chinle is unusual in mode of weathering, in color, and in composition. Where this shale is well exposed to weathering it appears as mammillary mounds outlined by gracefully curved slopes leading to shallow, broadly concave valleys. The sides of the mounds are scarred with innumerable runways cut through only the disintegrated surface material. (See pl. 8.) On some mounds are tiny benches produced by resistant ledges of limestone conglomerate, but in many mounds the heterogeneous material responds as a unit to weathering, and the slopes are continuous down to their flaring base. (See pl. 7, *C*.) Disintegration of the clay has produced a coat of fluffy material a foot or more thick, exceptionally light and incoherent. Walking on the surface in these areas is difficult. During heavy rains this superficial material is carried to drainage channels as streams and sheets of mud, and in places the mounds are stripped down to bare rock. With conditions so favorable for the removal of weathered material it is surprising to find so few areas that lack the powdery cover. The explanation lies in the readiness with which the shale absorbs water. A fragment of fresh rock immersed in water swells to nearly twice its bulk, and after drying is nothing more than a pile of disconnected, irregular grains; alternate drying and wetting produces a substance part of which passes through filter paper. Under the microscope most of the material appears to be colloidal. The following chemical analysis of a specimen of the gray shale was made by Prof. W. C. Blasdale, of the University of California:

Analysis of specimen of gray shale from Lees Ferry, Ariz.

SiO_2	53.45
Al_2O_3	18.56
Fe_2O_3	7.89
CaO	1.87
MgO	1.66
H_2O at 105° C	6.77
Ignition loss above 105° C	7.26
	97.46

In discussing this analysis Lawson[46] calls attention to the fact that the ratio of silica to alumina is far greater than that in clay composed of kaolin and that the amount of quartz present is insufficient to account for the excess of silica. He concludes:

> It seems probable, therefore, that a considerable proportion of the flocculent colloidal substance seen under the microscope is in reality silicic acid and that the presence of silica in this form may account for the peculiar behavior of the clay with water.

The friable "marls" and shales of the middle part of the Chinle are the most richly colored beds in the plateau province. Unweathered rock shows deep tones of yellow, ash-gray, lavender, purple, rose-pink, maroon, sienna, lilac, and cream color and various shades of red, blue, and brown. On weathered surfaces, especially when viewed from a distance, the colors are blended into bands of dark red, brown, pink, green, purple, white, and black.

From its lithologic character, local variations, bedding, and fossil content, the Chinle formation is evidently a fresh-water deposit. No marine fossils have

[46] Lawson, A. C., The gold of the Shinarump at Paria: Econ. Geology, vol. 8, p. 445, 1913.

been reported from it, but instead there is found abundant silicified wood and in places *Unio* and other fresh-water shells and the bones of land vertebrates. The marly beds appear to have been deposited in fresh-water lakes or ponds.

The position of the Chinle conformably above the evidently stream-borne Shinarump conglomerate and the more or less gradational nature of the beds near the contact of these formations further indicates the continental character of the Chinle deposition.

AGE AND CORRELATION

The Chinle formation is substantially the equivalent of the 400 feet of "variegated gypsiferous marls containing silicified wood" measured by Howell[47] along the Paria River and of the 300 feet of "variegated clay shale, purple and white above and chocolate below, with silicified wood," which constitutes "division a" of the "Shinarump group" of the Henry Mountains as described by Gilbert.[48] It is also the equivalent of the "upper Shinarump" "clays" and "shales" of Powell and of Dutton and a lower part of their Vermilion Cliff "group" or "series." Parts of the Chinle find their equivalents in the Dolores formation of southwestern Colorado. Correlation with the Chinle at its type locality in the Navajo country is made with assurance.

Evidence based on fossils as to the age of the Chinle of the Kaiparowits region, though meager, is quite satisfactory. The fossil wood has not been studied beyond its identification as several different species of coniferous trees closely related to those from the Upper Triassic of Arizona. Most of the mollusks collected have proved too fragmentary for specific identification, and saurian bones are known only as representative of species found in the Chinle of Arizona and Dolores of Colorado. In the collection of bones and scales of fishes Professor Lull[49] recognizes "*Pholidophorus* sp. (Lower and Middle Triassic) or *Seminotus* sp. (Triassic)."

Von Huene[50] has expressed the opinion that what have been called Upper Triassic vertebrates include also Middle Triassic types—that is, Chinle and Shinarump may include also Middle Triassic. The age of the Chinle seems clearly established as Triassic and is probably Upper Triassic.

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

[48] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 6, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

[49] Lull, R. S., personal communication.

[50] Huene, F. von, Notes on the age of the continental Triassic beds in North America, with remarks on some fossil vertebrates: U. S. Nat. Mus. Proc., vol. 69, art. 18, 1926.

CHINLE-WINGATE CONTACT

The contact of the Wingate and Chinle formations in southern Utah closely resembles that of similar exposures in Arizona. (See pls. 7, *C*; 8, *B*.) In most places the two formations meet as seemingly conformable beds of unlike color, texture, and composition and when traced along cliff faces show little evidence that indicates lapse of time. In fact, at localities where the uppermost beds of the Chinle are red sandstone it is difficult to determine the limits of the formation. Close examination, however, usually reveals staining and decomposition, which suggest exposure to the atmosphere, and also locally interrupted lenticular bedding. On Silver Falls Creek a bed of red conglomerate sandstone that contains large grains of quartz and pieces of blue-green limestone and chert 2 inches or less in diameter lies at the base of the Wingate, and stringers extend down into greenish Chinle limestone. At Paria the top of the Chinle is marked by a thin discontinuous bed of conglomerate in which grains of quartz, fragments of limestone, calcareous mud balls, and pellets of clay are conspicuous. At the Circle Cliffs and near Fruita, Utah, the top of the Chinle is uneven and the massive Wingate sandstone occupies depressions in the underlying shale. At several places ripple marks and mud cracks were noted in the basal few feet of beds assigned to the Wingate. These observations, added to those recorded for Glen Canyon, San Juan Canyon, and the Navajo country, show that at many places the Chinle was at least exposed to erosion before the Wingate was deposited. They also show that the unconformity is nowhere conspicuous and that the time elapsing between the end of the Chinle epoch of deposition and the beginning of the Wingate epoch was not great. It may well be that deposition was continuous in parts of the plateau province.

JURASSIC FORMATIONS

HISTORICAL SKETCH

Nearly all geologic reports on southern and eastern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado include descriptions of beds assigned to the Jurassic. Marcou[51] speaks of Jurassic rocks along the Puerco River, but it is impossible to determine what portion of his "Gypsum formation" is assigned to this age. On the evidence supplied by fossil plants Newberry[52] regarded a 12-foot bed of carbonaceous shale near Oraibi as Jurassic, "the sole representative of the Jurassic series."

[51] Marcou, Jules, Résumé and field notes: U. S. Pacific R. R. Expl., vol. 3, pt. 4, pp. 150–151, 1856.

[52] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 3, pp. 82–83, 129–131, 1861.

Howell assigned "20 or 30 feet of red marl" between White Rock Spring (in Steamboat Canyon?) and Pueblo Colorado (Ganado?) to the Jurassic and stated that "beds evidently belonging to this series were seen near the Moenkopi. * * * To the eastward it [the Jurassic] thins out rapidly, until in eastern Arizona and in New Mexico it probably disappears entirely."

The Jurassic of the Paria Valley is restricted by Howell [53] to 500 feet of "cross-bedded sandstone, variegated gypsiferous shales, calcareous shales, and marly shales and sandstones"—beds that constitute the lower part of the San Rafael group, as described in this paper. Beds in the Paria Valley that correspond to the Navajo sandstone and Wingate sandstone were considered by Howell and Gilbert [54] as the topmost 1,400 to 1,700 feet of a 2,250-foot section of the Triassic. For the Henry Mountain region Gilbert [55] used "Jura-Trias" as a term descriptive of all beds between the Dakota and the series now recognized as the Kaibab limestone. Dutton [56] likewise assigned to the "Jura-Trias" the beds in the Zuni region, New Mexico, that lie between the Permian and the Cretaceous and stated that "general considerations, however, strongly favor a Jurassic age for those beds which lie above the Wingate sandstone," which he correlated with the Vermilion Cliff "series" of southern Utah. In discussing the magnificent exposures that border the Colorado River on the north, Dutton [57] mentioned a "Jurassic white sandstone," which immediately underlies 300 to 500 feet of calcareous gypsiferous and arenaceous shale that contains typical Jurassic fossils, and concluded:

> The Jurassic white sandstone seems to be peculiar to the northern and western portions of the plateau province. In southern Colorado and western New Mexico no stratigraphic member has yet been found which can be identified with it. There remains, however, the possibility that in those more easterly regions the Jurassic sandstones may form the upper part of the sandstone series now reckoned as Triassic.

In Dutton's view both the Jurassic and Triassic strata gradually change in color and decrease in thickness in passing from the Virgin River to the Zuni Plateau. He added:

> So far as present knowledge is concerned, we are at liberty to suppose (1) that the Jurassic sandstone thins out completely in the interval, or (2) that it becomes the summit of the presumed Triassic of New Mexico and can not be distinguished from it.

Cross [58] assigned the La Plata sandstone, 250 to 400 feet thick, to the Lower Jurassic on the basis of its unconformable relation to the underlying Dolores (=Chinle in part), of Upper Triassic age, and assigned the "McElmo formation," 400 to 1,000 feet thick in southwestern Colorado, to the Jurassic and correlated it with the Morrison formation.

Gregory [59] recognized the La Plata sandstone of Cross as Jurassic and extended it southward and westward to include the Wingate sandstone and the White Cliff sandstone of the early surveys and assigned to the "McElmo formation, Jurassic (?)," all the beds between the top of the La Plata and the base of the Dakota, thus including the "fossiliferous calcareous shales" and the "gypsiferous shales and thin sandstones" of Dutton.

As described by Reeside and Bassler,[60] the stratigraphic series along the lower Virgin River includes "Jurassic sandstone" 2,100 feet thick and "Jurassic limestone and shale" about 460 feet thick.

As treated by Longwell, Miser, Moore, Bryan, and Paige,[61] the Jurassic of southeastern Utah includes from the base upward Wingate, Todilto (?), Navajo, "gypsiferous shales and sandstones," and "varicolored sandstone and shales," and unconformably above them lies the "McElmo formation, Cretaceous (?)," 125 to 565 feet thick. In their generalized descriptions of "gypsiferous shales and sandstones" the lowermost beds at least of the "marine Jurassic" are readily recognized, and "varicolored sandstones and shales" is an appropriate field name for the series of highly variable and brilliantly colored strata that commonly underlie the Cretaceous of the Colorado Plateaus province. Lupton,[62] Emery,[63] and Dake [64] set the lower boundary of the Jurassic at the top of the Chinle formation and recognized the top of the Navajo sandstone as a horizon above which are strata of known Jurassic age and also strata which hold the position of the "McElmo" and closely resemble the Morrison and which may prove to be Cretaceous. All field workers agree that the only unequivocal horizon markers are the Carmel and Curtis formations, from which faunas of Sundance age have been obtained. Because conclusive evidence is yet lacking concern-

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

[54] Gilbert, G. K., idem, p. 160.

[55] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 6, 1877.

[56] Dutton, C. E., Mount Taylor and the Zuni Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 138, 1885.

[57] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 35–38, 1882.

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

[59] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 50–68, 1917.

[60] Reeside, J. B., jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 63–65, 1922.

[61] Longwell, C. R., and others, op. cit., pp. 11–14.

[62] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, p. 124, 1914; Geology and coal resources of Castle Valley, Utah: U. S. Geol. Survey Bull. 628, p. 23, 1916.

[63] Emery, W. B., The Green River Desert section: Am. Jour. Sci., 4th ser., vol. 46, p. 564, 1918.

[64] Dake, C. L., Horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, p. 641, 1919.

ing the age of the sandstones between the Chinle and the fossiliferous marine Jurassic Carmel formation, these strata, which make up the Glen Canyon group, are designated in this report Jurassic (?).

Including the Navajo, Todilto (?), and Wingate tentatively assigned to it, the Jurassic of the plateau province is an assemblage of strata remarkably alike in extent, thickness, composition, and color. With most of its essential features present it extends from the San Juan Mountains, Colo., and the Zuni Mountains, N. Mex., westward and northward across Utah and Arizona far into Nevada. From a center at Glen Canyon it has been traced southward across the Navajo Reservation and northward to points beyond the San Rafael Swell. Throughout this great area the thickness of the Jurassic averages about 2,000 feet. Thicknesses of less than 1,000 feet appear only at its eastern and southern borders; at the head of Halls Creek 3,510 feet of beds lie between the Chinle and the "McElmo."

GENERAL LITHOLOGIC FEATURES

The Jurassic is essentially a huge pile of consolidated sand. Its massive beds and shaly beds alike are predominantly composed of quartz grains; limestone and gypsum constitute probably less than 1 per cent, and true argillaceous shale is present chiefly as small plasters included in irregular beds associated with local unconformities. Many thin beds and thick beds closely resemble each other; they are alike cross-bedded, traversed by bands and streaks of white along and across the planes of foliation, and when unweathered show similar range of color. The striking differences in appearance are the expression of the influence of such incidental features as texture and manner of weathering. Without much exaggeration some whole sections of the Jurassic might be described as fine-grained cross-bedded sandstone, the color and stratification of which are revealed by weathering. With the exception of the inconspicuous beds of siliceous limestone, the shalelike beds and massive beds are friable and crumble readily under pressure. Even on wind-swept surfaces the impressions of hobnails are visible, and experience in climbing cliffs soon leads to lack of faith in seemingly firm projections and crevices. The weakly cemented fragments pried from cliffs by frost soon disintegrate and are removed by rainwash and wind, leaving little or no talus.

The impression gained from a superficial view of the massive walls and dissected surfaces in the Kaiparowits region is that the Cretaceous beds are gray and dull and that the Jurassic strata are brightly colored in various tones of red. But even at a distance white patches are visible, and as the eye traces a continuous face of a plateau or flank of a monocline the color is seen to change from red to yellow, to white, or to brown abruptly or gradually and at irregular intervals. Nearer views show that "red walls" range from maroon to light yellow and that "white walls" range from almost flour whiteness to delicate shades of green or brown, and a detailed analysis of the strata shows that the general color is the resultant of many colors and that the prevailing tone arises in some places from the prominence of some bed and in other places from the degree of weathering or the state of the atmosphere. The color of a hand specimen is not that of the cliff as a whole, and specimens from the same stratum vary in tone with reference to their position along the strike, their nearness to bedding planes, and their texture.

PRESENT KNOWLEDGE OF THE JURASSIC OF SOUTHERN UTAH

Although the strata assigned to the Jurassic are the most conspicuous of all rocks in the plateau province, definite information regarding their mode of deposition and place in the time scale remains to be obtained. The lithologic evidence of equivalent age and origin of the broad subdivisions is strong; although the recognized members thicken and thin and form and re-form along the strike as single massive beds or series of thinner beds, they everywhere present a group of features which as a whole render them unlike the members above or below. The Wingate and Navajo sandstones, separated by the Todilto (?) formation or seemingly merged, constitute an unmistakable series; the combination of features that characterizes the overlying San Rafael group is not duplicated elsewhere, and the Morrison maintains its individuality throughout the plateau province. But neither the upper limit nor the lower limit of the Jurassic is confidently known, and subdivisions within the system have been made largely on the basis of texture, color, and arrangement of beds. Most of the beds have been deposited by streams or by the wind and consequently include many unconformities that perhaps are no less significant than the poorly defined hiatuses used in separating the Jurassic (?) from the Triassic or the Jurassic from the Lower Cretaceous, if the Morrison (McElmo) is of Lower Cretaceous age. Fossils of unmistakable Jurassic age have been found only in a few beds of the Carmel and Curtis formations. The organic remains in the Wingate, Todilto (?), and Navajo formations consist of fragments of wood and of bone, dinosaur tracks, unios, and worm trails that have Triassic as well as Jurassic affinities. In fact, no entirely satisfactory evidence exists for placing the Glen Canyon group in the Jurassic system, and it is possible that future studies may result in drawing the Jurassic-Triassic boundary within the Chinle or at any horizon between that formation and the top of the Navajo. Even the age of the Morrison has not been fully established. So far as detailed chronology is concerned, work among Jurassic rocks is still in an exploratory stage. The writing of an adequate history of the plateau province during Mesozoic time must await fuller knowledge.

MAJOR DIVISIONS OF THE JURASSIC

Because of lithologic dissimilarity, color contrasts, and evidences of breaks in deposition, three large subdivisions of the strata between the Chinle formation and the Dakota(?) sandstone are readily recognized in the field:

1. The Glen Canyon group, Jurassic(?). In stratigraphic position the Glen Canyon group is identical with the so-called La Plata "group" of the Navajo country as defined by Gregory, who considered it the equivalent of the La Plata sandstone of southwestern Colorado. Recent studies, however, indicate that probably only part of the so-called La Plata "group" of the Navajo country is represented in the La Plata sandstone as described by Cross. To avoid confusion the term Glen Canyon group is introduced. The essential components of the Glen Canyon group are two massive cross-bedded cliff-making sandstones, the Navajo sandstone above and the Wingate sandstone below, separated in most places by the Todilto(?) formation, which consists of thin-bedded calcareous sandstone, shale, and thin, dense limestone. Its mass, extent, color, and manner of erosion make the Glen Canyon group strikingly prominent.

2. The San Rafael group, Jurassic. The term San Rafael group has been proposed for the assemblage of strata which occupies the horizon of the marine Jurassic of the plateau province and which lies between the Navajo sandstone and the Morrison formation. It consists of the Carmel, Entrada, Curtis, and Summerville formations. Although with the possible exception of the Curtis formation all subdivisions of the San Rafael group are represented in the Kaiparowits region, where formation names were tentatively applied before neighboring areas were studied, the fuller development of the group as a whole in the San Rafael Swell seems sufficient reason to select the group name and three formation names from that area. The San Rafael group includes massive sandstone, shaly sandstone, gypsum, and limestone and is remarkable for variation in form, extent, and color. Beds that correspond to those included in the San Rafael have generally been classed as "McElmo."

3. Morrison formation, Cretaceous(?). The Morrison formation in the Kaiparowits region occupies the stratigraphic position of all but the basal part of the "McElmo" as that term has been used by Cross and by Gregory. It is the equivalent of the "upper McElmo" of Lupton and Dake and of the "McElmo" of Emery. For the region as a whole the Morrison consists of an upper series of variegated shale and a basal series of lenticular massive sandstones—the Salt Wash sandstone member—but the formation is exceptionally irregular in composition, color, and arrangement of beds.

GLEN CANYON GROUP (JURASSIC?)

Beds assigned to the Glen Canyon group extend entirely across southern Utah and eastward to the La Plata Mountains of Colorado. In Arizona and New Mexico they are nearly coextensive with the Navajo country. In Nevada they appear in the Muddy Mountains and the Spring Valley Mountains; traverses west of this district reveal no equivalent beds.[65] The term "Glen Canyon" seems appropriate for the group of rocks that form the walls of Glen Canyon of the Colorado throughout its 162-mile course from the Henry Mountains to the Echo Cliffs and likewise the walls of the lower parts of the canyons of the San Juan, the Paria, the Escalante, and many smaller tributaries. The Waterpocket Fold is an almost continuous ridge of sandstones of the Glen Canyon group which unites the walls of the Colorado River with the monoclinal eastern slopes of the San Rafael Swell, 80 miles to the north, and the lower Escalante Valley is a floor of sandstone of this group, 20 miles wide, which extends eastward across the Colorado River and south and west to join the Paria Plateau in the Lees Ferry region. Over most of southeastern Utah the Glen Canyon group might be considered the bedrock. It lies beneath the High Plateaus, and on it rests the Kaiparowits Plateau and the highlands about the Henry Mountains. Throughout this vast area the Glen Canyon group is nowhere less than 600 feet thick, and in many places it exceeds 2,000 feet. It is an unusually prominent group of beds, and there are few points of observation in southeastern Utah from which it is not visible. (See pls. 19, *A*; 21, *C*; 26, *C*; 27, *C*, *D*.)

In boldness of sculpture the sandstones of the Glen Canyon group stand first among the formations of the plateau province. Where the beds are horizontal, precipitous cliffs extend for miles, and on the crests of gentle folds great blocks of sandstone with vertical sides and sharp corners stand high above the bordering canyons. Where the beds are steeply upturned, erosion has cut the sandstones into unscalable pinnacles, which project above high, bare masses of rock that rest like flatirons against the limb of the fold. Likewise in variety of architectural features the Glen Canyon sandstones take high rank; they are surpassed, if at all, only by the Eocene limestone and the remarkable assemblage of strata included in the San Rafael group. Beautifully molded domes and rounded

[65] Gregory, H. E., and Noble, L. F., Notes on a geologic traverse from Mohave, Calif., to the mouth of San Juan River, Utah: Am. Jour. Sci., 5th ser., vol. 5, p. 231, 1923.

ridges mark the surface of the sandstones, and many cliff faces consist of a series of amphitheaters and pilasters, which extend from the top to the bottom and are carved without sharp edges. Within the rock itself have been carved innumerable recesses, many of them mere pockets and niches but some that have broad floors and arched roofs, forming rock shelters sufficiently large to accommodate the houses of the ancient cliff dwellers. Here and there appear windows and the gracefully formed arches of natural bridges.

In general view the Glen Canyon group is readily distinguished from the beds that lie below it. Its massiveness, color, and manner of erosion are quite unlike those of the underlying variegated shales of the Chinle formation. Where the overlying Carmel formation is well represented, its distinctive dull color and thin stratification are in strong contrast to the light color and the massiveness of the Glen Canyon.

In many places the overlying thin beds are stripped far back and expose the top of the Glen Canyon group as a sandstone-floored platform—an esplanade that winds in and out of valleys and around the beautifully banded San Rafael Cliffs. (See pl. 21, *C*.)

WINGATE SANDSTONE.

The definition and description of the Wingate sandstone of the Navajo country presented by Gregory [66] holds good for the Kaiparowits region. The composition, detailed structure, and arrangement of parts of the Wingate are essentially alike in the two regions, and the range of variation in color, texture, and stratification lies between the same limits. (See pls. 8, *B;* 9, *A;* 19, *B;* 22, *C;* 23, *B*.) Characteristically the Wingate of the Kaiparowits region is a very massive, fine-grained sandstone, about 300 feet thick, underlain at most localities by a few feet of lenticular sandstone and shale, in part conglomeratic. It commonly appears as a single vertical palisaded wall that rises above slopes of Chinle beds. Cross-bedding ranges from inconspicuous markings to larger-scale truncated laminae, but the great sweeping curves that characterize the Navajo sandstone are generally lacking. At places along the Waterpocket Fold cross-bedding is too little developed to be revealed by weathering; the only markings on the smooth, rounded surfaces of sandstone are small, shallow pits that have the appearance of a honeycomb. (See pl. 9, *B*.) Strong vertical jointing that cuts the sandstone into huge blocks is a common feature. The high, nearly vertical Wingate cliffs present an impassable barrier except where streams have carved narrow pathways across the outcrop.

Miser [67] described the Wingate on the lower San Juan as massive cross-bedded sandstone, 270 feet thick at Piute Farms, 330 feet thick near Spencer Camp, 350 feet thick at Copper Canyon, and 275 feet thick 12 miles above the mouth of the San Juan. In sections measured in upper Glen Canyon Longwell [68] describes the Wingate as a sheer wall of massive sandstone about 300 feet high at the mouth of Crescent Wash; as chiefly an unbroken cliff 366 feet high at Twomile Canyon; and as a massive member 300 feet thick, underlain by 3 to 30 feet of coarse-grained thin-bedded lenticular, extremely cross-bedded sandstone at Goodhope Bend. At Capitol Reef Wash the Wingate is a massive cliff-making bed 420 feet thick. Within the Kaiparowits region the Wingate consists of a single ledge of fine-grained cross-bedded, very massive sandstone 250 feet thick at the Circle Cliffs, 260 feet thick at the Burr trail and Muley Twist, in the Waterpocket Fold, 340 feet thick at the Bitter Creek divide, and 280 feet near the mouth of the Escalante. Along the Paria River the Wingate is represented by a series of cross-bedded massive strata 10 to 30 feet thick, which form the lowermost 160 to 200 feet of the canyon wall. Corresponding structure and thickness were noted in a cliff 3 miles northwest of Paria. At Lees Ferry Moore assigned to the Wingate the lowermost 400 feet of fine-grained medium-bedded to massive orange-red sandstone in the cliffs along the river. The average of 27 measurements of the Wingate within the plateau province is about 285 feet. The formation is thickest along a line that extends from the Chuska Mountains, on the Navajo Reservation, northward along the Waterpocket Fold to the San Rafael Swell. It is thinnest or most modified in the Echo Cliffs and is possibly not represented at all in regions west of the Paria River.

Typically the Wingate sandstone is orange-red, not uncommonly rather brilliant in tone, and it retains that color throughout most of Arizona and Utah, but in places all or parts of the formation are red-brown, and in the northwest wall of the Circle Cliffs and south of Fruita, in Wayne County, its color grades from orange-red into light creamy yellow or nearly white. In the Kaiparowits region the overlying Todilto (?) is typically maroon, much darker than the Wingate, and the Navajo sandstone ranges from white, cream-color, or tan to red or red-brown, and in parts of the Escalante Valley it is pink, with cream-colored bands. Although the color of each of the three formations differs from place to place, at no one place studied in Arizona or Utah is the color of the Wingate, the Todilto, and the Navajo the same.

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

[67] Miser, H. D., in Longwell, C. R., and others, op. cit., p. 17.

[68] Longwell, C. R., and others, op. cit., pp. 18, 19.

TODILTO (?) FORMATION

Early students of the geology of southern Utah recognized two divisions in the beds that lie between the Chinle ("Shinarump group," in part, of Powell and Dutton) and the assemblage of beds variously called "marine Jurassic," "Gray Cliff," "Flaming Gorge," and "McElmo." Powell used the terms White Cliff "group" and Vermilion Cliff "group"; Gilbert used the terms "Gray Cliff group" and Vermilion Cliff "group"; Dutton called the rocks Vermilion Cliff "series" and "Gray Cliff sandstone." In a section measured in the Paria Valley Howell[69] records 800 feet of "buff massive cross-bedded sandstone," underlain by 600 feet of "pale-vermilion massive cross-bedded sandstone" overlying 400 feet of "variegated gypsiferous marls containing silicified wood" (Chinle formation). The beds that occupy the general position of these two unmistakable sandstones were subdivided by Gregory[70] into the Wingate, Todilto, and Navajo formations, the Wingate roughly corresponding with the upper part of the Vermilion Cliff and the Navajo with the White Cliff. The name Todilto was introduced for the limestone, calcareous shale, and thin calcareous sandstone that appear in the midst of the great sandstone cliffs that tower above the Chinle formation.

In and near its type locality, Todilto Park, N. Mex., the Todilto is predominantly limestone and calcareous shale, commonly less than 10 feet thick. Northward and northwestward across the Navajo Reservation measured sections include increasingly less limestone and become thicker. At the mouth of Piute Canyon the position of the Todilto is occupied by 100 feet of thin and irregularly bedded red sandstone and a subordinate amount of calcareous shale, limestone, and limestone conglomerate arranged in overlapping lenses. At Navajo Mountain the formation is even thicker and contains but inconspicuous lenses of limestone and lime conglomerate. This observed departure from type of the Todilto of the northwestern Navajo Reservation led to the comment:

> The position of these beds between two massive sandstone strata, Wingate and Navajo, is the basis for their assumed equivalence with the Todilto formation. This expression, however, is so different from that in the type locality that this correlation must be considered only as a working field hypothesis.

Since the publication of Gregory's conclusions a series of thin irregular calcareous sandstone beds, including some limestone, which occupies a horizon between the Wingate and Navajo sandstones, has been traced by Paige, Longwell, Moore, and Miser from Navajo Mountain up the Colorado to the Henry Mountains, along the Waterpocket Fold to the San Rafael Swell, and into the San Juan Canyon. Similar beds have been mapped in the Kaiparowits region. It is clear that a distinct, widely traceable stratigraphic division occurs between the Wingate and Navajo sandstones in most of the Navajo country and in Utah. There is doubt, however, whether this middle division of the Glen Canyon group corresponds to Gregory's type Todilto; hence this name is applicable only with a query to the region here described. The Todilto (?) of the Kaiparowits region consists typically of maroon and reddish-brown calcareous sandstone with lesser and varying amounts of shale and limestone. The sandstone beds range in thickness from a fraction of an inch to more than 10 feet, but thick beds are much less common than thin beds. The beds commonly thicken and thin, overlap, tail out, or are replaced by shale within short distances along the strike. (See pls. 9, *A*; 26, *C*.) The quartz grains that compose the sandstone are well rounded, well sorted, and coarse and are arranged in cross-bedded laminae that meet at relatively sharp angles. The shaly beds are essentially very thin fine-grained quartz sandstones that contain here and there balls and lozenges of consolidated mud. Like the sandstones the shale beds are lenticular and present few even foliation surfaces; in degree of consolidation they differ greatly. The limestone appears as compact gray layers, as fragments embedded in sandstone and shale, and as lenses of limestone conglomerate. Lime is also present as cement. Small lenses of conglomerate composed of quartz chert and sandstone fragments cemented by lime and sand are present at most places within the lower half of the formation. The characteristic color of the Todilto (?) is maroon, which reveals the formation as a dark-red band in cliffs of Wingate and Navajo, but in some beds in the measured sections maroon is replaced by gray, purple, orange color, or pink, and on the northwest side of the Circle Cliffs the entire Todilto (?) is light creamy yellow. In the walls of the canyons that lead westward from the Waterpocket Fold the Todilto (?) appears as dark-red shale, thin-bedded calcareous sandstone, and lenticular conglomeratic limestone. One bed of purple limestone includes small angular chunks of white chert. At the Hole in the Rock the Todilto (?) consists of red shaly sandstone and thin discontinuous limestone. On the surface of one of the limestone lenses water emerges as a seep.

The Todilto (?) is readily distinguished in the field by thinness and irregularity of stratification of beds and by features that clearly indicate deposition in running water, thus contrasting sharply with the underlying Wingate and the overlying Navajo. Contacts with the beds above and below indicate a change in conditions of deposition. In some places the transi-

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

[70] Gregory, H. E., op. cit., pp. 52–59.

tion appears to be gradual; elsewhere unconformities exist. In places lenses of conglomerate mark the base of the Todilto (?), and "at many localities along the Colorado a distinct erosional unconformity separates the two formations, Wingate and Todilto (?), lenticular fluviatile beds filling valleys on the surface of the Wingate."[71] An unconformity at the top of the Todilto (?) is shown at places where the fine-grained, cross-bedded Navajo sandstone rests on an uneven surface of shale or slablike sandstone that is sprinkled with broken chunks of shale, fragments of limestone, and pellets of clay. At some localities the topmost bed of the Todilto (?) is sun baked, and at a few places ripple marks were observed. Near Warm Spring Canyon, Longwell noted in brown and purple shale numerous sun cracks, 3 inches wide at the top, filled with buff sandstone extending downward from the main mass of Navajo sandstone. Similar sand-filled sun cracks were observed at the top of the Todilto (?) in Muley Twist Canyon. But notwithstanding this evidence of unconformities the upper and lower limits of the Todilto (?) could not be definitely fixed in many measured sections, and the unconformities may have only local significance.

The Todilto (?) in southern Utah is represented by outcrops at many places east of the Paria Valley and the High Plateaus. South and east of Glen Canyon it appears wherever rocks at this horizon are exposed. The Todilto (?) is thinnest as well as most calcareous near the Arizona-New Mexico boundary but shows no regular gradation in thickness or in composition where traced northwestward. In the great sandstone cliffs that extend from the Paria Valley westward across Utah and into Nevada the formation has not been definitely recognized and may be absent.

In selected measured sections the following thicknesses are recorded. In New Mexico: Dutton Plateau, 2 feet; Todilto Park, 10 feet. In Arizona: Segihatsosi Canyon, 28 feet. In Utah: Piute Canyon, 100 feet; mouth of Copper Canyon, 185 feet; Twomile Canyon, 249 feet; Crescent Creek, 159 feet; Warm Springs Canyon, 220 feet; along the Waterpocket Fold, 150, 160, 214, and 220 feet; Circle Cliffs, 175 feet; San Rafael Swell, 40–180 feet.

In general the Todilto (?) tops a bench of Wingate sandstone, and from it the Navajo is stripped back for some distance, thus forming a shelf along which a feasible route extends around the buttress of Navajo sandstone and down the slopes on the limbs of monoclines. At the south end of the Waterpocket Fold access to the Colorado River is obtained down the dip slope of the Todilto (?) beds, and at the Hole in the Rock a bench of Todilto (?) forms a step in the canyon wall, thus making the crossing at this place possible. Where the beds are steeply upturned, as at the Burr trail, the Todilto (?) forms a valley.

[71] Longwell, C. R., and others, op. cit., p. 13.

NAVAJO SANDSTONE

DISTRIBUTION AND GENERAL APPEARANCE

The Navajo sandstone is remarkably well displayed in southern Utah. It appears in the San Rafael Swell, surrounds the Henry Mountains, and extends east of the Colorado River into San Juan and Grand Counties. It forms the surface of the Waterpocket Fold and the Escalante Valley and the walls of Paria, Johnston, and Kanab Canyons, and as the towering White Cliffs it extends to points beyond the Virgin River. Throughout its length Glen Canyon is rimmed with the Navajo sandstone, and complete sections are revealed in Paria Canyon, Escalante Canyon, Muley Twist Canyon, and the canyons of scores of tributaries that lead to the Colorado from the Kaiparowits Plateau.

The Navajo sandstone is everywhere a cliff maker. Unscalable walls of commanding height are common, but unlike the Kaibab, the Dakota (?), the Straight Cliffs, and the Eocene strata, which form extensive, almost horizontal terraces, plateaus, and mesa tops, the Navajo sandstone shows very uneven surfaces. The friable nature of the rock and the absence of resistant covering beds results in the production of rounded masses. The floor of the lower Escalante Basin is a maze of overlapping mounds, and erosion of the White Cliffs has produced conical towers and "nipples." The broad crest of the Waterpocket Fold is a bewildering mass of low, flat domes separated by intervening broad, shallow pits. An area of dissected Navajo sandstone is very difficult to traverse. The mounds that form the surface are smooth, and their rims end suddenly at the brink of deep, narrow canyons whose presence is little expected. "Hand holds" and "toe holds" are rare and inconveniently placed. Where they are cut in Navajo sandstone big canyons and little canyons alike have box heads and sheer walls, and many are inaccessible without special equipment. The explorer soon learns that the way by which he entered a canyon may be the only mode of exit. (See pls. 10, *C*; 19, *A*; 20, *B*; 25, *A*.)

STRATIGRAPHIC FEATURES

Sections measured at four localities and detailed examination at many others show that the Navajo sandstone north of the Colorado River differs in no essential from that south and east of the river, as previously described. It is essentially one bed of remarkably uniform texture and without features that permit the establishment of subdivisions. It consists of fine-grained massive sandstone, elaborately cross-bedded, and includes small amounts of limestone and of thin-bedded shaly sandstone that are distributed horizontally and vertically with no systematic arrangement. Longwell [72] describes the Navajo at Warm Springs Canyon as a vertical cliff of tan sandstone appearing as a single massive bed 600 feet thick; at Twomile Canyon as "massive tan sandstone 250 feet thick, capping a rounded hill"; at a point below the mouth of Crescent Wash as "tan and buff sandstone, cross-bedded on larger scale, 300 feet." For the Navajo along the San Juan Miser [73] records the following partial thicknesses, measured upward from the base: 200+ feet of cream-colored massive cross-bedded sandstone at Spencer Camp; 200+ feet of "massive, exceedingly cross-bedded fine-grained buff sandstone with a few bedding planes" at Copper Canyon; 140 feet of "buff cross-bedded massive sandstone" overlain by 4 feet of compact gray limestone at a point 12 miles above the mouth of the stream; and 310 feet of "buff massive cross-bedded sandstone" capped by 4½ feet of gray thin-bedded limestone at the mouth of the stream. At none of these places is the full thickness present. Measured sections of the Navajo within the Kaiparowits region show its typical features; at the Burr trail it consists of light-yellow to white medium-grained, very massive, highly cross-bedded sandstone 1,260 feet thick; at Bitter Creek divide, white to very light cream-colored sandstone, very massive, highly cross-bedded on a large scale, 1,400 feet thick; along Escalante Canyon, 430 to 680 feet of sandstone, everywhere cross-bedded and in most places massive, but along the Escalante monocline and at a point near the mouth of Sand Creek the upper 20 feet is somewhat unevenly bedded; at the mouth of Warm Creek, 800 feet of buff sandstone, one massive, highly cross-bedded stratum; at Meskin Bar, 900 feet of nearly white fine-grained sandstone, cross-bedded on a huge scale, all in one massive bed, except for a lens of compact limestone 1 foot thick and about 800 feet long.

STRUCTURE, TEXTURE, AND COMPOSITION

Cross-bedding in the Navajo is remarkably developed. Horizontal surfaces, slopes, and vertical walls alike are crossed and recrossed by singularly attractive designs. Series of parallel curves merge with other series of curves or are truncated by curves with the same or with different radii. The planes of some cross-bedding laminae appear as groups of straight lines or groups of curves at high angles. The prevailing design, however, is composed of curves tangent to curves; starting with arcs of small radii the laminae gradually decrease in curvature until they merge with adjoining curves as nearly horizontal planes. Many curves have uninterrupted sweeps that exceed 200 feet; commonly they extend for tens of feet; some are measured in inches and appear as delicate engravings of curvilinear pattern. In general, the laminae are etched in relief by the removal of the weakly cemented quartz grains that mark division planes. Here and there the surface is further roughened by projecting seams of quartz and by tiny faults that break the continuity of the ribbed surface. Here and there also groups of laminae are crushed or squeezed into close-set loops, and some appear to have been kneaded. Indistinct bedding planes are present, but they are very irregular and are traceable for no great distance. They are obscured by the dominant cross-bedding to a degree that gives most exposures of the Navajo the appearance of a single massive layer.

Lenses of dolomitic limestone are nearly universal constituents of the Navajo formation but are not abundant or conspicuous. Their outcrops are rarely more than 1 foot thick and a few hundred feet long. Most of them extend for less than 100 feet, and some are mere plasters 10 to 50 feet in diameter. Some of the lenses are nearly pure dolomite, so hard and so resistant to weathering that they serve as protecting caps of small mounds developed in the sandstone and form shelves on otherwise smooth surfaces. Others are mixtures of dolomite and quartz sand and at their ends merge with the surrounding rock. They lie at no one horizon, but nearly all the dolomitic lenses seen are within the topmost 100 feet of the Navajo, and for the formation as a whole they appear to increase in number upward.

The Navajo is cut by joints displayed in an interesting manner. The dominant joints are vertical, wide spaced, and arranged in two systems that trend northwest and north. In some places they are as much as 500 feet apart; elsewhere as many as 100 roughly parallel joints may be crossed in a distance of 100 to 300 feet, and zones of joints so closely packed that they resemble "shatter belts" are not uncommon. On the surface of the rock joints filled with calcite, dolomite, iron, or manganese may appear only as markings on a continuously smooth surface, but the position of many joints is shown by channels, and several gulches and narrow channels owe their position to joint zones. On canyon walls the joints and joint zones outline blocks and sheets of rock preparatory to their removal by frost and assist the cross-bedding structure in determining the shape and position of recesses, buttresses, and the open cracks that extend downward from the canyon rim.

The Navajo sandstone is essentially an aggregate of white, crystal-clear quartz grains, loosely held together by lime cement. Some hand specimens reveal no other minerals to the unaided eye, but most of them show specks of black and gray. In all thin sections that were examined grains of cloudy ortho-

[72] Longwell, C. R., and others, op. cit., p. 19.
[73] Idem, p. 17; manuscript notes.

clase, rarely plagioclase, appear in amounts ranging from 1 to 6 per cent, and a few fragments of magnetite, garnet, zircon, tourmaline, biotite, or muscovite are also present. In a few petrographic slides all these accessory minerals are present, and a thin section of rock from Paria Canyon includes little black knots of biotite and magnetite. Three sizes of grains make up each cross-bedded lamina surface. Grains scattered about or arranged as sheets coating foliation surfaces, averaging about 0.70 millimeter in diameter, constitute 3 to 5 per cent of the rock; grains ranging from 0.10 to 0.25 millimeter make up about 70 per cent; and the remaining 25 per cent consists of bits of dust.

In general the smallest grains and those of intermediate size are thoroughly intermingled and form a base over which the largest grains are strewn, but in some places portions of the rock exhibit almost perfect sorting and permit the recognition of four to five short, thin layers that are characterized by size of grain. Here and there are small pebbles of quartz, fragments of shale, of sandstone, or of limestone, and nodules and concretions of iron oxides that exceed in diameter the common sizes, but they constitute much less than 1 per cent of the rock. As a whole, the texture of the Navajo is remarkably uniform. Most of the grains are imperfectly rounded, but nearly all thin sections show round grains, and in some thin sections spherical grains predominate. Etched grains are not uncommon, and in one specimen from Paria Canyon nearly all the larger grains show pits and tiny facets.

The cement of the Navajo sandstone consists of lime and dolomite with varying amounts of iron oxides. The iron is most abundant in the finest-grained layers; from some beds it is nearly absent, and in places even the calcite cement has disappeared, leaving only a pile of separate grains of pure quartz. In general the cement is weak. Even where iron oxide forms the bond it is not easy to obtain a well-trimmed hand specimen, and much of the rock exposed at the surface is so friable that it crushes under the foot, and a single blow of the hammer may reduce a block of sandstone to a mass of dust. Blasting this rock with powder presents special difficulties.

The varying amounts and kinds of cement are reflected in the color. In general, the white parts of the Navajo sandstone have only calcite cement; the yellow, buff, tan, and red tones indicate the amount and chemical state of the iron. It is assumed that the sandstone was originally white and cemented with white calcite and that lime was progressively but irregularly replaced by iron.

To tangential cross-bedding, joints, weak cement, and uniformity of grain are largely due the erosion features that are characteristic of the Navajo. The rock has a tendency to split parallel to cross-bedding laminae and in less degree parallel to joint surfaces. The usual erosion fragment is a slab with curved faces. Thin slices whose length and breadth are measured in tens of feet peel off from the cliffs and canyon walls like bark from a tree. Along the canyons are commonly formed alcoves, amphitheaters, and overhanging cliffs. Gashes with crescent or semicircular outline—some of them mere "toe holes," others large enough to accommodate the buildings of cliff dwellers—appear in most walls, and few surfaces are free from pits, "wells," "water pockets," and short-curved channels. Many bridge arches and a few complete bridges add to the interest of Navajo topography. (See p. 144.) Much of the rock merely disintegrates in place or is crushed to sand as it drops to the base of a cliff. Continuously smooth surfaces are common, and talus deposits at the base of Navajo walls are conspicuously small.

COLOR

The prevailing colors of the Navajo of southern Utah are cream, tan, and buff. In general, the exposures west of Glen Canyon and the Waterpocket Fold show lighter tones than those about the Henry Mountains and southeast of the Colorado River. Some outcrops west of the Paria are appropriately called the White Cliffs, but light-red and yellow-red tints are also in evidence. No one color can be called characteristic. White streaks are common, and two or more colors appear in every extensive exposure. Over an area of about 3 square miles near Harris Wash, in the Escalante Valley, the color of the sandstone is distributed in frayed patches of light red, dark red, yellow, and white, a few hundred feet long and some tens of feet wide. At the south end of the Waterpocket Fold the nearly white Navajo is traversed by bands and patches of red that are distributed along and across the laminae. (See pl. 4, *D*.) At the Burr trail the Navajo is gray-white; on Sand Wash and Cottonwood Canyons, tributary to the Paria, the rock is light yellow, with dark-red streaks and blotches near the top.

An interesting color change was observed in Paria Canyon. Near the mouth of Sheep Creek the vertical walls of the canyon are cream-white above and dark red below, and the sharply drawn division line runs horizontally without regard to texture, stratification, or cross-bedding, as if a red basal border about 20 feet high had been painted with a brush on a white wall. This line marks the top of the alluvium, which at one time covered the canyon floor. Within the rock that was deeply buried by the fill the conditions for accumulating and retaining the iron pigment were more favorable than within the rock that was exposed to the atmosphere.

A study of the Navajo over wide areas in Arizona and Utah shows that its color has no stratigraphic significance. Neither vertically nor horizontally is the distribution of color causally related to texture, structure, or age. For reconnaissance reports such expressions as White Cliffs and Vermilion Cliffs are useful, but such terms as "Kanab sandstone" and "Colob sandstone," based on color and indicating time relations, have little in their favor.[74] Color is an entertaining guide in a superficial study of Jurassic strata but unreliable in determining chronology. Its chief value lies in the evidence that it affords of conditions of deposition and later physiographic history.

In so far as colors are significant they call for more precise definition than present usage provides. In most sections of the Navajo the color of the rock as a whole differs from the color of some highly tinted parts, and weathered parts differ from unweathered parts. The rock that is wet from rains or that is viewed under overcast skies differs in tone from dry rock that is seen in bright sunlight. Furthermore, the color assigned to the same exposure differs with each observer. It is interesting to compare the terms used by different field workers to express the color of the Navajo. In describing sections along the San Juan River Miser speaks of the Navajo as "cream-colored to yellow," "gray," and "buff," in place of Gregory's expressions, "light yellow," and "nearly white." For the Henry Mountain region Longwell described the Navajo as "tan" and "tan and buff" in rocks that are recorded by Gregory as "light red" and "yellow-red." For the Waterpocket Fold and the Escalante region the terms used by Moore closely parallel those used by Gregory, except that Moore sees different shades of yellow in certain rocks which Gregory describes as light red.

It may be significant that in all the descriptions Miser, Longwell, Moore, Bryan, and Gregory use a different expression for the color of the Wingate and of the Navajo where those formations occur in the same section, and that the Todilto (?) is everywhere described as of a color different from either the Wingate or the Navajo.

GLEN CANYON GROUP OF PARIA VALLEY AND WESTWARD

West of Lees Ferry and the Paria Valley the Glen Canyon group in whole and in part is prominently displayed. Along a line 200 miles long the characteristic features of the Navajo and perhaps of the Wingate are well represented, but the Todilto (?) has not been recognized and in places is probably absent. The dark-reddish fine-grained sandstones in the Vermilion Cliffs appear to correspond in lithologic, stratigraphic, and topographic character to the Wingate, but the strata are more thinly bedded than typical Wingate. In Zion Canyon the lower part of the Glen Canyon unit exhibits peculiarities of jointing and weathering that are characteristic of the Wingate but is not clearly separated from superjacent sandstone that very closely resembles the Navajo. This condition has led to the practice of describing the massive Jurassic sandstones west of the Paria as La Plata or as undifferentiated Navajo and Wingate. Bryan [75] classes "1,100 to 1,200 feet of massive tangentially cross-bedded red to buff sandstone" at Lees Ferry as Navajo and Wingate. Reeside and Bassler [76] speak of the Jurassic rock that constitutes Steamboat Mountain as

> massive cross-bedded sandstone that is locally all red but in most places red in lower part and white above * * * [having] a total thickness of 2,100 feet, mostly in sheer wall. There appears here to be no break of any kind in the sandstone wall; not even a single soft layer is observable.

In the Santa Clara Valley "the cross-bedding of the upper white part is a striking feature and resembles that of the Navajo sandstone farther east."

The Wingate and Navajo sandstones have distinctive features, but they also have many features in common. As compared with the Wingate, the Navajo is more generally cross-bedded, its constituent grains are less uniform in size and somewhat less firmly cemented, it is more calcareous, it includes lenses of limestone, and it is lighter colored. But in all these respects variations within the Wingate and within the Navajo are considerable; each feature of the Wingate probably is duplicated at some place in the Navajo; and hand specimens of the two sandstones might be selected in such a manner as to make impossible the determination of their source. Further difficulties are, first, the presence at the top of the Chinle of bedded sandstones similar to the Wingate in texture and composition—a condition which has led to different interpretations regarding the upper and lower limits of the Wingate; second, the expression of the Wingate in places as a series of strata instead of one massive bed; third, the great variation in Todilto (?) from limestone and calcareous shale to shale and thin sandstone, not uncommonly cross-bedded; fourth, the apparently uninterrupted deposition in places of all strata from the top of the Chinle to the base of the Carmel formation.

On the basis of present field knowledge the division plane between the Wingate and the Navajo can not be drawn with assurance where the Todilto (?), or an unconformity representing it, is absent.

The difficulty of distinguishing the Wingate from the Navajo is illustrated by the arrangement and

[74] 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.

[75] Bryan, Kirk, in Longwell, C. R., and others, op. cit., p. 16.

[76] Reeside, J. B., jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, p. 63, 1922.

composition of the strata in the Paria Canyon, where sandstones that occupy the stratigraphic position of Wingate, Todilto (?), and Navajo form the canyon wall between the mouths of Deer Creek and Kitchen Creek, tributaries to the Paria. Throughout this 10-mile stretch of canyon three roughly defined subdivisions are present:

1. Upon typical Chinle shales lies a series of red sandstone strata very irregular in thickness and extent, and the thickest and most continuous sandstone beds immediately overlie the Chinle. In places the series consist of one massive bed that forms a sheer wall 100 to 200 feet high; more commonly the sandstone beds are 10 to 30 feet thick and are separated by discontinuous very dark red shalelike lenses, the surfaces of which are conspicuously marked by sun cracks, worm trails, and ripples. The length of the longest lens noted is about 200 feet. Some of them are little more than short, thick piles of fragments of shale; others are mere films of sun-dried mud. The lenses occupy no definite horizon; their vertical and horizontal distribution appears haphazard.

2. Above the rudely bedded sandstone is a zone 20 to 40 feet thick, within which the sandstone beds are usually thin and, as in No. 1, are separated or replaced along the strike by lenses of very dark red sandy shale and conglomeratic masses 1 inch to 5 feet thick and 5 to 100 feet long composed of lumps of sandstone and shale. The cement is highly calcareous, and many of the shalelike fragments are essentially impure limestone. This zone, with little variation in position and character, was noted at four localities separated by several miles.

3. The top several hundred feet of the canyon wall is essentially one massive bed of white or buff-white sandstone intricately cross-bedded throughout. This is the "Gray Cliff sandstone" of Dutton, so prominently displayed between the Paria River and Kanab Creek.

In this series subdivision No. 1 differs from subdivision No. 3 in that its color is red, its grains are finer, its cross-bedding is much less developed, its joint systems are more complex, and its stratification is entirely different.

In the field notebooks No. 1 was designated Wingate, No. 3 Navajo, and No. 2 the equivalent of the Todilto, with recognition of the fact that as a whole it differs little from lenses in No. 1 and that if Todilto is present at all it may include parts of No. 1 or possibly all of it except the thick cross-bedded strata immediately above the Chinle. It was also recognized that No. 1 and No. 2 combined may be a modified form of the Wingate.

Near the mouth of the Paria the threefold division of the Glen Canyon group (Navajo, Todilto (?), Wingate) is not evident. Here and for a few miles upstream the walls of Glen Canyon are built essentially of tangentially cross-bedded sandstone, without the visible parting that on eroded cliffs usually marks the Todilto (?). The upper half is, however, much more calcareous and includes at intervals many lenses of dense gray limestone, 1 inch to 4 feet thick, each traceable along the cliff faces for distances of a few feet to more than 600 feet. Along Vermilion Cliff between the mouth of the Paria and Jacobs Pools the upper half of the Glen Canyon group, above scattered lenses of limestone, is distinctly lighter red than the lower half.

At Lees Ferry the Chinle is unconformably overlain by about 80 feet of orange-red to buff minutely cross-bedded sandstone in beds 5 to 30 feet thick; one of these beds, 26 feet thick, which is remarkably persistent and massive, extends up the Colorado into the Paria Plateau and along the Echo Cliffs and retains throughout the texture and structure characteristic of the Wingate. Above these heavy-bedded sandstones lies a series of sandy shalelike beds 6 inches to 6 feet thick. Within the layers of shale are calcareous lenses of flattened clay pellets and lime shale and fine-grained conglomerate that contains dinosaur bones. The upper two-thirds of the canyon wall is composed of light-red cross-bedded sandstone, which begins with beds 10 to 40 feet thick and continues upward as a bed 800 feet thick, massive except for the presence of thin lenses of blue-gray limestone. When this section was measured in 1915 Gregory hesitated to assign any part of it to the Todilto, in view of the facts that within short distances along the strike the alternating shale and thin sandstone become thick beds, the calcareous lenses lie at no particular horizon, and local unconformities are many. This doubt still remains, for Bryan[77] has published a section that shows 1,100 to 1,200 feet of sandstone with no visible partings and with the comment that "the Todilto (?) formation is apparently absent." Furthermore, Bryan includes in the upper part of the Chinle an unrecorded amount of "heavy-bedded sandstone and red shale," thus giving the Chinle a thickness much greater than any known elsewhere in this region. Recent study of this section by Moore leads to the conclusion that sandstone beds at Lees Ferry and westward along the Vermilion Cliffs have Wingate affinity and have been inappropriately included in the Chinle by several authors. A short distance west of Johnson Canyon he noted an unconformity at the base of the red sandstone.

Brief examinations of many outcrops of Mesozoic formations in northwestern Arizona, southern Utah, and Nevada, combined with detailed study of some of them, leaves no doubt that the major part of the enormous white and red Jurassic (?) cliffs, which extend with few interruptions from the Paria to Santa

[77] Longwell, C. R., and others, op. cit., p. 16.

Clara and reappear in the Muddy Mountains and Spring Mountains of Nevada, is composed of Navajo sandstone. To what extent the Todilto (?) and Wingate are represented remains to be determined. Certainly these formations, where they are preserved west of the Paria, lack the clear expression familiar to workers in regions farther east, but there is evidence to show that the Wingate in less massive form is traceable from Lees Ferry at least to Kanab, and that the change in conditions of sedimentation represented by Todilto (?) may be demonstrated at several places.

In Johnson Canyon, Utah, beds that are tentatively assigned to the Wingate include thin beds in addition to one red, massive, intricately cross-bedded, fine-grained bed more than 200 feet thick, and the Todilto (?) may be represented by 120 feet of thin calcareous sandstone, including thin sheets of resistant limestone, for the most part slabby and irregular. Erosion has stripped back the Navajo sandstone from the top of these beds and left a terrace more than a mile wide, above which rise the impressive White Cliffs. In the Kanab Valley the Chinle cliffs are capped by regularly bedded thin sandstone that leads up to heavy beds of massive sandstone. About 240 feet above the Chinle the sandstone is interrupted by a zone of sandy limestone and chert, which may represent the Todilto (?). It seems not improbable that by taking careful note of the features that distinguish the Wingate and the Navajo, and keeping in mind the wide variation in aspect of the Todilto (?), the Wingate may be traced from the Paria to localities beyond the Virgin River and the Todilto (?) to the Kanab Valley.

SAN RAFAEL GROUP (JURASSIC)

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The San Rafael group is well displayed in the Kaiparowits region. On the Paria River a few miles below old Paria village and north of the White Cliffs it is very widely exposed. At Cannonville it forms the beautifully banded walls which give that village its picturesque setting. The Dry, Round, and Butler Valleys are rimmed about with San Rafael sandstones, and the mounds, mesas, and "chimneys" that rise from their floors are remnants of widely spread friable sandstone, gypsum, and shale. (See pls. 11, *B*; 22, *B*.) Along lower Glen Canyon the San Rafael is trenched by Wahweap, Warm, Kane Springs, Last Chance, and Rock Creeks, which outline the brilliantly colored lower wall of the Kaiparowits Plateau as a crenulated line of cliffs whose carved edges meet abruptly the wavy red surface at their base. On both sides of the Colorado River the mesas and towers of San Rafael beds, capped by Morrison and Dakota (?), rise high above the wide platform of wind-swept Navajo sandstone. (See pls. 10, *A*, *C*; 22, *A*.) At the southeast end of the Kaiparowits Plateau the San Rafael beds stand high on the cliffs, a mass of color bands that are broken by scores of canyons.

In the Escalante Valley the San Rafael group forms an uneven floor from Willow Creek to Pine Creek, where erosion of the upper beds of the group, which are involved in the Escalante monocline, has produced the colored mounds, benches, and ridges that give the village of Escalante its attractive setting. The Straight Cliffs, the northeast front of the Kaiparowits Plateau, show San Rafael beds at their base. Beginning at Alvey Wash with a few feet of the upper strata, the thickness gradually increases until at Fifty-mile Point the whole group is exposed in a terrace that is capped by Morrison and Dakota (?) and underlain by Navajo sandstone. From Escalante the group can be traced along the base of the Aquarius Plateau but gradually thins until north of the Circle Cliffs it is cut out by the Cretaceous-Tertiary erosion surface. (See p. 116.) On the east side of the Waterpocket Fold the full thickness of the San Rafael group is exposed at the Bitter Creek divide. South of this point, where its upturned strata form the bed of Hall Creek, the San Rafael is partly concealed, except on the mesas that stand back from the Waterpocket Fold. (See pl. 19, *A*.)

In all these areas the usual topographic expression consists of brightly colored cliffs that are banded on a huge scale. A sloping base that is formed by the Carmel, which rests on the Navajo sandstone, is succeeded upward by the massive, thick cross-bedded Entrada sandstone and by steep slopes of color-banded rocks (Summerville) leading to green-white Morrison, which is overlain by a resistant Dakota (?) cap. As a unit in the succession of great terraces that express the Mesozoic rocks of the Kaiparowits region, the San Rafael beds are not an outstanding feature. The great cliffs of which they form a part owe their persistence to the Dakota (?) sandstone, which protects the friable beds beneath.

The thickness of the San Rafael group differs regionally and locally to a considerable degree. In the Paria Valley thicknesses of 640, 700, 380, 410, and 615 feet were measured; along Glen Canyon, 420, 860, 800, and 725 feet; in the Escalante Valley, 336, 470, 164, 600, and 380 feet; east of the Waterpocket Fold, 910, 1,260, and 1,610 feet. These differences in thickness are explained in part by the unequal development of the formations of the San Rafael group, in part by the different amounts removed by pre-Morrison erosion, and also in part by the difficulty in some localities of determining the base of the Morrison.

Striking small-scale erosion forms are characteristic of the San Rafael. The great irregularity of bedding, the different amounts and kinds of cement, and the capricious distribution of color favor the production of mounds, tables, balls, and mushrooms, tilted at various angles and decorated with color stripes of various widths and tones. Especially in the thin-bedded sandstones erosion has left spools, spindles, and "stone babies" of fantastic shapes, some of which have smooth surfaces and others ribs and boxlike shelves. With changing lights they assume the appearance of birds and animals and the legendary beings of Piute mythology. Although these figures are commonly but a few inches or at most a few feet high, the absence of surrounding débris makes them conspicuous and gives the effect of grotesquely carved surfaces hundreds of square feet in area.

GENERAL STRATIGRAPHIC AND LITHOLOGIC FEATURES

When traced along the strike, the beds that constitute the San Rafael group reveal many changes in thickness, texture, and aggregate composition. Notebook sketches of these beds show cliffs and slopes differently related to each other and at different altitudes above the Navajo. In the section at Cannonville thick massive cliff-making beds occur in the middle and near the bottom. In the corresponding section on Cottonwood Creek the first cliff maker is near the top. In some places very soft sandstone and shalelike beds constitute as much as 75 per cent of a section, but elsewhere the horizon above the Carmel formation is occupied in a large part by thick fairly hard massive beds. Single beds of sandstone split up along the strike, and their top or bottom or middle is replaced by shale; also the continuity of a series of beds of shale may be interrupted by huge lenses of sandstone. Within a distance of 40 feet a bed measured near Cannonville breaks up into six beds separated by lumpy shale. In a broad sense the San Rafael is composed essentially of sandstone in massive beds and shalelike beds and contains subordinate amounts of gypsum and limestone, but in detail two exposures that lie less than 10 miles apart may be sufficiently unlike to justify different subdivisions and descriptions. Gypsum occurs at several horizons. It ranges in amount from disseminated grains to beds that exceed 50 feet in thickness and are continuous for several miles. Limestone is inconspicuous at the exposures studied in the Kaiparowits region, but calcareous layers constitute perhaps one-sixth of the beds.

Cross-bedding is characteristic of all the sandstones of the San Rafael group. In the thicker beds it is displayed as a beautiful tracery of curves, raised in relief by weathering, and closely resembles that of the Navajo sandstone. In the thinner beds it appears as curves and as truncated series of short parallel lines abruptly terminated by other lines at different degrees of inclination. Commonly the cross-bedding laminae are separated by a film of scattered grains of larger size than those in the body of the rock.

The dominant color of the San Rafael group and of its parts differs from place to place. In the Glen Canyon district prominent bands of dark red are interstratified with white, and in the upper valley of the Paria the prevailing tone of the sandstones is bright yellow-red. In a few places the group loses its attractive features and becomes in general dull gray. The color of the San Rafael sandstones—massive beds and shaly beds alike—varies directly with the amount and character of the cementing material. Rocks from which cement is practically absent are white, as are also the crumbling surfaces and the dunes that have immediately resulted from the removal of unconsolidated material. The grains that compose the white rocks, the dunes, and also the hand specimens after the cement has been eliminated are composed of clear quartz, associated with some white feldspar, very small amounts of biotite, and rare magnetite. Where present, the cement of the white and green-white rocks is calcite, or calcite and ferrous iron, or calcite and gypsum, or calcite, ferrous iron, and gypsum; the grains of rocks that show dominant yellow tones are held together by calcite and limonite, and the distinctly red rocks have for cement calcite and ferric iron. The deeply colored red rocks are those that have the finest grains. In some of them the iron between and around the quartz grains equals in amount the grains themselves.

The patches and streaks and large continuous areas of color are distributed without reference to any known controlling factor. In general, it appears that uniformly yellow or light-red tones characterize large rock masses of uniform texture, and that discontinuous areas of dark red, green, and white characterize masses of varying texture. Also in general, white bands associated with yellow and light red are most common at or near foliation surfaces and along cross-bedding laminae. But there are many exceptions. Disks of white stand out conspicuously on an otherwise red wall, and frayed ribbons and streamers of white cross and recross cliff faces, seemingly regardless of structure or texture, as if white paint had been capriciously applied by human hands.

Observation seems to warrant the suggestion that the white quartz sand of the San Rafael sandstones was converted into rock by the infiltration of calcite and that the calcite cement was progressively replaced by iron. On this assumption part of the white rock remains as originally formed and part doubtless owes its whiteness to the bleaching of all or part of the cementing material. That the cement from the interior of the rock is in process of removal to the surface is indicated by "casehardening." The surface of many outcrops, especially of massive beds, consists of a shell of tightly cemented material, back of which the rock is merely an aggregation of loose sand grains. Waters from the few small springs that issue from the red and yellow rocks and the rainwash over their surfaces have very little calcium sulphate but hold greater amounts of calcium carbonate and iron oxides than the waters from the white rocks or even from the brown rocks of the overlying Cretaceous. The efflorescence about some seeps has a reddish tone.

An unconformity appears to exist locally at the base of the San Rafael, and there is a widespread erosional break at its top; in some places an unconformity may be demonstrated in beds that immediately overlie the lowest thick cross-bedded sandstone (Entrada). But in many places those relations are by no means clear, and correlations between measured sections are made more difficult by the presence of many local unconformities that perhaps have regional significance. Certainly some of them have only local meaning, for it is unreasonable to assume that such unlike beds as make up the San Rafael have resulted from uniform conditions of deposition.

AGE AND CORRELATION

The series of beds that overlies the Navajo sandstone and is terminated upward by the Dakota(?) sandstone presents problems in correlation and in determination of the conditions of deposition that so far have not been solved. In the plateau country these beds extend from the Zuni Mountains of New Mexico northward across the Navajo Reservation into western Colorado and eastern Utah and northwestward through southern Arizona and Utah to points beyong the Virgin River. Throughout this vast area the series has some features in common, but these features are not continuously displayed and do not all occupy the same stratigraphic positions. The attempts to correlate these diverse beds chiefly on the basis of lithologic studies at widely separated localities, on the border of an area exceeding 100,000 square miles, has naturally led to unsatisfactory results. In the Henry Mountains Gilbert [78] assigned to the "Flaming Gorge group" all beds between the White Cliff (Navajo) sandstone and the Cretaceous, and in the Paria Valley Howell [79] included equivalent beds in a measured section that is difficult to interpret. Of the beds in the Escalante Basin Dutton [80] remarks:

> Around the network of canyons tributary to the Escalante, the Trias and Jura were utterly inaccessible, and the location of the separating horizons was inferred from the color of the beds and the arrangement of the rocky ledges viewed from a distance.

Most geologists working in Colorado, Arizona, and Utah have found it advantageous to base correlations on the well-defined lithologic units established by Cross,[81] who chose the term "McElmo formation" for beds that "correspond closely to the Morrison and Como beds and the Flaming Gorge group of Powell" and concluded that "it is probable that the marine Jurassic horizon belongs between the La Plata and the McElmo formations." Lupton [82] followed Cross in treating the strata between the La Plata sandstone and the Dakota as a single formation, the "McElmo," but outlined "members" that have widely divergent features and history and made the significant remark: "It is possible that the bed containing this [marine Jurassic] fauna is older than the basal beds of the typical McElmo." Dake [83] subdivided the "McElmo formation" into "upper McElmo, Salt Wash member, and lower McElmo" (fossiliferous zone with Sundance fauna). The terminology of Cross was adopted by Gregory in mapping the Navajo country, but satisfactory correlation of the beds that overlie the Navajo with the "McElmo" at its type locality increased in difficulty as the series was traced northwestward. On the Moenkopi Plateau the presence of limestone and much calcareous shale between typical "McElmo" sandstone and Navajo sandstone and the unfamiliar expression of the Navajo itself made it seem desirable to describe the beds occupying the general horizon of the marine Jurassic as "undifferentiated Navajo and McElmo."

A study of the equivalent strata north of Glen Canyon showed that although beds that resemble the "McElmo" sandstone and shale of McElmo Creek are present, beds quite different in composition and origin and probably in age occupy the stratigraphic position of the "McElmo" and led to the belief that a continuation of the previous correlation is likely to serve no useful purpose. A new classification was therefore adopted for the series of beds in southern Utah between the top of the Navajo sandstone and the lowermost stratum assigned to the Dakota (?) sandstone. In this tentative classification three formations with local names were assigned to a lower group, determined as of Upper Jurassic age, and the remaining strata were recognized as the equivalent of the "McElmo" or Morrison, of Jurassic or Lower Cretaceous age. While the present report was being prepared, studies by Gilluly and Reeside showed that Jurassic formations corresponding in general with those in the Kaiparowits region are represented in the San Rafael Swell. To avoid duplication of formation names stratigraphic terms applicable to both regions were selected. Beginning at the top of the Navajo these formations are the Carmel, Entrada, Cur-

[78] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 6, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

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

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

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

[82] Lupton, C. T., Geology and coal resources of Castle Valley, Utah: U. S. Geol. Survey Bull. 628, pp. 23–26, 1916.

[83] Dake, C. L., Horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, p. 641, 1919.

tis, and Summerville formations, which constitute the San Rafael group. Above them lies the Morrison formation, which is tentatively considered Lower Cretaceous. The Curtis formation is essentially restricted to the country north of the Fremont River. These relations are shown in Plate 5.

CARMEL FORMATION

HISTORICAL SKETCH

Powell[84] noted the presence of "limestone containing Jurassic fossils" as a capping of the gray cliffs next above the Vermilion Cliffs, and Gilbert[85] says:

> Upon both forks of the Virgin River and upon Kanab Creek I found Jurassic forms (including *Camptonectes bellistriatus* and *Pentacrinus asteriscus*) in a cream-colored arenaceous limestone, and they appeared to be restricted to a brief vertical range.

Section near Rockville, Utah[86]

		Feet
Shales with coal.		
Gypsiferous shales:		
Red clay shale	100	
White clay shale with bands of gypsum	50	
		150
Cream-colored sectile fossiliferous calcareous and arenaceous beds:		
Bedded limestone (*Camptonectes, Inoceramus*)	30	
Calcareous shale with some fossils	60	
Calcareous sectile sandstone; sandstone shaly toward the base (*Pinna*)	60	
		150
Soft red shale		50
Massive cross-bedded sandstone.		

Howell's "section from Last Bluff [Table Cliff] south-southwest 36 miles"[87] lists 500 feet of beds as Jurassic:

Section from Table Cliff south-southwestward, Utah

	Feet
Pale-red massive cross-bedded sandstone	125
Variegated gypsiferous shales, with green and slate colors at the top	175
Pale-yellow cross-bedded calcareous sandstone	75
Red, yellow, purple, and gray marly shales and sandstones	125

Howell[88] recognized equivalent strata on Dirty Devil (Fremont) River, 780 feet thick; "on the southwest side of Escalante River," 980 to 1,180 feet thick; at Pine Mountain, 1,200 feet.

> Eastward it thins out rapidly, until in eastern Arizona and in New Mexico it probably disappears entirely. Beds evidently belonging to this series were seen near the Moenkopi, but no definite idea of their thickness could be obtained.

Dutton[89] speaks of the Jurassic as

> a series of bright-red fossiliferous shales * * * beds which vary much in quality, some being calcareous, some gypsiferous, and others thinly bedded sandstone; * * * the calcareous layers abound in typical Jurassic fossils.

In the Kanab Valley they comprise 500 feet of "calcareous shales, limestones, and gypsiferous shales."

Walcott[90] records 960 feet of beds between White Cliff sandstone and demonstrably Cretaceous beds. In "cream-colored magnesian limestone and sandy shale," 115 feet above the base, *Myalina* sp.?, *Camptonectes bellistriatus*, *C. extenuatus?*, *C. stygius*, *Pecten* n. sp., *Myophoria ambilineata*, *Astarte?* sp.?, *Trigonia?* sp.?, *Ostrea strigilecula*, and *Solarium?* sp. were collected.

Near Glendale, Utah, Stanton[91] found 1 to 8 feet of red shale, 292 feet of fossiliferous limestone and shale, 135 feet of soft red sandy shales, and 15 to 30 feet of gypsum in turn above the Navajo.

In sections measured on the Colob Plateau Lee[92] includes 40 feet of red shale and gypsum and 250 feet of brown earthy limestone overlying massive Jurassic sandstone, and Richardson[93] records 800 feet of varicolored shale, sandstone, gypsum, and marine limestone below beds referred by him to the Colorado group.

Fossiliferous and gypsiferous marine beds on the east flank of the San Rafael Swell were noted by Gilbert,[94] who placed them at the base of his "Flaming Gorge group"; by Lupton,[95] who classed them as basal "McElmo"; and by Emery,[96] who considered them equivalent to the Todilto of the Navajo country. Near Loa, in the Fremont Valley, Dake[97] measured 859 feet of shale, sandstone, limestone, and gypsum above white cross-bedded Navajo sandstone. From equivalent beds a few miles distant *Pentacrinus whitei* Clark, *Camptonectes platessiformis* White, and *Trigonia quadrangularis* were collected. From limestone 22 feet above the Navajo sandstone in Capitol Reef Wash fossils collected by Gregory in 1918 were identified by Stanton as *Ostrea strigilecula* White, *Cardinia* n. sp., *Camptonectes stygius* White, and *Trapezium?* sp.

[84] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, p. 190, 1875.

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

[86] Idem, p. 159.

[87] Howell, E. E., op. cit., p. 271.

[88] Idem, pp. 281, 247.

[89] Dutton, C. E., Report on the geology of the High Plateaus of Utah, p. 151, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880; Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 35, 1882.

[90] Walcott, C. D., Section measured in Kanab Valley in 1879, in Cross, Whitman, and Howe, Ernest, Red beds of southwestern Colorado and their correlation: Geol. Soc. America Bull., vol. 16, pp. 484–485, 1905.

[91] Stanton, T. W., unpublished notes.

[92] Lee, W. T., The Iron County coal field, Utah: U. S. Geol. Survey Bull. 316, p. 362, 1907.

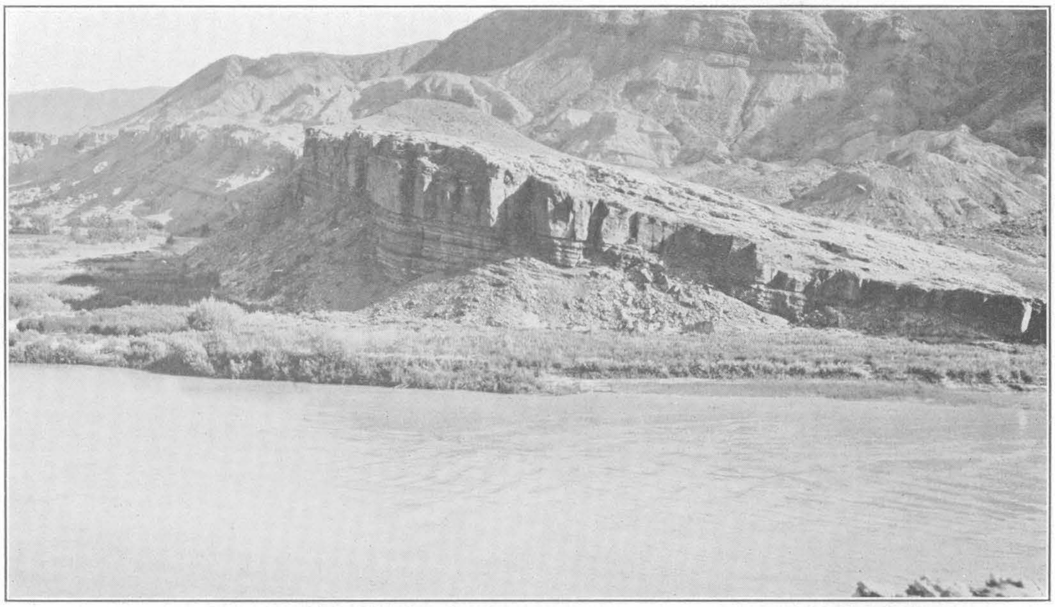
[93] Richardson, G. B., The Harmony, Colob, and Kanab coal fields, southern Utah: U. S. Geol. Survey Bull. 341, p. 381, 1908.

[94] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 6, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[95] Lupton, C. T., Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah: U. S. Geol. Survey Bull. 628, p. 24, 1916.

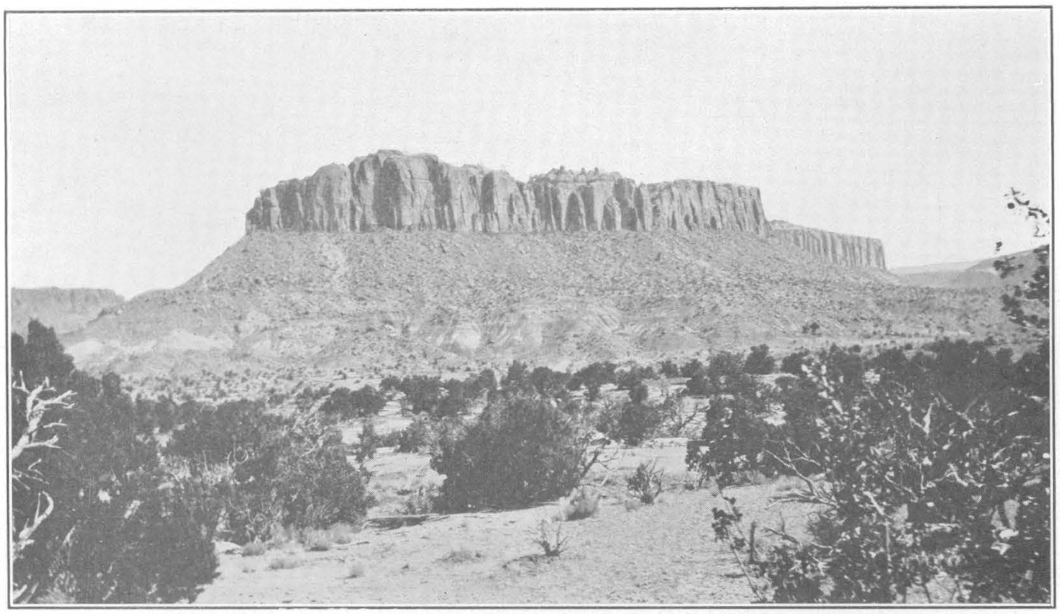
[96] Emery, W. B., The Green River Desert section: Am. Jour. Sci., 4th ser., vol. 46, pp. 551–557, 1918.

[97] Dake, C. L., The horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, p. 636, 1919.



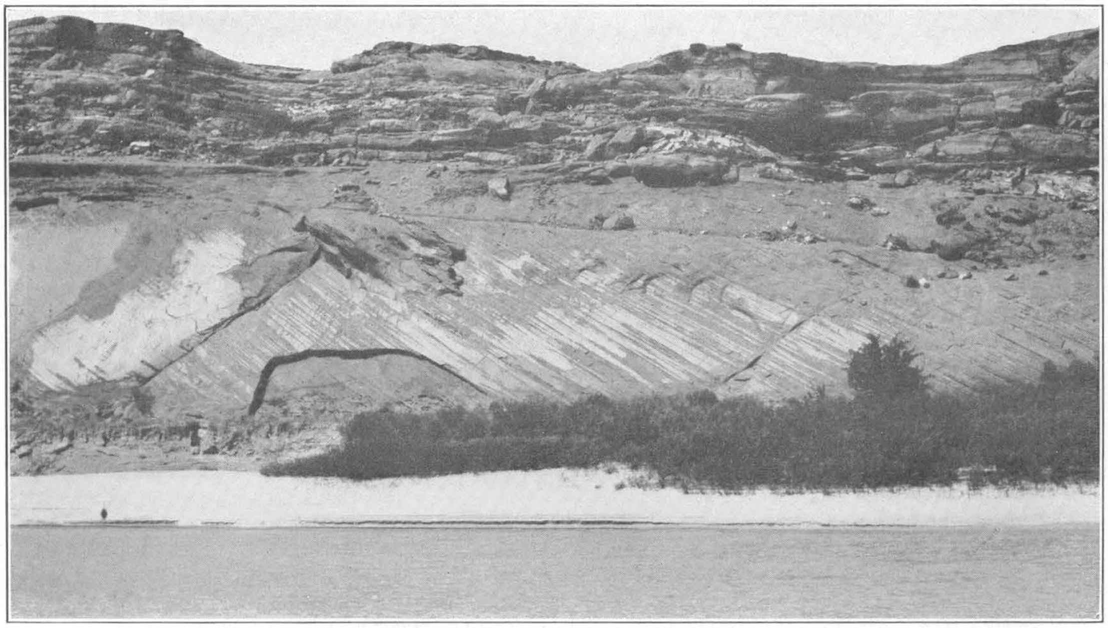
A. VIEW LOOKING NORTH ACROSS COLORADO RIVER NEAR LEES FERRY

Tilted bench is made by massive Shinarump conglomerate. Banded Moenkopi strata unconformably underlie the Shinarump. Chinle formation in background.



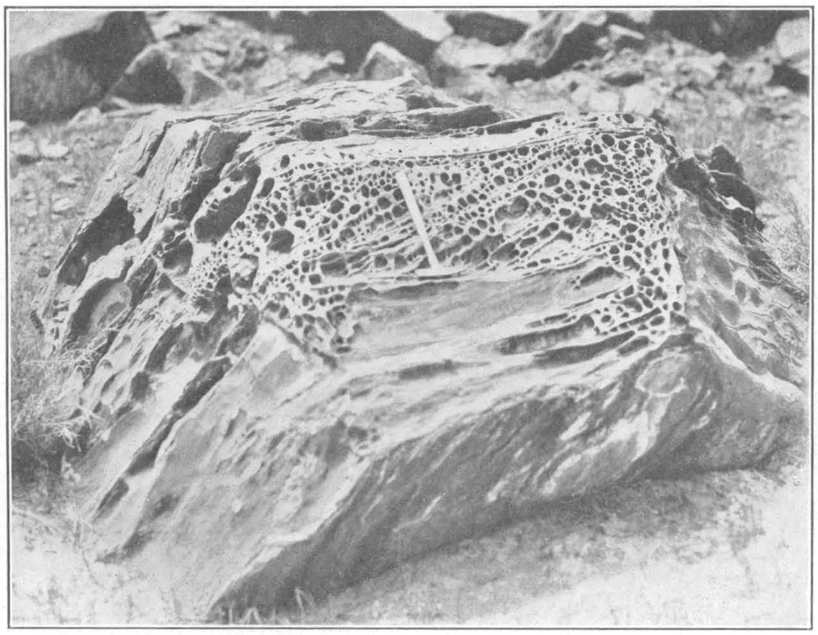
B. BUTTE OF CHINLE SHALE CAPPED BY JOINTED WINGATE SANDSTONE IN SOUTHWESTERN PART OF CIRCLE CLIFFS

Note effect of joints on weathering of the sandstone. The slope is formed by Chinle strata, and the flat in foreground by the Shinarump conglomerate.

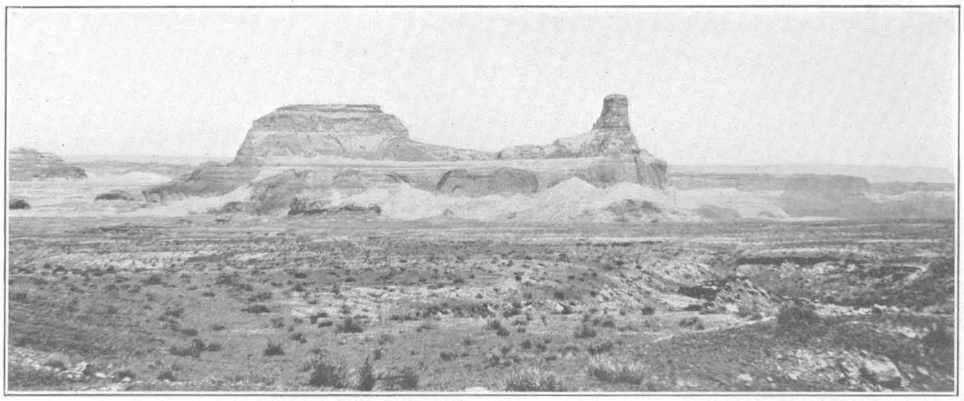


A. WALL OF COLORADO RIVER 8 MILES ABOVE MOUTH OF THE ESCALANTE

Wingate sandstone overlain by Todilto (?) formation. The cross-bedding in the Wingate is not commonly so clearly shown.

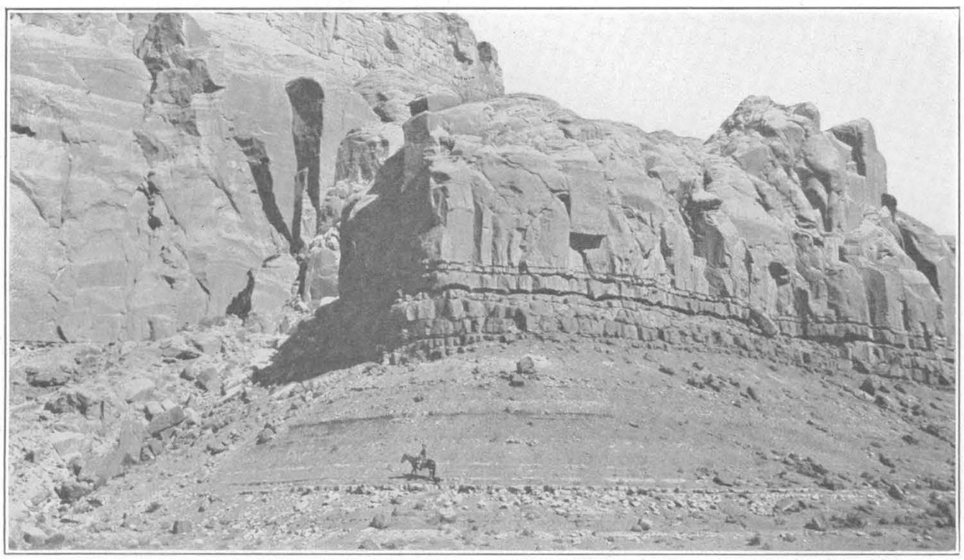


B. HONEYCOMB WEATHERING IN BLOCK OF WINGATE SANDSTONE, SILVER FALLS CANYON



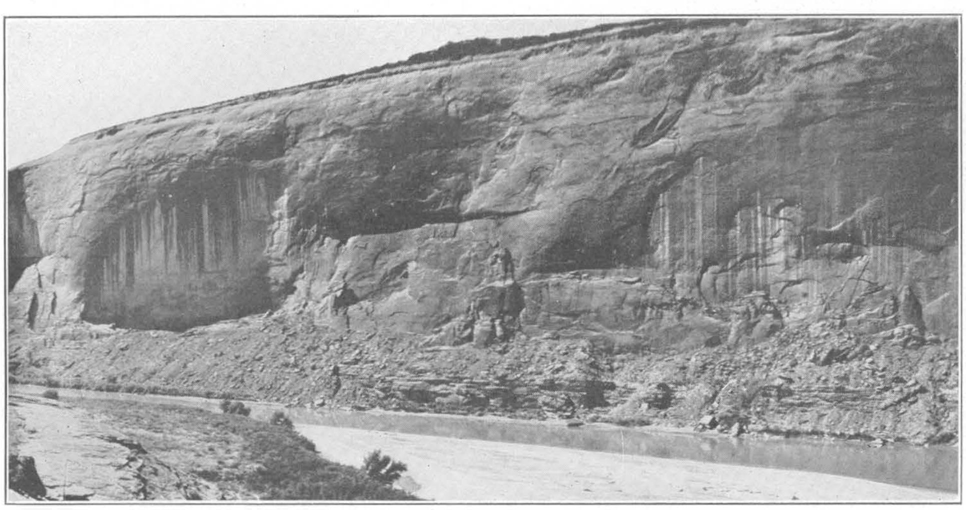
A. GLEN CANYON WEST OF KANE CREEK

Gunsight Butte, shown in the view, is composed of the Morrison, Summerville (?), and Entrada formations on a wide bench of the Carmel formation, which extends to the foreground.



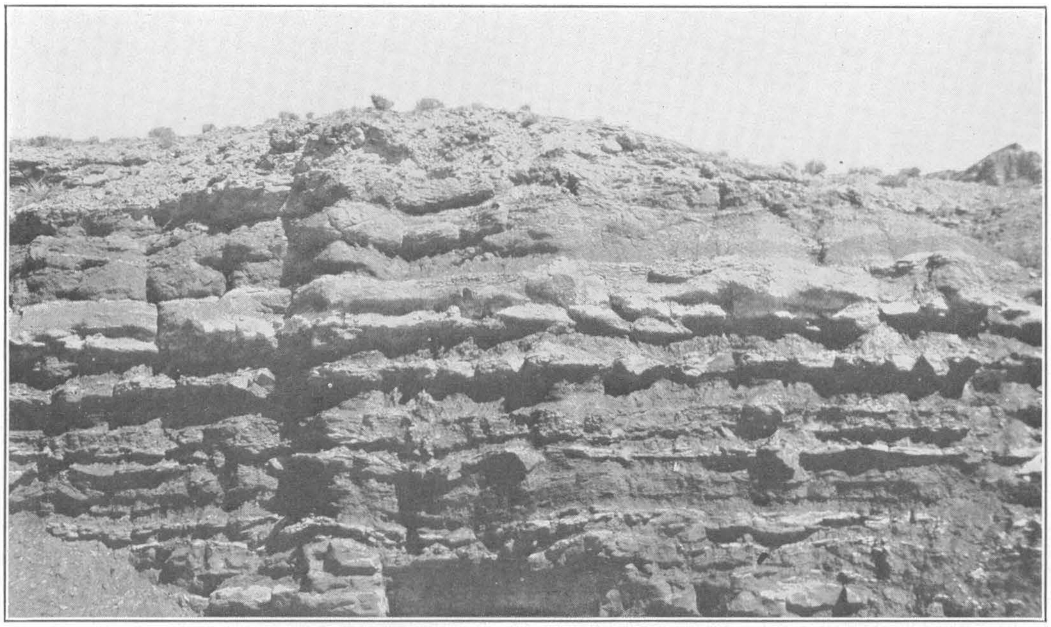
B. WALL BORDERING KANE CREEK

Contact of Entrada sandstone and Carmel formation.

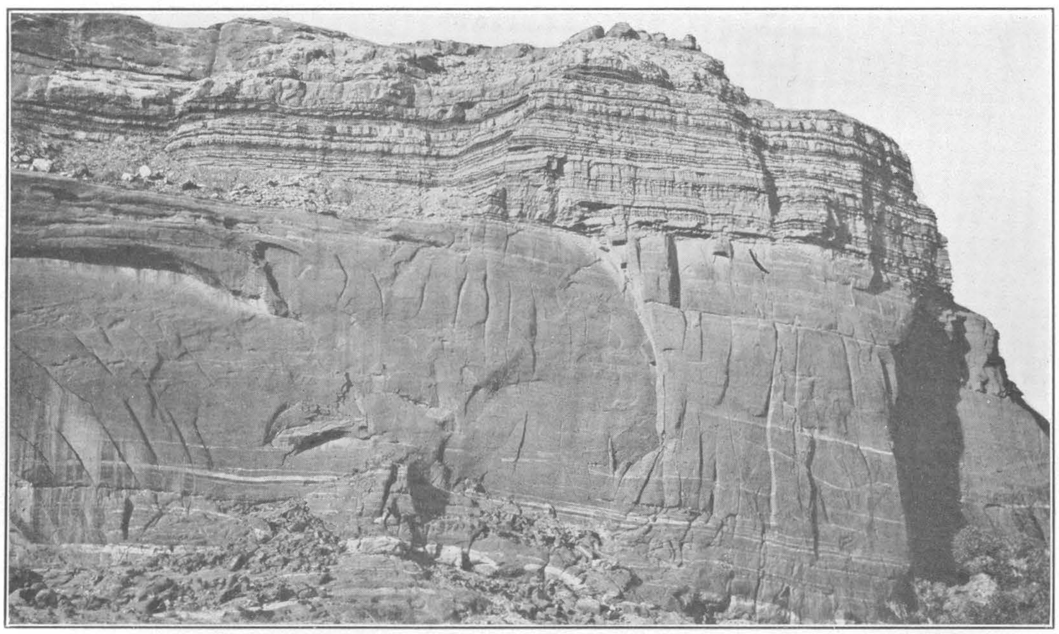


C. GLEN CANYON NEAR MOUTH OF WARM SPRINGS CREEK

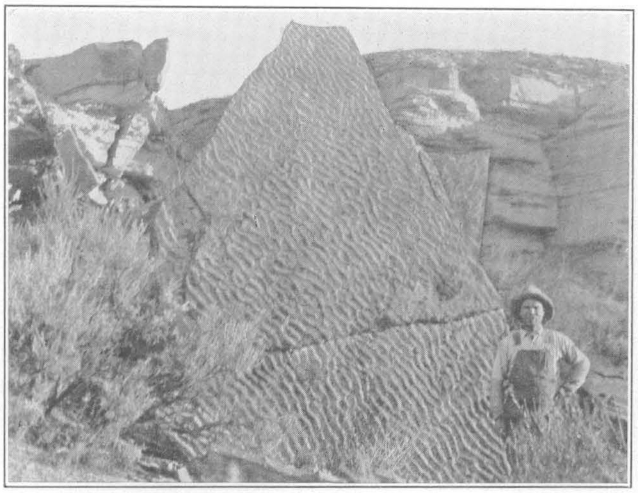
The nearly vertical cliff is formed of Navajo sandstone. The Todilto (?) formation is exposed near the river level. Photograph by E. C. La Rue.



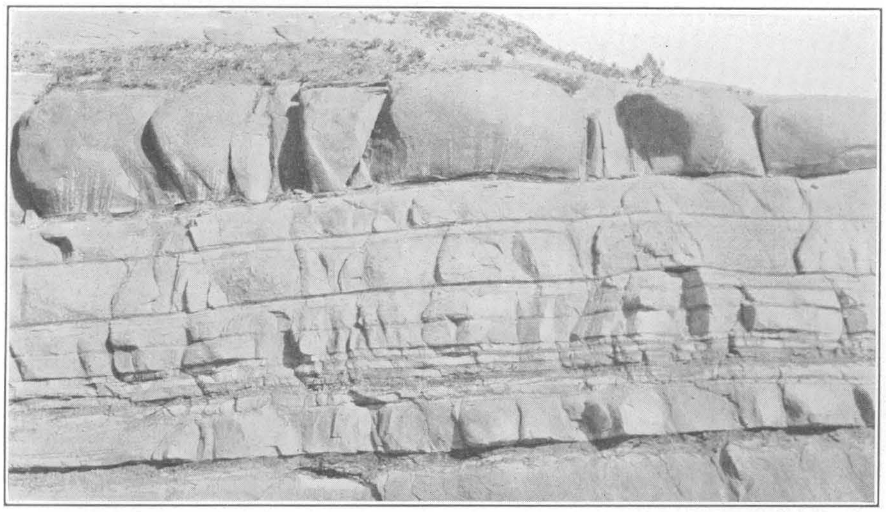
A. BANDED RED AND WHITE SANDSTONE AND CALCAREOUS SHALE OF CARMEL FORMATION NEAR THE CROSSING OF THE FATHERS



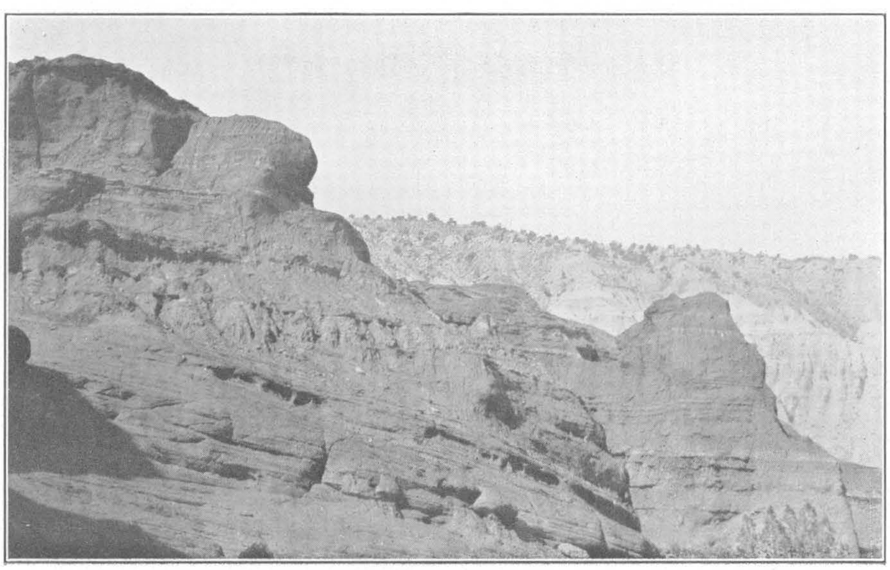
B. CLIFF OF MASSIVE ENTRADA SANDSTONE OVERLAIN BY BANDED SUMMERVILLE STRATA AND CAPPED BY REMNANTS OF MORRISON SANDSTONE, HALLS CREEK VALLEY NEAR BAKER RANCH



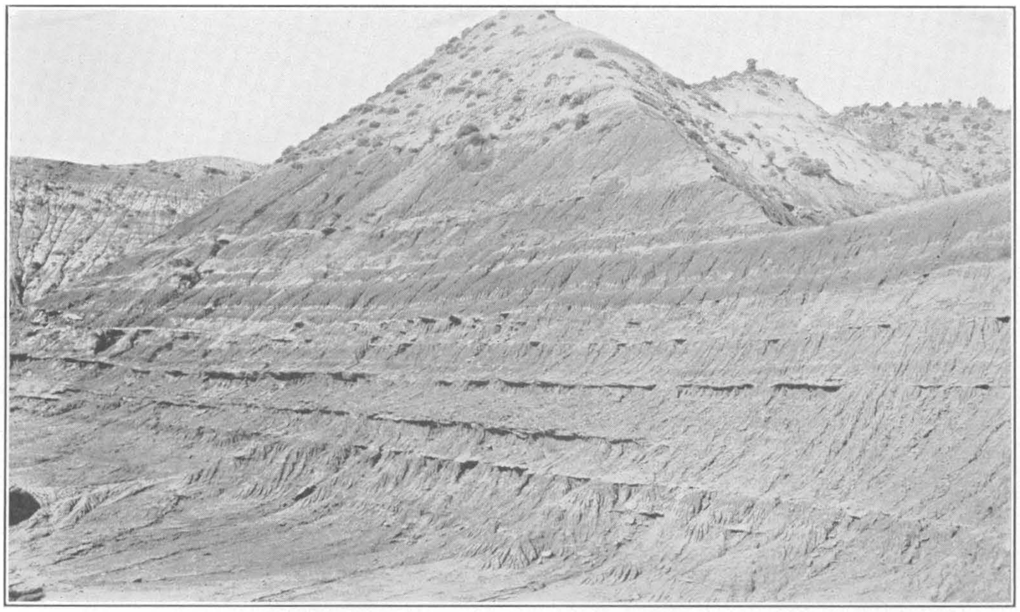
A. SLAB OF RIPPLE-MARKED SHALY SANDSTONE IN CARMEL FORMATION, 40 FEET ABOVE TOP OF NAVAJO IN DRY CANYON, SOUTHWEST OF CANNONVILLE



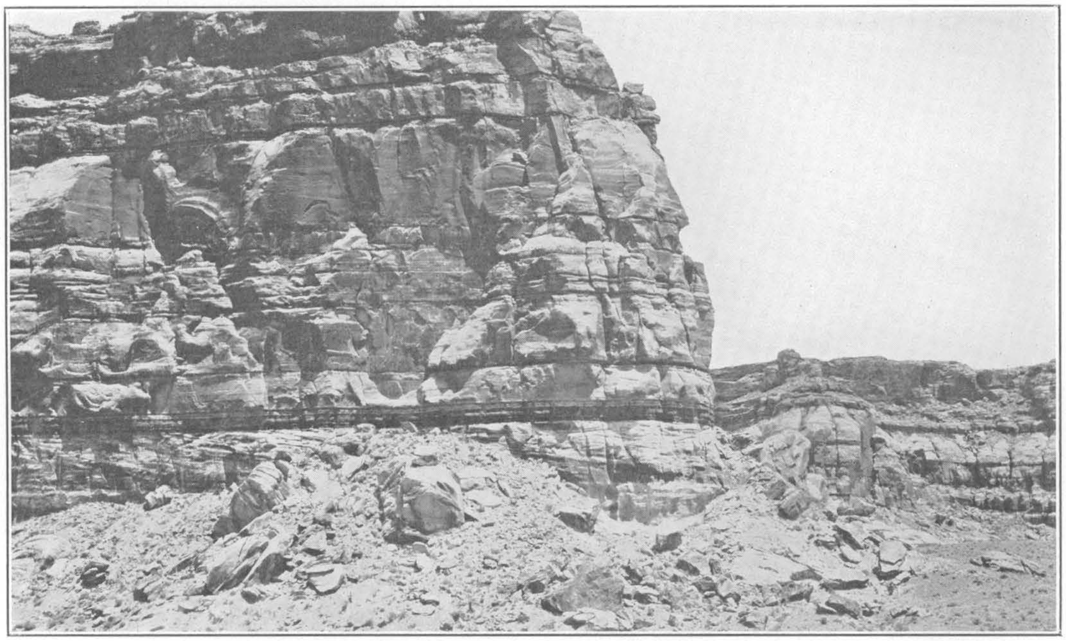
B. EVENLY STRATIFIED ENTRADA SANDSTONE NEAR CANNONVILLE



C. CROSS-BEDDED ENTRADA SANDSTONE NEAR CANNONVILLE



A. BANDED SHALY SUMMERVILLE (?) SANDSTONE 1 MILE SOUTHWEST OF CANNONVILLE



B. MORRISON (?) SANDSTONE ON LOWER WAHWEAP CREEK

The 45 to 450 feet of beds along upper Glen Canyon and the Waterpocket Fold that lie between the Navajo sandstone and a "very massive soft light creamy-white, tan, orange-red cross-bedded sandstone" were grouped by Longwell and Moore[98] as "gypsiferous shales and sandstones" and placed at the "horizon of marine Jurassic"—"Todilto (?) formation of Emery," "included in McElmo formation by Lupton."

In the Diamond Valley, 15 miles north of St. George, Utah, and overlying undifferentiated Wingate and Navajo, Reeside and Bassler[99] found about 460 feet of "greenish-gray, cream-colored, and brown fossiliferous marine limestone, underlain by brick-red sandstone, shale, and gypsum." Included fossils "fix the age as undoubtedly that of the marine Jurassic of the region."

The obvious utility of fossiliferous beds as a horizon marker in the midst of thousands of feet of unfossiliferous strata led Gregory and Noble[1] to study the "marine Jurassic" in the Parunuweap and Kanab Valleys at localities where fossiliferous limestones had been noted by Powell and Dutton and to trace these beds or their equivalents westward to the Diamond Valley and eastward to Rock Creek.

In the Long Valley (upper Virgin Valley), beginning at the head of Parunuweap Canyon, fossiliferous marine Jurassic is exposed on the down-thrown side of the fault that marks the west base of the Paunsaugunt Plateau—the Sevier fault of Dutton. Near the village of Mount Carmel beds that lie between the Navajo sandstone and strata assigned to the Cretaceous form low cliffs, mesas, ridges, and rounded knobs that are distributed as foothills leading upward to the intricately dissected Colob Plateau. Measured sections include at their base a series of limestone, shale, gypsum, and friable sandstone, for which the name Carmel formation has been proposed.

STRATIGRAPHIC SECTIONS

A composite section made up of five partial sections at the type locality of the Carmel formation—all the beds not exposed at any one place—consists of the following beds:

Section of Carmel formation between Virgin River bridge and a point about 2 miles west of Mount Carmel village, Utah

[Measured by Herbert E. Gregory]

	Feet
Cretaceous:	
23–30. Sandstone, buff, brown, coarse, and shale, with coal	200+
Cretaceous (?):	
Morrison (?) formation—	
22. Sandstone, white, with greenish shale: disintegrates readily; thickness estimated	50
Jurassic:	
Summerville (?) formation—	
21. Sandstone, banded alternately pale red and white, thin bedded, weakly consolidated; is essentially a calcareous and gypsiferous silt	130
Carmel formation—	
20. Limestone, gray, sandy, oolitic in part, a lens 30± feet long; fragments of *Trigonia* and *Ostrea*	⅓
19. Sandstone, banded pale red and white, fine grained, friable	13
18. Gypsum, white, lumpy; absent 120 feet distant along strike	3
17. Sandstone, red and green, white banded; in composition like No. 19	12
16. Gypsum, white-green, kneaded into masses like gristle in bacon	16
15. Shale, white, gypsiferous and arenaceous	2
14. Gypsum, white and green, with pink lenses near top; evenly bedded, breaks into sheets about 1 inch thick	4
13. Unconformity; pockets in eroded surface are filled with gravel that consists of pebbles and fragments of quartz, green mud shale, and red shale.	
12. 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; in composition like No. 19	68
11. 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
10. Shale, gray to buff, in paper-thin overlapping beds, calcareous; foliation surfaces smooth and glistening	10
9. Limestone, cream-colored, dense, hard, siliceous, with thin lenses and seams of chert; breaks with conchoidal fracture	1½
8. Shale like No. 6; forms slope on all mesas in this vicinity	35
7. Limestone, buff, earthy, one massive bed; top consists largely of broken shells	2
6. 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
5. Sandstone, gray to buff, very calcareous; top few inches coated with beautifully preserved stem joints of *Pentacrinus asteriscus* Meek and Hayden	4

[98] Longwell, C. R., and others, op. cit., p. 4.
[99] Reeside, J. B., jr., and Bassler, Harvey, op. cit., pp. 54, 64.
[1] 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, p. 237, 1923.

Jurassic—Continued.

Carmel formation—Continued.

	Feet
4. Limestone and calcareous shale in beds less than 1 inch thick	18
3. Limestone, cream-colored, earthy at bottom, few feet pink, and very sandy in cliff sections, apparently in beds 4 to 8 feet thick but weathers into thin slabs	20
2. Shale, brick-red, breaks into thin hard chips, calcareous at the top	5
1. Sandstone, green-white, in places conglomerate with red quartz grains, green mud pellets and shale fragments; along strike this bed thickens, thins, or disappears	6
Total Carmel formation	269+

Unconformity.

Jurassic(?):

Navajo sandstone.

The complete list of fossils collected from the lowermost 150 feet of the Carmel formation on the Virgin River embraces the following forms:

Pentacrinus asteriscus Meek and Hayden.
Rhynchonella sp. undet.
Eumicrotis curta (Hall).
Ostrea strigilecula White.
Cardinia? n. sp.
Trigonia quadrangularis Hall and Whitfield.
Trigonia americana (Meek).
Camptonectes platessiformis White.
Camptonectes stygius White?
Modiola subimbricata Meek.
Modiola pertenuis Meek and Hayden.
Modiola sp. undet.
Astarte packardi White.
Dosinia jurassica Whitfield.
Ammonite fragment?

Section of Carmel formation at the head of Parunuweap Canyon, Utah

[Measured by L. F. Noble]

	Feet	
6. Limestone; makes two cliffs with a ledgy slope between them:		
Limestone, very massive, bluish gray, crystalline, in beds that range from 2 inches to 3 feet in thickness; forms a strong cliff; fossiliferous, but the fossils are poorly preserved	8	
Limestone, buff, crystalline, and shale, platy, calcareous, in alternating beds; make slope; the limestone beds average 4 inches in thickness, the shale beds 1 foot	12	
Limestone, platy, buff, somewhat sandy, in beds ranging from one-fourth inch to 4 inches in thickness; forms a cliff; contains seams of calcite; some beds are crystalline; topmost bed, 6 inches thick, is very fossiliferous	15	
		35
5. Shale; makes a slope:		
Shale, thin bedded, buff, calcareous; upper half almost a limestone	53	
Shale, buff, sandy; a few beds are red	15	
Limestone, hard, buff, platy, in paper-thin, wavy laminae	5	

5. Shale; makes a slope—Continued.

	Feet	
Clay shale, buff to smoke-gray; contains local beds of platy buff calcareous shale; a few beds, 1 to 2 feet thick, are reddish or purplish	23	
		96
4. Shale and limestone; make a weak cliff, or a steep ledgy slope:		
Limestone, buff; in massive bed that contains many fragments of small shells; makes cliff	1½	
Shale, sandy, buff; makes slope	10	
Limestone, sandy, buff, sparingly fossiliferous; makes small cliff	3	
Shale, buff, sandy; makes slope	5	
Sandstone, calcareous, platy, containing several fossiliferous beds, made up largely of fragments of shells; the prevailing color of the sandstone is buff, but some beds are slightly purplish; the fossiliferous beds average less than 4 inches in thickness; the sandstone makes a weak cliff	5	
		24½
3. Shale, sandy, buff; makes slope; most of the shale is in paper-thin laminae; contains local beds of buff platy calcareous shale, most of which are less than 2 inches thick		20
2. Limestone; makes cliffs:		
Limestone, sandy, made up almost entirely of small fragments of shells; everywhere a very conspicuously fossiliferous bed	½	
Limestone, cherty (like No. 4), in beds that average 6 inches thick, alternating with beds of buff arenaceous platy limestone (like No. 3) that average 4 feet thick; makes a set of cliffs broken by ledges	17	
Limestone, fossiliferous, platy, buff, mottled with many small masses of white chalcedony or chert; weathered surfaces are rubbly; the bedding is wavy, and the laminae average one-fourth inch thick; fossils very poorly preserved	1	
Limestone, dense, buff, somewhat arenaceous, crystalline; forms strong cliffs; the rock appears massive in many outcrops, breaks with a conchoidal fracture, and seemingly forms solid beds that range from 6 to 10 feet in thickness, but weathered exposures show that it is actually thin bedded and platy, being made up of laminae that range from one-fourth to one-half inch in thickness; some laminae are as thin as cardboard; the basal 5 feet of the limestone is purplish and is much more sandy than overlying portions	17	
		35½
1. Shale, reddish or purplish, soft, sandy, and thinly laminated; the upper part is calcareous; forms a slope		12
Total Carmel formation		222

The base of No. 1 is a level line that truncates the inclined wedges of the underlying Navajo sandstone, a white, fine-grained sandstone that is cross-bedded on a huge scale.

In sections of the Carmel formation in the Virgin Valley and also in the Kanab Valley the beds that include limestone pass upward into banded sandstone without clear evidence of change in conditions of deposition. The upper limit of the Carmel is somewhat arbitrarily drawn to include only fossiliferous limestone and associated arenaceous shale. Within the Kaiparowits region, with the possible exception of beds exposed at Cannonville, no such uncertainty exists; shale and limestone assigned to the Carmel are sharply bounded by the Navajo beneath and the massive cross-bedded Entrada sandstone above. (See pl. 22, *A*.)

The arrangement of beds in the Paria Valley, along Glen Canyon, in the Escalante Valley, and in the Hall Valley is shown in the following sections:

Section in Dry Canyon (Rock Springs Gulch, Cedar Wash), about 2 miles above junction with Paria River

[Measured by L. F. Noble]

	Feet
Jurassic:	
Entrada sandstone—	
23. Sandstone, yellow-white, massive, cross-bedded	119
22. Shale, red, sandy, very unevenly bedded	2
Carmel formation—	
21. Limestone, gray, weathering buff, massive, fine grained, crystalline, probably sandy; contains obscure fossils	1
20. Shale, red	½
19. Limestone, like No. 12	1
18. Shale, red	½
17. Limestone, like No. 12	3
16. Shale, buff to whitish, calcareous; forms a weak cliff	8
15. Bed of porous travertinelike calcareous material; a horizon at which springs issue; forms an alcove	1
14. Clay shale, buff to brown; contains a layer of bluish calcareous shale near the top	4
13. Clay shale, red, with greenish blotches; includes a few greenish beds at irregular intervals	13
12. Shale, red, sandy	10
11. Shale, greenish, sandy, calcareous, in wavy, thin laminae; many laminae as thin as paper; foliation surfaces ripple marked; worm trails and markings common; some beds several inches thick are practically limestone; they appear massive in many exposures, but weathered outcrops show thin lamination	8
Jurassic—Continued.	
Carmel formation—Continued.	
10. Shale, greenish and buff, sandy, calcareous; many beds as thin as cardboard, some as much as an inch thick; the thicker beds are calcareous, the thinner ones sandy	5
9. Clay shale, brownish, in laminae that range in thickness from that of paper to that of cardboard; some outcrops stained black	4
8. Clay shale, greenish, in paper-thin laminae	1
7. Clay shale, red, sandy, not so thinly laminated as No. 19	4
6. Shale, greenish, sandy	1
5. Shale, bluish, soft, calcareous; exhibits marked concretionary structure; largely concealed	6
4. Shale, bluish-gray, calcareous; in places passes into limestone; appears to form a single massive bed, but weathered surfaces show very thin lamination; in places the laminae are as thin as paper; many of them are slightly wavy, owing probably to ripple marking; a few beds are dense, very finely crystalline limestone and contain tiny masses of chalcedony	8
3. Sandstone greenish, soft; becomes increasingly calcareous upward and passes at the top into platy calcareous sandstone	4
2. Limestone, brown, ferruginous; contains scattered grains of quartz, most of which are less than 5 millimeters in diameter	½
1. Sandstone, greenish and yellowish, fine-grained; in very thin wavy laminae but weathering as a massive bed	7
Total Carmel formation	89
Jurassic(?).	
Navajo sandstone, white; its inclined wedges are truncated by No. 1.	

Noble divides this section, beginning at its top, into limestone that forms a cliff (beds 21–17); shale that forms a slope (beds 16–12); ripple-marked calcareous shale that forms a weak cliff (bed 11); shale that forms a slope (beds 10–5); shale that forms a weak cliff (bed 4); and sandstone that forms a slope (beds 3–1).

Bed 11 is a prominent feature of the lowermost 40 feet of the Carmel formation in the Paria Valley. At all the outcrops studied the ripple marks are persistent, and the resistance of the rock to weathering favors the accumulation of ripple-marked slabs on talus slopes and canyon floors. (See pl. 12, *A*.) Careful search for fossils in calcareous beds of the Carmel resulted in finding indeterminable fragments and imperfect casts that strongly suggest identity with the marine Jurassic fauna of the Virgin River. Worm trails and borings are common.

Section of Carmel formation about 2 miles west of Meskin Bar, Colorado River, Utah

[Measured by L. F. Noble]

Carmel formation:	Feet
5. Sandstone, reddish, fine-grained; forms a cliff. Layers massive but irregularly bedded; basal 2 feet hard and calcareous	6
4. Shale, red; forms a slope—	
Shale, very soft, red, sandy; in paper-thin laminae	23
Shale, red, fine-grained, sandy; upper 1 foot massive, but friable	3
	26
3. Calcareous sandstone, forming a cliff—	
Sandstone, massive, pink, calcareous; in places practically a limestone	1
Sandstone, pink, platy, calcareous; in places practically a limestone; laminae as thin as cardboard	1
Shale, conspicuously ripple marked, platy, greenish white, calcareous; practically a thin-bedded limestone: laminae as thin as cardboard; this bed and the two overlying beds (4 and 5) form ledges just above the top of the cliff formed by bed 2	1
Sandstone, reddish, compact, calcareous, in two massive beds, each 2½ feet thick, separated by 1 foot of red sandy shale; much calcite present along cracks	6
	9
2. Sandstone, reddish, soft; forms a slope—	
Sandstone, red, shaly; a consolidated sandy mud	2
Sandstone, massive, compact, red; probably calcareous	1
Sandstone, red, shaly; like No. 5	2
Sandstone, in massive gnarly bed, brecciated red	2
Sandstone, red, shaly; like No. 5	5
	12
1. Sandstone, pinkish or reddish, very hard, compact, fine-grained, quartzitic; practically a quartzite; forms a very persistent tiny cliff at the summit of the Navajo sandstone; the rock is ripple marked in places, and its surfaces are coated with black desert varnish; the thickness ranges from 4 inches to 2 feet; it resembles beds in the Cambrian Tapeats sandstone of the Grand Canyon	2
Total Carmel formation	55

Navajo sandstone, white, cross-bedded on a huge scale.

Near the Crossing of the Fathers the sandstone and shale that make up the lowermost 35 feet of the Carmel formation are calcareous and include a bed of hard pink limestone 3 inches thick and several lentils of limestone within ripple-marked shaly sandstone. (See pls. 10, *B*, 11, *A*.) At the mouth of Rock Creek the only limestone noted within 30 feet of red lumpy, irregularly bedded calcareous shale is a bed 2 inches thick made up of paper-thin laminae almost as hard and as brittle as porcelain.

Section of Carmel formation about 2 miles east of Escalante village

[Measured by Herbert E. Gregory]

Entrada sandstone, yellow-red, massive; in texture resembles Navajo.

Carmel formation:	Feet
10. Gypsum and gypsiferous shale, with subordinate shaly sandstone; gray, red, purple, and ash-colored; forms a plain across upturned strata; largely concealed; thickness estimated	85
9. Sandstone, thin-bedded, or sandy shale, gray; highly calcareous, imbricated; glistening foliation surfaces covered with ripple marks and patches of hardened sand; very irregular in thickness, composition, and extent of beds	24
8. Shale, calcareous, and thin sandy limestone	12
7. Gypsum, white, massive, with few lenses and stringers of white sandy shale; forms gulch; partly concealed	45
6. Sandstone, red-yellow, massive, cross-bedded	7
5. Shale, red, sandy, unevenly bedded	4
4. Sandstone, buff, regularly bedded; one bed 4 feet thick; other beds thin	11
3. Shale, sandy, or shaly standstone, pink, with irregularly placed patches of red, calcareous; thin lenses of limestone; foliation surfaces sun dried, ripple marked, and dotted with mud lumps	8
2. Limestone, pink, brittle, and paper-thin sandy shale, imbricated, ripple marked	2
1. Sandstone, red, shaly, calcareous, with patches of coarse sand grains	8
Total Carmel formation	206

Navajo sandstone, yellow-white.

Section of Carmel formation in Halls Valley near Burr trail

[Measured by Herbert E. Gregory]

	Feet
Entrada sandstone, white to yellow-red, massive	600±
Carmel formation:	
7. Shale, gypsiferous, light red, brown, greenish white; includes beds of gypsum 3 to 8 feet thick, thin white sandstones, sandy red shales, and partly concealed	230
6. Limestone, brown, sandy, and lenses of lumpy shale; very irregularly bedded, many lateral unconformities; some foliation surfaces ripple marked	6
5. Shale, white, calcareous, even bedded	12
4. Limestone, buff, earthy	1
3. Shale, bright red, calcareous and arenaceous, very unevenly bedded; resembles compacted silt; and gray nodular limestone, lenticular	40
2. Sandstone, gray, and red shale	5
1. Sandstone, brown, lumpy, imbricated, lenticular; includes lenses and pockets of quartz pebbles; rests on uneven surface of underlying sandstone; average thickness	4
Total Carmel formation	298

Navajo sandstone.

Near the mouth of Halls Creek the limestone that is commonly associated with the Carmel formation is inconspicuous, but from the Burr trail northward to the east flank of the San Rafael Swell an increasing amount of brittle siliceous limestone, earthy limestone, and highly calcareous shale appear in measured sections, and the fossil fauna likewise increases in abundance and variety.

ENTRADA SANDSTONE

The Entrada sandstone is conspicuous alike for color, massiveness, and boldness of sculpture. On both sides of Glen Canyon between Wahweap and Rock Creeks the sandstone rises above an intricately dissected badland floor of Carmel strata as high, unscalable walls of projecting spurs and of detached mesas, which stand in front of promontories that extend outward from the Kaiparowits Plateau. (See pl. 10, *A*, *B*.) East of Rock Creek these walls continue around the end of the Kaiparowits Plateau and thence northwestward for 30 miles along the Straight Cliffs and reappear near the village of Escalante. In the upper Paria Valley they are prominently displayed and along the east side of Halls Creek constitute an outstanding topographic form. (See pl. 11, *B*.) The sandstone is traced northward into the country about the San Rafael Swell, from a point in which, indeed, the name is derived.[2] The thickness ranges from 20 feet to more than 600 feet.

The Entrada sandstone is included in sections of "McElmo" measured by Lupton and is readily recognized as the lower part of the Jurassic "varicolored sandstones and shales" of Longwell, Miser, Moore, Bryan, and Paige. Emery[3] and Lee[4] correlated the Entrada with the Navajo.

The Entrada is essentially a fine, even-grained sandstone that contains subordinate amounts of shale. Some exposures consist of a single massive sandstone ledge that has inconspicuous irregular bedding planes; others show a series of heavy-bedded sandstones or sandstones with interbedded shales. The Entrada includes conglomeratic masses of shale and sandstone fragments and lenses of green-gray sandstone, which in some places stand out like shelves on slopes that otherwise weather as shale. Cross-bedding is common; in some sections cross-bedded and horizontally bedded strata alternate, but nearly all the rock of some great cliffs is cross-bedded, with tangential sweeps that simulate the Navajo. Within the beds are local unconformities; broken fragments lie in pockets; and short, fat lenses of overlapping shale and tiny concretions are distributed unevenly over eroded surfaces.

In the Kaiparowits region the prevailing colors of the Entrada are tan, light red, and brown. Some outcrops are gray or even blue-gray, and in the Dry Valley the tone is yellow-white to lemon-yellow. Patches and ribbons of white of irregular thickness and length appear on the cliff faces in a seemingly haphazard fashion.

Microscopic study of selected specimens shows that the sandstone consists of clear grains of quartz (about 95 per cent) and fragments of clouded orthoclase (about 5 per cent). Some biotite is present in all specimens. Six per cent of the grains average 0.15 millimeter in diameter, 90 per cent average 0.08 millimeter, and 4 per cent make up a powder-like silt that includes flakes of biotite arranged in layers. There is little evidence of sorting. Most of the grains, especially the smaller ones, are angular. The cement consists of calcite and ferric iron. The white blotches and bands in the rock are identical with the red in composition except that the discontinuous cement is wholly calcite. A specimen of white rock from equivalent beds on the crest of the Echo Cliffs near Tuba, Ariz., consists likewise of quartz and orthoclase, but 96 per cent of the grains are about 0.16 millimeter in diameter and remarkably well rounded, and about 25 per cent of them are wind etched. All cement has disappeared. As compared with the Navajo, the Entrada sandstone has finer, more uniform, less sorted grains and more silt, and appears to be lacking in magnetite, garnet, zircon, and tourmaline.

Because of the weak cement the massive Entrada sandstone is friable and weathers into dome-shaped masses and round-edged cliffs generally grooved along bedding planes.

SUMMERVILLE FORMATION

In southeastern Utah many measured sections include a variable thickness of thin-bedded or rarely thick-bedded sandstone, interstratified with sandy shale and containing some conglomerate and a small amount of gypsum and limestone—a highly variable assemblage of strata resting unconformably on the Entrada and terminated upward by a surface of erosion at the base of the Morrison. The sediments that occupy this interval at the San Rafael Swell have been divided into the Curtis formation, which consists of greenish-gray conglomerate, shale, and gray heavy-bedded sandstone, 76 to 253 feet thick, and the Summerville formation, which consists of thin-bedded chocolate-colored sandstone, earthy red-brown sandstone, and shale, with some gypsum and a little limestone in some sections, 125 to 331 feet thick. From the Curtis formation, which immediately overlies the

[2] Gilluly, James, and Reeside, J. B., jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, pp. 76–78, 1928.

[3] Emery, W. B., op. cit., pp. 576–572.

[4] Lee, W. T., Early Mesozoic physiography of the southern Rocky Mountains: Smithsonian Inst. Misc. Coll., vol. 69, p. 27, 1918.

Entrada, fossils of Sundance age were obtained, thus making the relation between the Entrada and the Curtis similar to that between the Navajo and the Carmel. In the Kaiparowits region beds that occupy the position of the Summerville are generally present, but vary widely in thickness and lithologic features, and no fossiliferous beds comparable to the Curtis formation have been recorded. Correlation therefore can not be made with assurance, especially at places where the usually thick, massive Entrada loses its identity, where the Summerville-Morrison unconformity is poorly marked, or where the Morrison itself is inconspicuous or absent. Gilluly and Reeside[5] have found that the Curtis formation thins southward from its type locality in the San Rafael Swell and disappears before reaching Muley Twist Creek, on the Waterpocket Fold. It seems reasonable to assign to the Summerville formation beds at this horizon on Halls Creek, in the Escalante and Paria Valleys, and along Glen Canyon. As thus interpreted, the Summerville formation averages about 100 feet thick along Hall Creek, 100 feet in the Escalante Valley, 250 feet in the Paria Valley, and 150 feet south of the Kaiparowits Plateau.

As a topographic feature the Summerville of the Kaiparowits region appears as strikingly colored rocks that slope steeply outward from the base of vertical sandstone cliffs. Horizontal color bands of alternating red and white, so narrow as to appear like lines, are characteristic. They make the Summerville one of the most attractive formations in the plateau province. Where not protected by caps of Morrison or Dakota (?), the strata crumble readily, forming miniature ridges, mesas, buttes, and canyon walls, unevenly painted with tones of white, red, brown, yellow, and gray-green.

There are many lenticular beds and beds that include lenses of hardened mud lumps and of shale fragments. Unconformities within the formation are common. Substantially the formation consists of poorly cemented sandstone, arranged in thin beds. Gypsum forms part of most sections, but beds of limestone are rare. The few beds of clay shale noted have rippled foliation surfaces that are coated with grains of sand. Microscopic examination of "banded shale" at Cannonville revealed the presence of clear quartz, 90 per cent; clouded orthoclase and albite, 10 per cent. About 20 per cent of the grains have average diameters of 0.2 to 0.3 millimeter; 80 per cent range from grains 0.2 millimeter in diameter to dust. About 15 per cent of grains that exceed 0.2 millimeter in diameter are well rounded and wind etched; the smaller grains are angular. The cement of the red shales is ferric iron and calcite, and that of the white parts is calcite only or in a few specimens calcite and gypsum.

SAN RAFAEL GROUP AND MORRISON FORMATION (CRETACEOUS?) UNDIFFERENTIATED

In most of the Kaiparowits region strata of the San Rafael group and the Morrison formation combine to make a topographic and color unit, in which brightly variegated slopes and cliffs rise above a well-defined floor of uniformly colored Navajo sandstone and are protected from erosion on top by a resistant platform of dull-colored Dakota (?) sandstone. In measuring sections and studying stratigraphic and lithologic features it was found convenient to treat the San Rafael and Morrison together and to describe their combined features as they are represented in four areas—the Halls Creek Valley, the Escalante Basin, the Paria Valley, and the Glen Canyon region.

HALLS CREEK VALLEY

Along Halls Creek (Hoxie Creek) the San Rafael and Morrison are well displayed between the Navajo sandstone, which forms for long distances the enormous roll of the Waterpocket flexure, and the Upper Crataceous beds, which are built as a giant stairway that leads up to the base of the Henry Mountains. Halls Creek at its mouth is sunk in the Navajo sandstone, and as the winding course of the stream is followed northwestward progressively higher beds appear. At the head of the creek the San Rafael and Morrison occupy the middle portion of a series of magnificent cliffs and slopes, including, as measured by Moore,[6] all formations from the base of the Moenkopi to the top of the Masuk sandstone—7,460 feet of strata arranged in huge bands of color.

At the north end of the Waterpocket Fold, between Notom and Bown's ranch, the land surface is developed in the limestone and powdery shale beds of a formation that contains marine Jurassic fossils. Above it rise cliffs that include 60 feet of massive and shaly, earthy gypsum and 160 feet of banded light-red and dark-brown shale and gypsiferous "marl," all assigned to the Carmel formation. The Entrada is here represented by about 200 feet of fine and even grained light-red sandstone, the lower one-third massive. The 600 feet of arenaceous shale in thin alternating beds of light-red and green-gray, the 12 feet of impure gypsum, and the 36 feet of cream-colored, dark-red, and greenish nodular limestone, intermingled with red sandy shale, which overlie the Entrada, are probably equivalent to the combined Curtis and Summerville formations.

[5] Gilluly, James, and Reeside, J. B., jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 78. 1928.

[6] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, pp. 21–22, 1923.

Near the mouth of Halls Creek the base of the San Rafael group consists of 3 to 12 feet of hard, gritty sandstone that has clean-washed, white subangular quartz grains and of sandstone intermingled with red arenaceous, calcareous shale, which rest on an uneven surface of Navajo sandstone that forms the walls of the Colorado Canyon. Above this bed lies about 130 feet of lumpy arenaceous and calcareous shale that is interbedded with red, gray, and white fine-grained sandstone in irregular beds of different thicknesses. Gypsum is disseminated throughout and forms thin, short lenses in the uppermost 20 feet. The space between these gypsiferous beds and the thin stratum of red arenaceous shale that immediately underlies the Dakota (?) sandstone is occupied by towering cliffs of red massive cross-bedded Entrada sandstone, somewhat like the Navajo in composition, structure, and color, and in having a division plane that is made by thin-bedded sandstone about 225 feet from the base of the 1,000-foot wall. (See pls. 11, *B*, and 19, *A*.)

At the Baker ranch, 7 miles from the mouth of Halls Creek, the broad subdivisions of the San Rafael and the Morrison, beginning at the base, are (1) sandstone grit, red, gray, and white sandstone, and red arenaceous, calcareous shale, with gypsum (Carmel formation); (2) red massive cross-bedded sandstone that weathers into smooth, rounded knobs, on the sides of which are many pits and miniature caverns, and forms a prominent heavy-bedded, unevenly bedded terrace (Entrada sandstone); (3) red thin-bedded sandstone, together with some arenaceous shale, sparingly gypsiferous (Summerville formation); (4) red and light green-gray massive cross-bedded friable sandstone, in places coarse grained and lenticular, which is irregularly streaked with white and includes white beds (Morrison formation); and (5) arenaceous shale, banded light red and green-white (Morrison formation). In places the lower massive sandstone (No. 2) is even redder than the typical Navajo, but within a few miles its color becomes light yellow-red, brown, or red streaked horizontally and diagonally with broad bands of white. The upper sandstone (No. 4) likewise varies in color and along the strike breaks up into thin friable beds, which are eroded into badland mesas and buttes that are crossed and capped by lenses of conglomeratic sandstone. In places beds 4 and 5 unite to form one mass of banded sandstone; elsewhere bed 5 is absent or becomes massive and the upper beveled surface of thick-bedded green-white or light-red sandstone comes into contact with the Dakota (?) sandstone.

In several sections that were measured in the vicinity of the Burr trail, where a large part of the Mesozoic is exposed in beds that dip 5°–50° E., the base of the San Rafael is marked by 4 to 11 feet of brown-gray nodular, lenticular, very irregular coarse sandstone which rests in hollows and on rounded surfaces of the Navajo, here more than 1,200 feet thick. Above this sandstone lie 75 to 100 feet of strata, which include six beds of limestone, the thickest measuring 5 feet, interbedded with thin gray sandstone and bright-red sandy imbricated calcareous shale. Some of the limestone beds are composed of white paper-thin layers that have smooth glistening surfaces; others are brown, sandy, and nodular, are intermingled capriciously with lumps of shale and accumulations of clean sand, and show many lateral unconformities and areas of ripple marks. The uppermost limestone bed is overlain by about 100 feet of impure gypsum and gypsiferous shale, above which comes a massive cross-bedded yellow-red to white sandstone about 500 feet thick, and this in turn is followed by about an equal thickness of bedded friable sandstone (Entrada formation). The top of each section consists of about 300 feet of interbedded yellow-red and green-white sandstone and red sandy shale. One of these sandstone beds 120 feet below the cap rock of Dakota (?) sandstone is very coarse grained and strongly cross-bedded and includes small pebbles of chert, agate, jasper, and quartzite from which water emerges as seeps. Two miles south of the Burr trail this bed is 25 feet thick and consists of a series of lenses of calcareous sandstone, calcareous shale, and limestone conglomerate, within which is a stratum that contains masses as large as 2 by 12 feet of attractively colored red, yellow, and pink chert that resembles jasper.

In all the sections studied south and east of the Baker ranch no continuous bed of gypsum more than 1 foot in thickness was seen, but the prevalence of slumping suggests the presence of such a bed. Six miles to the north 15 feet of massive gypsum lies 60 feet above the Navajo sandstone, and from Muley Twist Creek to the Bitter Creek divide gypsum appears as one or more beds within the lowermost 100 feet of the San Rafael group. Farther north, at Tantalus Creek and along the east flank of the San Rafael Swell, gypsum is persistent in the lowermost 200 feet and appears also at horizons above the massive cross-bedded Entrada sandstone. Likewise the limestone that is commonly present at or near the base of the Carmel formation is inconspicuous along lower Halls Creek, and no limestone beds were noted in a section measured on lower Hanson Creek (Pine Alcove Creek). From the Burr trail northward brittle siliceous limestone and highly calcareous shale appear in all sections. No determinable fossils were found along the Waterpocket flexure, but from Tantalus Creek northward fossiliferous Jurassic limestone that contains gypsum and red shale forms the base of the San Rafael group. A heavy bed of red sandstone (Entrada) above and another one (Navajo) below this limestone give a series of beds similar in color and arrangement and to a less degree in structure and composition to the Glen Canyon group. This remarkable similarity appears to have led Emery[7] to correlate the fossiliferous limestone and gypsum beds with the Todilto of the Navajo country.

The variation and arrangement of beds comprising the San Rafael and Morrison in a distance of about 35 miles along Halls Creek is shown in the following sections:[8]

A. Section about 8 miles above mouth of Halls Creek, Utah

[Measured by Raymond C. Moore]

	Feet
Cretaceous(?):	
Morrison formation—	
5. Sandstone, reddish brown and light greenish gray, massive, hard, irregularly bedded; conglomeratic, forms prominent escarpment; thickness reduced by erosion	76+
Jurassic:	
Summerville formation—	
4. Sandstone, thin bedded, red	123
Entrada sandstone—	
3. Sandstone, tan and brown, massive, soft, cross-bedded	850
Carmel formation—	
2. Shale, light red and greenish, sandy; contains beds of white sandstone and gypsum	90
1. Shale, maroon, and hard fine-grained quartzitic sandstone; forms escarpment	50
	1,189+

Jurassic(?): Navajo sandstone at base.

B. Section 3 miles below mouth of Muley Twist Creek, Utah

[Measured by Raymond C. Moore]

	Feet
Cretaceous(?):	
Morrison formation—	
5. Shale, greenish red and purple, sandy	200+
4. Conglomerate, red and gray, massive, irregularly bedded; weathers brown; grades to coarse gritty sandstone	202
Jurassic:	
Summerville formation—	
3. Red shale and thin-bedded sandstone	93
Entrada sandstone and Carmel formation—	
2. Sandstone, massive, soft, cross-bedded, white; grades downward to tan-brown; weathers in smooth rounded slopes; disintegrates very readily and in part is covered; gypsiferous light-red sandy shale at base, mostly concealed	1,220
1. Shale, dark-red to maroon, sandy; capped by hard quartzitic sandstone	40
	1,755

Jurassic(?): Navajo sandstone at base.

C. Section at Burr trail, 7 miles above mouth of Muley Twist Creek, Utah

[Measured by Raymond C. Moore]

		Feet
Cretaceous(?):		
Morrison formation—		
5. Shale, soft, sandy, light bluish, with thin bands of red		230
4. Sandstone and sandy shale in five beds—		
Sandstone, yellowish brown, conglomeratic	5–7	
Shale, bluish drab and red, sandy	20	
Sandstone, reddish brown to light greenish, coarse grained and massive	5	
Shale, yellowish brown, sandy	15	
Conglomerate and coarse grit, reddish and light greenish gray, massive, hard, very irregularly bedded; forms prominent hogback	80	126
Jurassic:		
Summerville formation and Entrada sandstone—		
3. Sandstone, red, thin bedded, soft, partly concealed; and sandstone, massive, soft, cross-bedded, white; grades downward to tan-brown; weathers readily; partly concealed		1,430
Carmel formation—		
2. Shale, light red and greenish, gypsiferous; contains some beds of hard white sandstone and gypsum		170
1. Shale, maroon and light greenish, sandy; capped by hard, dense siliceous massive to flaggy limestone		45
		2,001

Jurassic(?): Navajo sandstone at base.

D. Section at Bitter Creek divide, head of Halls Creek, Utah

[Measured by Raymond C. Moore]

	Feet
Cretaceous(?):	
Morrison formation—	
8. Shale, grayish blue, maroon, and purple banded, soft, sandy; weathers in valleys and badlands	415
7. Conglomerate and sandstone, grayish white to light bluish green; contains pebbles as as much as 2 inches in diameter; consists in part of thick beds and lenses of coarse conglomerate and in part of coarse gritty very irregularly bedded sandstone	150
Jurassic:	
Summerville formation—	
6. Shale, red and gray banded, sandy; grades to soft thin-bedded sandstone	90
Entrada sandstone—	
5. Sandstone, tan-brown, massive, soft, cross-bedded; weathers in smooth rounded surfaces	260
4. Sandstone, reddish brown and bluish gray, very soft, shaly; weathers readily, forming valley; partly covered	470

[7] Emery, W. B., The Green River Desert section: Am. Jour. Sci., 4th ser., vol. 46, pp. 551–557, 1918.

[8] Longwell, C. R., and others, op. cit., pp. 21–22 (sections A and D).

Jurassic—Continued.

	Feet
Entrada sandstone—Continued.	
3. Sandstone, tan-brown, massive, soft, cross-bedded, fine grained; weathers in smooth rounded surfaces	340
Carmel(?) formation—	
2. Shale and sandstone, light red and bluish gray; gray to white sandstone in alternating beds; contains several beds of bluish to white gypsum as much as 3 feet thick; the gypsum occurs also in numerous thin veins	400
1. Shale, dark to light red, sandy; contains two beds of very hard reddish and light-green mottled dense siliceous massive and flaggy limestone that form escarpments	50
	2,173

Jurassic(?):
Navajo sandstone at base.

ESCALANTE VALLEY

The Escalante Valley is essentially a great amphitheater that has been developed by the removal of Upper Jurassic, Cretaceous, and Tertiary rocks. Its floor of Navajo sandstone is continuously exposed for many miles back from the Colorado River and along both sides of the Escalante River and is warped upward to form the Escalante monocline. Elsewhere this floor is wholly or partly concealed by beds of the overlying San Rafael group, which are displayed as areas of flat-lying or tilted rocks and as mesas, buttes, and detached mounds. The southwest wall of the amphitheater is the steep, straight escarpment of the Kaiparowits Plateau, at the base of which the San Rafael and Morrison strata appear for a distance of more than 40 miles, standing as a terrace in front of the Upper Cretaceous cliffs. From the flank of the Waterpocket Fold, which bounds the Escalante Valley on the northeast, the Upper Jurassic beds have been stripped, but they reappear along streams that issue from the Aquarius Plateau. At the head of the amphitheater around the village of Escalante lie erosion remnants that have been carved from folded beds of green, red, and gray sandstone, shale, and gypsum, which include all the strata assigned to the San Rafael and the Morrison.

A mile west of Escalante the topmost Morrison bed is 18 feet thick and is composed of white and green-white fine-grained friable sandstone. Below this bed in turn lie 28 feet of shaly, lumpy sandstone in thin wrinkled and curved beds that alternate dark red and dull white and about 50 feet of white massive sandstone with cross-bedding displayed in sweeping curves.

At Tenmile Point, beneath an extensive flat developed on Dakota (?) sandstone, lie in turn 30 feet of red crumbly, irregularly bedded sandy shale; 60 feet of white friable sandstone, in part massive; 15 feet of dark-red unevenly bedded sandy shale; and 120 feet of white and green-white sandstone, in part massive, in part thin bedded.

At the mouth of Collett Canyon the Morrison is composed of green-white soft, intricately cross-bedded and lenticular sandstone that includes a conspicuous series of lenses in horizontal and diagonal positions of green poorly compacted mud, which taper to single layers of concretionary balls and angular lumps. In form and composition this material is identical with lumps and sheets of mud strewn along the bed of a near-by wash by a recent shower.

As exposed at Fiftymile Point, the Morrison and the upper part of the San Rafael group contain more shalelike beds and fewer massive sandstone beds than at most other exposures in the Escalante Valley. They closely resemble the beds that are characteristic of the "McElmo formation" at its type locality in Colorado.

Near Boulder, where the Morrison is absent and most exposures of the San Rafael are less than 150 feet thick, a measured section of the beds that overlie the Navajo shows gritty buff sandstone and yellow sandy shale, 10 feet; limestone and red calcareous shale, 25 feet; yellow-white cross-bedded massive sandstone, 15 feet; red calcareous and gypsiferous shale, 8 feet; gypsum, 20 feet.

Throughout the Escalante Valley gypsum is abundant near the base of the San Rafael group. In several measured sections it constitutes as much as 20 per cent of the lowermost 100 feet of strata and is displayed as a single bed with green-red shale partings or as two to five beds that are separated by shale. Near Escalante a gypsum bed that averages 45 feet in thickness with associated gypsiferous shale has been effective in guiding erosion. It has produced much of the rough country immediately north of Escalante and on both sides of the Escalante monocline. Lower Pine Creek has established its course in gypsum, and at Tenmile Spring the banks of Harris Wash include nearly 100 feet of gypsum and gypsiferous shale interbedded with red limestone and sandstone. Gypsum and gypsiferous shale are involved in the intricately dissected surface about the mouth of Collett Canyon and below Panther Seeps, and for about 10 miles west of Willow Creek gypsum beds have been eroded to form a trough in which runs the old trail to the Hole in the Rock crossing of the Colorado. Along the northeast face of the Kaiparowits Plateau the gypsiferous strata of the Carmel formation stand at or below the floor of the Escalante Valley from its head to the vicinity of Collett Canyon, concealing the Navajo beneath. Southeast of Collett Canyon these beds are exposed increasingly near the plateau front, and at Fiftymile Point and at the heads of the short steep canyons that enter the

Colorado opposite the mouth of the San Juan the gypsum forms part of the Kaiparowits Cliffs, from which extends the profoundly trenched floor of Navajo sandstone.

Along the base of the Aquarius Plateau the gypsiferous lower beds of the San Rafael group are cut by the western branches of Pine Creek and by Deadman, Sand, and Mamie Creeks. On upper Boulder Creek these beds are the only part of the group present; they consist of thin lenticular, irregular beds between Tertiary sandy limestone and lava above and strongly developed Navajo sandstone below. (See p. 116.)

Section of San Rafael group and Morrison (?) formation 2 miles east of Escalante, Utah

[Measured by Herbert E. Gregory]

	Feet
Cretaceous:	
Dakota (?) sandstone at top.	
Cretaceous (?):	
Morrison (?) formation—	
14. Sandstone, gray and red, and red arenaceous shale, irregularly deposited; partly concealed	48
Jurassic:	
Entrada sandstone—	
13. Sandstone, yellow, in places white or green-white and red, fine grained, with coarse grains on lamination surfaces; contains some iron concretions; friable, crumbling readily to dust; upper part massive, intricately cross-bedded; lower 40 feet evenly bedded; shows smooth foliation planes; forms cliff; thickness estimated	130
12. Sandstone, red, fine grained, thin bedded, and sandy red shale; crossed by bands and patches of green-white; friable; calcareous and gypsiferous; very irregular in bedding and structure	60
11. Sandstone, yellow-red, massive, cross-bedded, fine grained; resembles Navajo sandstone	22
Total Entrada sandstone	212
Carmel (?) formation—	
10. Gypsum and gypsiferous shale, with subordinate shaly sandstone; gray, red, purple, and ash-colored; forms a plain across upturned strata; largely concealed; thickness estimated	85
9. Sandstone, thin bedded, or sandy shale, gray, highly calcareous, imbricated; glistening foliation surfaces covered with ripple marks and patches of hardened sand; very irregular in thickness, composition, and extent of beds	24
8. Shale, calcareous, and thin sandy limestone	12
7. Gypsum, white, massive, with few lenses and stringers of white sandy shale; forms gulch; partly concealed	45
6. Sandstone, red-yellow, massive, cross-bedded	7
5. Shale, red, sandy, unevenly bedded	4
Jurassic—Continued.	
Carmel (?) formation—Continued.	
4. Sandstone, buff, regularly bedded; one bed 4 feet thick, other beds thin	11
3. Shale, sandy, or shaly sandstone, pink with irregularly placed patches of red, calcareous; thin lenses of limestone; foliation surfaces sun dried, ripple marked, and dotted with mud lumps	8
2. Limestone, pink, brittle, and paper-thin sandy shale, imbricated, ripple marked	2
1. Sandstone, red, shaly, calcareous, with patches of coarse sand grains	8
Total Carmel (?) formation	206
Total Morrison formation and San Rafael group	466
Jurassic (?):	
Navajo sandstone, yellow-white.	

Section of San Rafael group and Morrison formation, northeast base of Kaiparowits Plateau, about 16 miles southeast of Escalante, Utah

[Measured by Herbert E. Gregory]

	Feet
Cretaceous:	
Dakota (?) sandstone—	
Unconformity shown by erosion surface covered with conglomerate composed chiefly of clay pellets, chunks of shale and white sandstone, and pebbles of red, gray, and black quartz and chert.	
Cretaceous (?):	
Morrison formation—	
8. Sandstone, yellow-white, with lenses of yellow, green, and drab mud shale	45
7. Sandstone, thin-bedded, arenaceous shale, and highly calcareous and sandy earthy limestone; alternating bands of dark red and gray, very unevenly bedded; lenticular	40
6. Sandstone, yellow-gray, part cross-bedded, part regularly bedded; includes lenses strings, and isolated fragments of yellow, green-white, and slate-colored clay lumps; two lenses of conglomerate with pebbles of shale, sandstone, and quartzite; may be separated into four beds, but exposure appears as a single bed with remarkable variation in texture and in detailed structure; similar materials in the bank of a wash; poorly consolidated, crumbling readily to sand	110
Total Morrison formation	205
Jurassic:	
Summerville (?) formation—	
5. Sandstone, yellow-white, in regular beds, 3 to 10 inches thick; very fine grained	9
4. Shale, dark red, very calcareous; some thin limestones; thin imbricated layers, with stubby lenses of red and gray calcareous sandstone	25
3. Sandstone, banded yellow, green, and red, thin bedded; weathers to powdery dust	7
Total Summerville (?) formation	41

Jurassic—Continued.	
Entrada sandstone—	Feet
2. Sandstone, cream-colored and yellow-green, in places bright green, massive, cross-bedded, uniformly fine grained except for slightly coarser grains on lamination surfaces; weathers in smooth rounded knobs; crumbles under the feet; forms a terrace; thickness estimated	240
Carmel(?) formation—	
1. Shale, red, gypsiferous, thin gray siliceous limestone, and thin red and gray calcareous sandstone; only top exposed	8
Total Morrison formation and San Rafael group	475

An unusual feature of this section is the amount of lime in beds 4 and 7 and the mingling of colors and textures in bed 6. The almost abrupt variation in texture and arrangement of beds characteristic of the San Rafael group and Morrison formation is indicated in a section measured by Moore [9] at a near-by locality, where calcareous beds are absent and the bedding is much more regular.

Section of Entrada and Carmel formations near Owl Cave on Harris Wash, about 20 miles east of Escalante

[Measured by Raymond C. Moore]

Entrada sandstone:	Feet
3. Sandstone, tan-brown, massive, soft; weathers readily to sand that forms dunes; thickness estimated	300+
Carmel formation:	
2. Shale, pinkish red and bluish gray, sandy; contains beds of gypsum 4 feet or less in thickness; outcrops are very irregular on account of slumping; lenticular gray sandstone beds 3 feet or less in thickness	120
1. Sandstone and shale, dark maroon, medium grained; the shale very sandy and grading to shaly sandstone	60
Total Carmel formation	180

Section of San Rafael and Morrison (?) beds at Fiftymile Point, east end of Kaiparowits Plateau, Utah

[Measured by Herbert E. Gregory]

Dakota(?) sandstone.	
Morrison(?) formation and San Rafael group:	Feet
13. Sandstone, red-yellow, massive, cross-bedded, full of caves and pits; weathers into rounded knobs; very soft; single ledge; thickness estimated	200
12. Shale, arenaceous, or thin sandstone, ash-green, lavender, and shades of red; irregularly bedded	30
11. Sandstone, white, soft, mottled	3
10. Shale or thin sandstone, red, imbricated, nodular, calcareous, and gypsiferous	35
9. Sandstone, green-white or white mottled, lumpy, friable	4
8. Shale or sandstone, like No. 10	25
Morrison (?) formation and San Rafael group—Con.	Feet
7. Sandstone, white, friable	5
6. Shale, like No. 10	25
5. Sandstone, white, calcareous, ripple marked	2
4. Gypsum, dark red, white spotted, lumpy, and calcareous sandy shale	10
3. Sandstone, irregularly bedded	8
2. Shale, red, sandy, calcareous	15
1. Limestone, red and gray, very sandy, lumpy, and unevenly bedded	4
Navajo sandstone.	
	364

[9] Longwell, C. R., and others, op. cit., p. 21.

PARIA VALLEY

The flat land that immediately surrounds Cannonville and extends down the Paria for about 6 miles is developed in the lower beds of the San Rafael group, and the steep-faced mesas that form a crenulated wall for the irrigated lands about Henrieville are composed of Summerville and Morrison (?) strata that are prevented from crumbling by a resistant cap of Dakota (?) sandstone. The Dry and Butler Valleys likewise have been formed by the removal of friable San Rafael beds. (See pl. 22, *B*.) The exceptional roughness of the country that extends from the head of Cottonwood Creek westward across Hackberry Creek to and beyond the Paria is the expression of the extent to which streams have succeeded in stripping the Navajo sandstone of the overlying beds, which are highly variable in composition, texture, and arrangement. The relations of the Upper Jurassic formations in this area have not been satisfactorily determined. West and north of Cottonwood Creek no complete section is exposed, and the incomplete sections which are separated by several miles, require more study before correlation in detail can be made with confidence. If the 120 feet of yellow cross-bedded sandstone that forms a single massive stratum at Dry Canyon is assigned to the Entrada formation, the Carmel formation, with its characteristic limestone and ripple-marked shale, is unusually thin at this locality and contains no gypsum. If the yellow-red sandstone cliffs at Cannonville, which lie between thin, banded sandstone above and gypsum below, are correlated with the Entrada, the Carmel in the upper Paria Valley includes prominent members that are not observed elsewhere in this formation. The assignment of beds to different formations is made more difficult by the absence of Morrison strata—at least of beds that show the characteristic features of the Morrison. (See p. 91.) The present tentative interpretation restricts the Morrison (?) to 45 feet of white sandstone at the top of the banded Cannonville cliffs and treats all beds between that horizon and the yellow sandstone on Dry Creek as one formation about 800 feet thick, which occupies the position of the Summerville. (See pl. 13, *A*.) In favor of this view is the observation that the red strata in the banded white and red slopes beneath the assumed Morrison gradually increase in number downward and thicken until the yellow-red sandstone constitutes the valley walls. These massive red beds are lithologically much like the beds above and are markedly dissimilar to the shale and gypsum underneath.

As shown in the section below, these massive sandstones include dark-red shale as lenticular partings. In the Dry Valley above the 119 feet of shale and gypsum that rests on sandstone assigned to the Entrada formation (see section, p. 85) lies about 400 feet of intricately eroded beds that form the much broken floor of the valley. They appear as rounded knobs of banded and variegated "marl;" flat-topped mesas, and buttes that rise above a surface deeply buried in alluvium. (See pl. 22, *B*.) The beds present include yellow, red, dark-red, and white banded friable sandstone, calcareous and gypsiferous shale, and at least six thin beds of gypsum, one of them cut by bands of pink chalcedony. Nearly all the beds that are exposed on the floor are unevenly bedded and change their character within short distances. At one place a bed of yellow-red sandstone, massive except for inconspicuous lenses of red shale, appears as a huge mass about half a mile long and 180 feet thick, standing in the midst of thin red sandstone and variegated shale. (See pl. 12, *B*, *C*.) The north wall of the Dry Valley consists of about 250 feet of San Rafael and Morrison (?) beds that underlie Cretaceous sediments. At a distance these lower cliffs resemble one great bed of white sandstone that is crossed by several dark-red bands. On closer view, the lowest 200 feet is seen to be composed of a series of thin, uneven beds of white consolidated sandy mud with two dark-red bands near the top like the border on wall paper. Above these beds comes a bed of white cross-bedded gritty sandstone, 4 feet thick, which is resistant enough to form a projecting bench. Still higher lies 90 feet of white sandy shale and sandstone crossed by several red bands in the lower half and succeeded upward by 60 feet of inconspicuously bedded white sand. All the material in the valley wall is poorly consolidated and crumbles rapidly to very fine sand. Where it is protected by the Dakota (?) sandstone it stands along cliff faces and out from the walls as needles and towers, of which Chimney Rock (pl. 28, *A*) is a conspicuous example.

At the hogback that is trenched by the Paria River below Paria settlement the upturned strata of the San Rafael group and the Morrison (?) formation are revealed in the bed and immediate banks of Cottonwood Creek. They here constitute essentially three distinct divisions. The uppermost division, which lies unconformably below the Dakota (?) sandstone, includes more than 600 feet of medium-grained very friable sandstone in massive white beds that are separated by beds of dark-red and green-white sandstone 3 inches to 1 foot thick, which thus produce the appearance of a white cliff unevenly banded with red. In the lowest 20 feet the banding is regular and the contrast between dark red and white is unusually strong. The middle division, which is correlated with the Entrada sandstone, is substantially a bed of massive white to blue-gray friable sandstone that is elaborately cross-bedded and has a thickness of about 150 feet. The lowest division, about 250 feet thick, consists of thin, unevenly bedded friable sandstone that varies in texture from fine mud to coarse sandstone and includes flat lenses and oblong masses of small angular pebbles. Its general color tone is maroon, but bands of white of different thicknesses, lengths, and positions traverse the surface in a seemingly haphazard fashion, and thin beds of light-gray sandstone form shelves on slopes that otherwise weather like shale. Beds of gypsum, if present, are concealed by surface débris, but gypsum forms part of the cementing material. Toward the base of this group lime cement is increasingly common, and thin limestones interlayered with deep-red thin sandstone are plastered over the uneven surface of the Navajo.

Near the abandoned site of Adairville, on the Paria River, the beds above the Carmel formation consist of two thick massive sandstones separated by about 70 feet of thin, alternately bedded red and white sandstones that weather like shale. The lower, a white sandstone bed, is persistent for several miles; the upper, a yellow-white bed, changes along the strike to a series of thin-bedded, banded sandstone.

Section of Morrison (?) formation and upper part of San Rafael group at Cannonville, Utah

[Measured by Herbert E. Gregory. See pl. 13, *A*]

Dakota (?) sandstone.	
Unconformity shown by erosion.	
Morrison (?) formation and San Rafael group:	Feet
42. Sandstone, white, stained with yellow; very unevenly bedded; top 1 foot composed of interlaced bands of dark-brown and yellow sand; all crumbles readily to variegated sand	45
41. Sandstone, red; highest red bed in the Cannonville region	1
40. Sandstone like No. 42	18
39. Sandstone, yellow, concretionary, as if white sandstone were impregnated with iron	6
38. Sandstone, friable, 1 foot white, 1 foot red, 4 feet white, 3 feet red	9
37. Sandstone, white, gypsiferous	15
36. Sandstone, firm; three bands of red separated by white; forms step on slopes and caps of near-by buttes	12
35. Sandstone, white, friable, lenticular, with 22 discontinuous bands of red in lower half; in red material occur lenses and scattered fragments of green-white clay	145
34. Sandstone, white, cross-bedded, very fine grained, lenticular, relatively resistant; forms bench on slope and caps of near-by towers and mesas	3

Morrison(?) formation and San Rafael group—Contd.	Feet
33. Sandstone, light red, in places dark red, very irregularly bedded, poorly consolidated	4
32. Sandstone like No. 34	⅔
31. Sandstone like No. 33	8
30. Sandstone, buff-yellow; has a considerable range in thickness	4
29. Sandstone like No. 33	4
28. Sandstone like No. 34	6
27. Sandstone like No. 33	4
26. Sandstone like No. 34	½
25. Sandstone like No. 33	4
24. Sandstone, white; three beds divided by red sandstone; nodular, concretionary; forms bench	1
23. Sandstone like No. 33	8
22. Sandstone like No. 34	¼
21. Sandstone, buff, shaly, thin bedded, very unevenly bedded	12
20. Sandstone, dark red, shaly, friable	½
19. Sandstone, light red, thin bedded, cross-bedded	5
18. Sandstone, light red, thin bedded, and dark-red shale, remarkably irregular in texture, structure, and continuity and arrangement of beds; the shale is sandy mud in beds as much as 1 foot thick and 10 to 150 feet long and in oblong mud chunks embedded in sand or weathered to form "toe hole" cavities; sandstone strata tangentially cross-bedded; white streaks appear at joints, on foliation planes, and along cross-bedding laminae and outline some mud chunks; forms uneven top of mesa	45
17. Shale, dark red, irregularly stained white	4
16. Sandstone, light red, massive, cross-bedded	13
15. Sandstone and shale like No. 18	5
14. Sandstone, light red, irregularly bedded; some streaks of white	7
13. Sandstone, light red, many white round blotches at base; very irregular; includes one persistent thin bed of white sandstone	9
12. Shale, dark red, a series of overlapping sandy mud flakes; rests in most places on white firm sandstone shelf about 1 inch thick	1
11. Sandstone, light red, cross-bedded	3
10. Shale, dark red	⅙
9. Sandstone, light red, uneven, lumpy, cross-bedded; contains small quartz-lined geodes	12
8. Sandstone, yellow-red and buff, in beds 1 to 3 feet thick, discontinuous, cross-bedded; grains of translucent quartz together with some red and black grains; contains quartz-lined geodes in lenses and as scattered individuals; carries a diagonally placed bed of white sandstone bordered by dark-red shale that ranges within 100 feet from 10 inches to 12 feet in thickness	16
7. Shale, dark red; sandy, unevenly bedded; carries lenses of yellow-red sandstone; weathers as a groove or string of rectangular cavities on cliff face	10
6. Sandstone, light yellow-red massive; breaks up along strike into cross-bedding; laminae alternately red and white; thickness ranges within 200 feet from 36 to 8 feet	28
5. Sandstone, light red, cross-bedded; white streaks along laminae	20
4. Shale, dark red; lumpy; forms groove	2
3. Sandstone, white; very fine grained; bed differs much in thickness from place to place	12
2. Sandstone, yellow-red, streaked and dotted with white; massive beds, 6 feet thick, separated by very unevenly bedded shale; weathers as knobs and hoodoos; at a place 2 miles distant these beds form a cliff about 70 feet high	26
1. Gypsum and shale, white, yellow, dark red, rarely greenish; gypsum in five or more beds 1 to 5 feet thick, largely concealed	45
	474

Beds totaling 180 feet in thickness below No. 1 appear on the east bank of the Paria, but the base of the San Rafael group is not exposed.

Section of part of the San Rafael group in Dry Valley (Rock Spring Gulch, Cedar Wash), Utah, about 2 miles above its junction with Paria Creek

[Measured by Herbert E. Gregory]

Entrada sandstone and Summerville (?) formation:	Feet
9. Gypsum, massive bed; caps highest hill in this vicinity	1
8. Shale, pinkish, sandy, in very irregular beds	58
7. Gypsum, massive bed	1
6. Shale, pinkish, sandy, with many thin stringers of gypsum; foliation surfaces ripple marked; together with No. 5 forms low rounded hills	32
5. Shale, greenish and red, sandy; many thin stringers of gypsum	11
4. Gypsum, white, massive bed; summit of bed forms a terrace	13
3. Clay shale, soft, very thinly laminated; some greenish laminae; nodular, concretionary; forms an alcove	3
2. Sandstone, pale yellowish white to lemon-yellow, fine-grained, massive but soft and very poorly cemented; grains transparent and uniformly small; outcrops of the rock resemble those of the Navajo sandstone; most of it is cross-bedded or obscurely bedded; forms a cliff	119
1. Shale, red, sandy	2
Carmel formation.	
	240

Section of Morrison (?) formation and San Rafael group near head of Cottonwood Creek, Kane County, Utah

[Measured by Herbert E. Gregory]

	Feet
Dakota (?) sandstone with lenses of course conglomerate and of coal.	
Unconformity.	
Morrison (?) formation and San Rafael group:	
28. Sandstone, yellow and buff, massive, fine, even grained; forms cliff	60
27. Sandstone, in alternating beds of yellow white and dark red, fine, even grained; thickness estimated	100
26. Sandstone, light red to yellow, very friable, massive, strongly cross-bedded; forms vertical cliff	120
25. Sandstone, shaly, pink and green-white; uniformly very fine grained except for pockets that contain fragments of relatively resistant green shale; forms cap for No. 24	30

Morrison (?) formation and San Rafael group—Contd.

	Feet
24. Gypsum, white, specked with green; includes some gypsiferous shale	6
23. Sandstone, white	3
22. Gypsum, like No. 24	4
21. Sandstone, white, banded with red; very fine grained	5
20. Gypsum, white and pink	4
19. Sandstone, pink, green-white, and light red, in discontinuous beds 1 to 4 feet thick; appears as variegated cliff	85
18. Shale, drab, highly calcareous, in beds less than 1 inch thick; weathers to a rounded knoll	45
17. Sandstone, white, flaggy	4
16. Sandstone, red; in five irregular beds, foliation surfaces wavy, firm; forms projecting ledge	4
15. Shale, red, sandy, lumpy, in irregular beds; includes lenses made of porous aggregates of chunks of white and red clay with some small pebbles and fragments of plants	45
14. Sandstone, gray, hard, made of pebbles of shale, quartz, and quartzite averaging about one-eighth inch in diameter, set in coarse sand	1
13. Sandstone, in thin beds, and very thin shale, dark-red, specked with white and yellow; unevenly bedded, cross-bedded; includes lenses composed of red and gray flattened mud lumps; rests on wavy surface of No. 12	28
12. Sandstone, yellow-white; separated by obscure foliation into beds that average about 5 feet in thickness; massive, soft, weakly cemented by lime and iron; grains very small, most of them transparent quartz; cross-bedded throughout; near the top is a hard dark-brown coarse cross-bedded layer; forms prominent cliff	110
11. Shale or thin sandstone, red	4
10. Sandstone, white, fine-grained, cross-bedded; crumbles readily to sand	15
9. Shale, sandy, red and buff, unevenly bedded	7
8. Sandstone, shaly, green-gray, in beds less than 1 inch thick; all highly calcareous, some beds siliceous limestone; on foliation surfaces a remarkable display of ripple marks and worm trails; resistant to weathering	12
7. Shale, red, sandy, calcareous	2
6. Limestone, gray, thin bedded, siliceous, smooth, glistening foliation surfaces	¾
5. Shale, red, sandy; includes two thin beds of gray limestone like No. 6	2½
4. Shale, red, very unevenly bedded, highly calcareous	6
3. Shale, drab or bluish; foliation planes inconspicuous but weathers into thin hard chips; includes layers of fissile calcareous sandstone and of dense limestone, in which are embedded fragmentary fossils	15
2. Sandstone, gray; interbedded with reddish and green-tinted shale in thin wavy and crumpled laminae; weathers as one bed	10
1. Sandstone, gray-green, coarse, discontinuous; in places represented only by scattered sand grains, in other places by a layer of sand an inch or less thick, or by accumulations of sand in hollows or joint cracks in the underlying rock	1
	729+

Unconformity.

Navajo sandstone, yellow-white top, base stained dark brown.

Section 1 mile south of the mouth of Cottonwood Creek, Kane County, Utah

[Measured by Raymond C. Moore]

Cretaceous:

Dakota (?) sandstone.

Jurassic:

San Rafael group—

	Feet
Sandstone, light bluish gray, massive, uniform in color and texture, in part rather hard and projecting as a ledge but mostly very soft and easily eroded	515
Sandstone, maroon, very soft, banded with thin beds of light bluish gray	195
Sandstone, light bluish gray, very soft; contains a few thin bands of maroon sandstone	180
Sandstone, maroon, very soft, with some bands of light-gray hard sandstone as much as 2 feet in thickness; soft gray sandstone increases upward	240
	1,130

Jurassic (?):

Navajo sandstone—

Sandstone, light gray to nearly white, massive, cross-bedded; forms prominent hogback to west.

GLEN CANYON REGION

The southwest front of the Kaiparowits Plateau consists essentially of two enormous escarpments. The lower one, which rises above the Navajo sandstone and has been stripped back from the walls of Glen Canyon, is built of San Rafael and Morrison strata; the upper one is formed of Cretaceous shale and sandstone. The Tropic shale, which separates the two escarpments, has been removed to such an extent that the Morrison, capped by the Dakota (?), forms a bench many miles wide, which is separated into mesas by the deeply trenched streams that flow south to join the Colorado. The trail from Wahweap Creek to Rock Creek winds about the ends of these mesas and into the valleys between, like the course of a ship that is making its way along the bays and promontories of an intricately broken coast line. (See pl. 10, *A*.)

From the Paria River the old Indian trail that leads from the Kanab and Virgin Valleys to the Crossing of the Fathers runs almost continuously between walls or around buttresses of Upper Jurassic sandstone. Little White Rock Gulch, a western tributary to Wahweap Creek, is cut in Morrison strata about 150 feet thick and almost as white as flour. Along Coyote Creek the next lower beds appear—a banded series of cross-bedded white or buff sandstone and dark-red or brown shale that is correlated with the Summerville formation. Some of these sandstone beds are marked by parallel sets of straight cross-bedding laminae; others are evenly bedded and display foliation surfaces covered with sun cracks and patches of mud. They consist of very fine grains of white quartz and some black, green, and red grains and contain also flakes of green-white consolidated mud. The red shale consists of irregular wavy imbricated beds, 3 to 8 inches thick, the lowest beds marked in places by patches and nodular lenses of manganese. For 6 miles above Lone Rock the immediate banks of Wahweap Creek are made up of white and light-red sandstone (Entrada) that forms cliffs 200 feet or more high. Southeastward the Carmel beds appear, and beyond Warm Creek, on the trail through Gunsight Pass, the entire Morrison formation and San Rafael group are exposed. (See pl. 4, *C*.)

Although they differ widely in color, style of bedding, and thickness from place to place, the beds above the Navajo on both sides of Glen Canyon eastward to the mouth of the San Juan present a similar appearance; a variegated basal slope leads to a red wall of massive cross-bedded sandstone that is continued upward by a series of banded red and white sandstone and green-white sandstone. The lower red sandstone, the dominating feature, forms a wall of attractively colored and beautifully decorated rock, in some ways remarkably like the Navajo sandstone but marked by persistent small differences that are easily recognized in the field.

Along Glen Canyon the Carmel formation is exposed to view over large areas, and innumerable shallow canyons make it possible to study its variable features in detail. (See pl. 10, *B*.) In most places the Entrada, Summerville, and Morrison combine to make unscalable cliffs, but in canyons tributary to the Colorado the edges of all beds are successively exposed. On a branch of Kane Springs Creek the Morrison consists of approximately 100 feet of banded red and green-white thin sandstone that overlies 200 feet of gray and brown sandstone whose base rests on the eroded surface of lumpy purple shale. In places along Last Chance Creek the top of the Morrison is irregularly bedded, cross-bedded, and prominently and closely jointed and includes lenses and stringers of conglomerate that carries pebbles more than 2 inches in diameter. The horizon between these beds and the Entrada is represented by only 20 to 50 feet of banded maroon and light-gray sandy shale, which grades along the strike into soft sandstone, and in outlying buttes west of Rock Creek the Entrada and Morrison make a continuous escarpment, the usual intervening shale and sandstone that represent the Summerville being absent.

Near the mouth of Rock Creek the lower beds of the San Rafael group are well displayed. Immediately above the Navajo lies 35 feet of red crumbly very unevenly bedded calcareous sandy shale that includes patches of lumpy sandstone. These beds are succeeded upward by 94 feet of red sandstone, mottled with white, alternating with unevenly bedded sandy red shale that presents many smooth and rippled foliation surfaces. Toward the top these beds become increasingly irregular in thickness and extent, and the highest beds are merely short overlapping lenses that are slightly channeled and together form an uneven surface on which rests the massive Entrada sandstone. This evidence of unconformable contact with the Carmel formation is strengthened by the fact that both the shale and the massive sandstone thicken and thin along the strike to a considerable degree.

Section of Morrison formation and San Rafael group near mouth of Warm Creek, Utah

[Measured by Herbert E. Gregory]

	Ft.	in.
Dakota(?) sandstone; caps buttes and mesas.		
Unconformity shown by erosion channels.		
Morrison and Summerville(?) formations:		
Shale, arenaceous, or shaly sandstone, with lenticular bands of gypsum, dark red; thins, thickens, changes to red-white massive or bedded sandstone, or disappears along strike	28	
27. Sandstone, white and green-white, very friable, even where unweathered; beds 3 to 8 feet thick, marked by planes roughly horizontal; inconspicuous tangential cross-bedding; very fine grains, cemented with gypsum, lime, and ferrous iron; few short red shaly bands in different positions; within a distance of 2 miles this bed is about 130 feet thick and strongly cross-bedded	42	
26. Sandstone or sandy shale, very fine grained, in alternating beds 6 inches to 2 feet thick, dark red and faintly green-white; wavy, crumpled, sun-baked, lenticular on a minute scale; weathers into spools, "rock babies," and hoodoos, fantastic in color and shape; within a mile along the strike this bed is represented by about 10 feet of red and white bands and about 60 feet of massive sandstone	40	
Total Morrison and Summerville(?) formations	110	
Entrada sandstone:		
25. Sandstone, white and green-white, massive, intricately cross-bedded with conspicuous long, flat curves and smaller loops of tangential laminae; very fine grained, most of it in grains too small to be seen with the unaided eye; gypsum and lime cement; contains some angular chunks and flat chips of green mud shale; about 50 feet from the top are three bands, each about 4 feet wide, composed of deep-red shaly sandstone, and a few thin, short bands of the same material are irregularly placed; thickness estimated	400	
Carmel formation:		
24. Shale, sandy, red, in thin, very uneven beds, irregularly imbricated; small patches of sand grains and of mud-shale lumps	30	

Carmel formation—Continued.	Ft.	In.
23. Sandstone, red, and lenses of red shale; at top is a relatively resistant bed of white sandstone 8 inches thick	12	
22. Shale, like No. 20	6	
21. Sandstone, gray, irregular, lumpy; in places massive, cross-bedded; elsewhere breaks into thin slabs covered with tiny ripple marks	1	8
20. Shale, dark red, and beds of thin gray sandstone that become white at the contacts; stratification very irregular, lumpy, wavy; sandstone is slightly cross-bedded and contains fragments of shale; calcareous and ferruginous gypsum as cement and disseminated grains; has appearance of adobe and hardened playa muds	16	4
19. Sandstone, in eight beds, lowest six beds white, 6 to 10 inches thick, separated by paper-thin, imbricated mud shale, crushed and folded, sun-baked; topmost two beds sandstone, banded red and black, with thin, short lenses of dark-red mud shale and streaks of white; much gypsum and some fragments of shale irregularly distributed; grains are white and black quartz, angular and poorly assorted; cement is composed of iron, lime, and gypsum; black grains are bunched in sags of wavy bedding surfaces	20	
18. Shale, dark red, sandy, imbricated, wavy foliation, thin as cardboard		6
17. Sandstone, light red, massive or unevenly bedded, slightly cross-bedded; becomes white from bleaching near the top; much gypsum in crystals, grains, and small lenses; some of nodules lime and crystals of salt	3	
16. Shale or shaly sandstone and sandstone like No. 17, in alternating beds that produce attractive decorative banding on windswept slopes; the shale is lumpy and imbricated, is mottled with round, white dots, and appears like adobe; sandstone fits into pockets made by wavy foliation surfaces of the shale; both shale and sandstone carry much gypsum and lime; in seven beds—		

	Ft.	In.
Shale		5
Sandstone	2	
Shale		6
Sandstone	2	
Shale		6
Sandstone	5	
Shale		8
	11	1

Carmel formation—Continued.	Ft.	In.
15. Shale, very light red, in regular beds as thin as cardboard; beds folded and crushed in places; gypsum, lime, and iron cement; like hardened brittle playa mud; at the base lies white sandy shale, mottled dark red, 2 inches thick, which contains dendrites and many seams of lime and gypsum	8	5
14. Sandstone, light red, friable, in irregular beds 1 to 2 feet thick that have lumpy, wavy foliation surfaces and are separated by thin discontinuous beds of dark-red imbricated sandy shale	6	7
13. Limestone, white, resistant; breaks with conchoidal fracture		1
12. Sandstone, like No. 14	5	5
11. Shale, dark red, imbricated, lumpy; in beds as thin as cardboard; calcareous and gypsiferous	2	
10. Limestone, like No. 13		¾
9. Shale, like No. 11	1	
8. Sandstone, light red, massive, cross-bedded; carries scattered grains of chert and quartz the size of bird shot; a local ground-water horizon	3	
7. Shale, like No. 11		4
6. Limestone, like No. 13		½
5. Shale, like No. 11		5
4. Sandstone, dark red, irregularly bedded; contains lenses and stringers of red and of white shale; all highly calcareous; weathers in rounded knobs	4	
3. Shale, red, lumpy, imbricated, in paper-thin beds; breaks into irregular chips; highly calcareous	2	
2. Sandstone, red, massive, lenticular, cross-bedded, friable, calcareous	1	
1. Conglomerate or coarse sandstone; white to reddish; lenticular; composed of clean-washed irregularly shaped pebbles of white quartz, sandstone, and rare limestone as large as buckshot; along the strike ranges in thickness from layer of grains to accumulations 8 inches thick; contains a ground-water horizon		4
Total Carmel formation	128+	
Total section	638+	

Unconformity, indicated by eroded, wavy, slightly channeled surface of underlying sandstone, by different thicknesses of No. 1, and by abrupt change in lithology.

Navajo sandstone, 800 feet; forms wall of Glen Canyon.

Section in cliff near mouth of Last Chance Creek, Utah

[Measurements by alidade by Raymond C. Moore]

	Feet
Dakota(?) sandstone.	
Morrison formation (and Summerville? formation):	
3. Sandstone, greenish gray; contains some purplish and brown layers and staining; very massive, distinctly but massively bedded, vertical joints rather prominent, gritty	393
Entrada sandstone:	
2. Sandstone, light yellowish gray or cream-colored with irregular brownish patches and layers, very massive, a prominent cliff maker; weathers in smooth, subrounded surfaces with very rare joints; rather uniform in texture, highly cross-bedded, but stratification is not strikingly evident, as in the Navajo	660

	Feet
Carmel formation:	
1. Sandstone, mostly in shades of brick-red to maroon but has some thin grayish-blue layers; thin bedded, in part shaly; contains thin beds of gypsum; a weak formation that makes slopes and flat benches	200
Navajo sandstone.	
	1,253

Bed 3 of this section is 490 feet thick at a point 5 miles above the mouth of Last Chance Creek and is lacking on Wahweap Creek above Wire Grass Spring. Bed 2 is 611 feet thick at a point between Warm Creek and Wahweap Creek, and bed 3 is 166 feet thick at the mouth of Rock Creek.

CRETACEOUS FORMATIONS

PREVIOUS WORK

In his "Last Bluff" section Howell[10] records 2,550 to 2,650 feet of Cretaceous sedimentary rocks in the upper Paria Valley. These strata include 1,500 feet of "cream sandstones and shales," 500 feet of "dark argillaceous shale" (Tropic shale), a "coal series" 150 feet thick, "light-gray sandstone or fine conglomerate" 250 feet thick (Dakota?), and 251 feet of beds believed to be the equivalent of the Morrison and Summerville formations as these terms are used in the present report. Gilbert[11] briefly lists Cretaceous rocks in sections measured on the North Fork of the Virgin River and the West Fork of the Paria River. Both these early observers express doubt regarding the division plane between the Cretaceous and Jurassic—a difficulty experienced also by more recent workers.

For areas that lie within or border the High Plateaus Dutton[12] recognizes the Cretaceous as a widely variable series of sandstone and argillaceous shale that contains coal and has conglomerate of undetermined age at the base. He says that "the upper and lower divisions can be correlated with a high degree of probability with the Laramie and Dakota groups of Colorado, respectively." From distant views he reached the conclusion that

> the Kaiparowits Plateau is a broad belt of Cretaceous strata reaching out southwardly from the Aquarius Plateau and from Table Cliff (an outlier of the Aquarius). At a distance of 60 miles from the latter the Colorado River cuts right across the Kaiparowits, forming the great gorge of the Glen Canyon. South of the river the platform resumes its character, and the Cretaceous spreads out into great mesas deeply dissected by canyons tributary to the San Juan. These Cretaceous mesas cover almost the entire northeastern quarter of Arizona and reach indefinitely eastward.[13]

Like Howard and Gilbert, Dutton expresses uncertainty regarding the Cretaceous-Jurassic boundary.

For the Henry Mountains Gilbert[14] subdivided the Cretaceous into seven formations, which he named, in descending order, Masuk sandstone, Masuk shale, Blue Gate sandstone, Blue Gate shale, Tununk sandstone, Tununk shale, and Henrys Fork group, of which the last consists of yellow fossiliferous sandstone, underlain in turn by arenaceous shale and coarse sandstone and conglomerate with silicified trunks of trees. He remarks:

> The three upper sandstones, the Masuk, the Blue Gate, and the Tununk, are so nearly identical in their lithologic characters that I was unable to discriminate them in regions where their sequence was unknown * * * there is almost equal difficulty in discriminating the Masuk, Blue Gate, and Tununk shales.

Cross[15] met this situation by introducing the term Mancos for the shales above the Dakota and adopting Holmes's term Mesaverde for the series of sandstone. Two divisions thus became the substantial equivalent of the six divisions described by Gilbert. Beds assigned to the Mancos and Mesaverde have been mapped at many places in New Mexico, Arizona, and Utah. However, as the distance from their type locality increases their differences increase likewise. In recognition of this variation it seems desirable to establish for the Kaiparowits region the field terms Tropic shale, of lower Colorado age, roughly the equivalent of the Mancos, and Straight Cliffs and Wahweap formations, which together resemble lithologically the Mesaverde. A series of shales and soft gritty sandstones above the sandstone of the Wahweap formation is here termed the Kaiparowits formation.

The age and correlation of the Morrison formation, now tentatively classified as Cretaceous (?), has been widely discussed by Berry,[16] Lee,[17] Lull,[18] Mook,[19] Osborn,[20] Stanton,[21] Simpson,[22] and others.

[10] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 271, 1875.

[11] Gilbert, G. K., idem, pp. 159–160.

[12] Dutton, C. E., Report on the geology of the High Plateaus of Utah, pp. 154–158, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[13] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 33, 1882.

[14] Gilbert, G. K., Report on the geology of the Henry Mountains, pp 4–5, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

[15] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Telluride folio (No. 57), 1899; La Plata folio (No. 60), 1899 [1901].

[16] Berry, E. W., Paleobotanic evidence of the age of the Morrison formation: Geol. Soc. America Bull., vol. 22, pp. 335–342, 1915.

[17] Lee, W. T., Reasons for regarding the Morrison as an introductory Cretaceous formation: Geol. Soc. America Bull., vol. 26, pp. 303–314, 1915.

[18] Lull, R. S., Sauropoda and Stegosauria of the Morrison of North America compared with those of Europe and eastern Africa: Geol. Soc. America Bull., vol. 26, pp. 323–334, 1915.

[19] Mook, C. C., Origin and distribution of the Morrison formation: Geol. Soc. America Bull., vol. 26, pp. 315–322, 1915; A study of the Morrison formation: New York Acad. Sci. Annals, vol. 27, pp. 39–191, 1916.

[20] Osborn, H. F., Close of Jurassic and opening of Cretaceous time in North America: Geol. Soc. America Bull., vol. 26, pp. 295–302, 1915.

[21] Stanton, T. W., Morrison formation and its relation with the Comanche series and the Dakota formation: Jour. Geology, vol. 13, pp. 657–659, 1905; Invertebrate fauna of the Morrison formation: Geol. Soc. America Bull., vol. 26, pp. 343–348, 1915.

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

Because of its economic significance the Upper Cretaceous of areas adjacent to the Kaiparowits region has received much study. For the Book Cliffs, the San Rafael region, and the eastern Wasatch Plateau several papers have been published.[23] For south-central Utah Richardson's study [24] includes brief descriptions of the coal-bearing Cretaceous of the Kanab region.

AREAL DISTRIBUTION

Approximately half of the Kaiparowits region is occupied by Cretaceous rocks. (See pl. 2.) Unlike the outcrops of the older formations, that of the Cretaceous is fairly compact. Except the comparatively narrow westward extension around the head of the Paria Valley, the Cretaceous area forms a roughly equilateral triangle a little over 50 miles on each side. The base, toward the Colorado River, is very irregular, for there are northward-reaching indentations along each of the streams and southward extensions along each of the divides. The northeast boundary of the triangle is very regular, as it is marked by the appropriately named Straight Cliffs. The west side of the triangle is also remarkably straight from the southwest corner to the point where the Cretaceous beds swing westward into the Paria Valley. This line is defined by the northward-trending East Kaibab monocline. Except the marginal lower benches, the area just described is an upland and is commonly designated the Kaiparowits Plateau.

Southwest of Canaan Peak and the Table Cliff Plateau and southward on the west side of the Paria River, along the east edge of the Paunsaugunt Plateau, extends a somewhat narrow, irregular band of Cretaceous exposures from 2 to 10 miles in width. With some changes in character, particularly of the lower members, this outcrop continues westward, around the south end of the Paunsaugunt and Markagunt Plateaus, into southwestern Utah.

Observations on the Paunsaugunt Plateau show that, contrary to previous mapping, the Tertiary cover is not continuous there. For several miles along the East Fork of the Sevier River near the place where it crosses the Kane-Garfield county boundary erosion has reached the base of the Tertiary and in some places has exposed more than 100 feet of the upper part of the Cretaceous. This condition prevails also along several of the tributaries of the East Fork. Cretaceous rocks lie between the Waterpocket Fold and the Henry Mountains and extend northward a considerable distance toward Castle Valley, forming a connecting link with the Cretaceous of the Wasatch Plateau and Book Cliffs.

TOPOGRAPHIC EXPRESSION

Differences in hardness of the Cretaceous rocks, like those in the other rock formations of the plateau country, are strongly expressed in the topography. Hard massive sandstone is the dominant rock type, and accordingly, throughout most of the Cretaceous area, there are broad plateau surfaces bounded by steep, high cliffs. Valleys carved in the sandstone are narrow, steep-walled canyons. Where the sandstone beds are upturned in the East Kaibab monocline there are long, sharp-crested serrate hogbacks.

The thick shale in the lower part of the Cretaceous section commonly forms more or less intricately dissected slopes beneath the overlying sandstone, and in places, as around the head of the Paria Valley, it is eroded to form broad valleys. The Round and Horse Valleys are rather striking basins that have been excavated in this shale. To the weakness and comparative thickness of this shaly portion of the Cretaceous is doubtless due much of the recession of the Cretaceous cliffs.

The presence of thin beds of sandy shale and shaly sandstone in the middle portion of the Cretaceous sandstone accounts for the clear-cut topographic division into an upper and lower plateau bench. The upper sandstone is overlain by poorly consolidated grit and sandy shale, which in the vicinity of Canaan Peak have been locally carved into badlands.

CLASSIFICATION

As treated in this report the Lower Cretaceous is doubtfully represented in the Kaiparowits region by the Morrison formation, and the Upper Cretaceous comprises all strata between the Morrison and the Eocene (Wasatch formation).

Lithologically and topographically the Upper Cretaceous can be divided readily into five main parts. At the base of the series, resting unconformably on the subjacent rocks, lies a relatively thin formation that consists of irregular conglomerate, hard and soft lenticular sandstone, sandy, more or less carbonaceous shale, and thin beds of dirty coal. This bedding, composition, and texture and the presence in places of considerable petrified wood are features suggestive of the Dakota sandstone. In the Paria Valley, however, the abundant marine fossils in sandstone and thin shale between or below some of the coal beds and the apparent conformity with the overlying shale suggest that this basal grit is intimately related to these succeeding deposits. The coal-bearing basal beds are here termed

[23] Richardson, G. B., Reconnaissance of the Book Cliffs coal fields: U. S. Geol. Survey Bull. 371, p. 14, 1909. Clark, F. R., The Farnham anticline, Carbon County, Utah: U. S. Geol. Survey Bull. 711, pp. 1–13, 1920. Lupton, C. T., Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah: U. S. Geol. Survey Bull. 628, 1916; Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, pp. 115–134, 1914. Spieker, E. M., and Reeside, J. B., jr., Cretaceous and Tertiary formations of the Wasatch Plateau, Utah: Geol. Soc. America Bull., vol. 36, pp. 435–454, 1925.

[24] Richardson, G. B., The Harmony, Colob, and Kanab coal fields, southern Utah: U. S. Geol. Survey Bull. 341, pp. 379–400, 1909.

Dakota (?) sandstone, with recognition of the probability that they are merely homotaxially equivalent to the Dakota of other areas.

Above the Dakota (?) lies a persistent dark shale formation that ranges in thickness from 550 to 1,400 feet. The lower part of this shale contains a typical and fairly abundant basal Mancos fauna. The same fauna and lithologic character are found in the lowest Cretaceous shale division of the Henry Mountains ("Tununk shale" of Gilbert), and there can be no reasonable doubt that the lower part of the shale in the Kaiparowits area corresponds to that division. The upper part, which contains few fossils, probably corresponds to the Tununk sandstone of Gilbert and the Carlile horizon of the lower part of the Mancos shale. In the light of present knowledge it seems best to apply a local name to the division just above the Dakota (?), and the name Tropic shale has been selected on account of the typical exposures and greater thickness of the shale in the vicinity of Tropic, in the northern part of the Paria Valley.

The lower of the two main sandstones that overlie the Tropic shale is partly marine and partly continental. The collections of fossils that have been made indicate that it is of uppermost Colorado age. Faunal evidence indicates that this sandstone corresponds approximately to the lower part of the "Blue Gate shale" of Gilbert in the Henry Mountains. The name Straight Cliffs sandstone is here applied to it because of its typical development in the prominent cliffs south of Escalante.

The upper main sandstone division of the Upper Cretaceous of the Kaiparowits Plateau has yielded almost no fossil evidence, but it probably corresponds to the upper part of the "Blue Gate shale" and to the Blue Gate sandstone of Gilbert in the Henry Mountains. The name Wahweap sandstone is here applied to this formation on account of typical exposures on upper Wahweap Creek.

Above the Wahweap sandstone are coarse but weak grits and sandy muds that contain fresh and brackish water fossils. These beds, which are very readily distinguishable from the underlying formation, are here named the Kaiparowits formation, as they are excellently exposed on the highest part of the plateau of this name.

MORRISON FORMATION (CRETACEOUS?)

CORRELATION

Unconformably beneath the lowermost sandstone beds assigned to the Dakota (?) are the light-colored conglomerate, sandstone, and variegated shale which in Utah, southwestern Colorado, and northern Arizona generally have been mapped as "McElmo formation." Correlation of these beds with those described as "McElmo" by Cross, Darton, Gregory, Lupton, Miser, Moore, and other students of the geology of the plateau province is made with confidence. With few slight breaks they may be traced from the type locality, McElmo Creek, Colo., northwestward to San Rafael, Utah, southwestward to Hopi Buttes, Ariz., and westward to the Paria Valley. It has long been recognized that the "McElmo" includes both marine and terrestrial sediments and that an important (Jurassic-Cretaceous) time break may lie within its variable beds.

The determination by Gregory and Noble [25] that the fossiliferous Upper Jurassic limestones of the Virgin River Valley occupy the position of the basal part of the "McElmo" of the Navajo country, and the discovery by Gilluly and Reeside [26] of another fossiliferous formation in the middle sediments heretofore classed as "McElmo," have led to a reclassification of these beds as the San Rafael group, comprising the Carmel, Entrada, Curtis, and Summerville formations, of known Jurassic age, and the Morrison formation, which is tentatively considered Lower Cretaceous. There is no doubt that the beds here assigned to the Morrison find equivalents in the upper part of most "McElmo" sections and that parts of the San Rafael group are also represented. The Morrison formation of this area consists of the same kind of sandstone, conglomerate, and variegated shale that characterize this formation in northern and eastern Colorado. It includes undetermined amounts of the upper part of the "McElmo formation," as that formation has been defined in papers that deal with the geology of southwestern Utah, northeastern Arizona, northwestern New Mexico, and southwestern Colorado.

AREAL EXTENT AND THICKNESS

In the Kaiparowits region the Morrison formation is well represented along Glen Canyon, the Escalante Valley, and Halls Valley. It appears also in parts of the Paria Valley. The Little White Rock Valley, a western tributary of the Wahweap, derives its name from the white Morrison sandstones that form its walls, and combined with the Dakota (?) and the Summerville the Morrison stands in cliffs that extend from a point near Wahweap Valley to the southeastern extremity of the Kaiparowits Plateau. (See pl. 10, *A*.) Along the Straight Cliffs, the southwestern wall of the Escalante Valley, the formation is continuous for nearly 40 miles. (See pl. 21, *A*.) On Halls Creek it forms nearly vertical westward-facing cliffs from the Bitter Creek divide nearly to the Colorado River.

[25] Gregory, H. E., and Noble, L. F., op. cit., p. 237.
[26] Gilluly, James, and Reeside, J. B., jr., op. cit., pp. 78–79.

In thickness the Morrison shows a great range. From a maximum of about 500 feet on Halls Creek and Rock Creek it decreases generally westward and seems to disappear in the upper Paria Valley. It also thickens and thins within short distances. In most places inaccessible cliffs and extreme irregularity of bedding make it difficult to trace the formation boundaries, but the general lithologic character and topography are so different from those of beds above and below that instrumental measurements are practicable. Thus a section that was carefully measured with alidade at the mouth of Last Chance Creek shows 393 feet of beds above massive Entrada sandstone (see p. 88), which is here 660 feet thick. About 3 miles above the mouth of Last Chance Creek a measurement on the east side of the canyon shows 330 feet of Morrison. At a point near the mouth of the Croton Branch of Last Chance Creek, where the top of the Entrada sandstone is only a short distance above the bottom of the canyon, the Morrison beds (with possible Summerville) are 490 feet thick. On Rock Creek, where the general character and thickness of the Morrison beds are very similar to those on Last Chance Creek, a measurement gave 450 feet in this division.

Westward the thickness of the Morrison gradually decreases, as is readily ascertained by inspection of the sandstone cliffs between Wahweap and Warm Creeks. Near the Crossing of the Fathers, which is 8 miles east of Warm Creek, this formation is about 280 feet thick. Near Castle Butte, between Warm and Wahweap Creeks, it is 140 feet thick. On Wahweap Creek, just east of Lone Rock, the Entrada sandstone is covered by a thin conglomerate that apparently belongs to the Dakota (?) rather than the Morrison, and farther north on Wahweap Creek the Dakota (?) sandstone rests directly on an eroded surface that is carved in the Entrada sandstone. (See pl. 13, *B*.) Likewise at places in the upper Paria Valley and farther west the Dakota (?) appears to rest unconformably on the Summerville. If the Morrison ever existed in this part of the plateau province it was wholly or at least largely removed before the Dakota (?) sandstone was deposited. In the Escalante Valley the Morrison formation ranges in thickness from less than 20 feet to more than 300 feet.

LITHOLOGIC AND STRATIGRAPHIC FEATURES

In mapping the beds between the Navajo sandstone and Dakota (?) sandstone field subdivisions were made that do not correspond wholly with those adopted for the present report. Equivalents of the Carmel formation and the Entrada sandstone were everywhere recognized, and also the massive sandstone phase of the Morrison where it was present. But the presence of many unconformities within the strata above the Entrada made it difficult to set the upper limit of the series of variegated banded sandstone and shale that occupy the general position of the Summerville formation in the San Rafael Swell. Some of the following descriptions of the Morrison therefore doubtless include beds that further study would place in the Summerville.

In many places the Morrison appears as one massive bed, gray, white, green-white, yellowish brown, or reddish brown. In weathering, the formation commonly presents a single massive unit that forms an essentially vertical cliff. Instead of the smoothly rounded, slightly sloping surfaces that characterize the Entrada sandstone, numerous angular projecting joint planes and fracture faces, combined with slight overhanging narrow shelves or depressions along bedding planes give the cliff surface a markedly uneven texture. Tracing the beds along the strike mile by mile, however, reveals an irregularity of stratification not suggested by the general views. In the Escalante Valley the massive sandstone that corresponds to the Morrison becomes in places a series of shalelike beds of the same composition; at Fiftymile Point only shale represents this bed. At the Burr trail and at places along Glen Canyon the massive thick white bed that is so conspicuous along parts of Halls Creek and at the San Rafael Swell is broken up into beds 3 to 10 feet thick. Elsewhere the beds are 30 to 40 feet thick.

In places shale that is assigned to the Morrison lies below massive conglomeratic sandstone; at other places similar shale lies above the sandstone and is terminated upward by the Dakota (?). In different places and at several horizons lie thin beds and lenses of red shale 2 to 3 feet in thickness. This shale is commonly suncracked, the crevices being filled with bluish-gray sand that shows very plainly on the edges of the bed or on sandstone surfaces above the bed. In the portion of the Warm Creek Canyon that is carved in the Morrison some of these interbedded red muds show very clearly the form of broad saucer pans. The suncracked red mud is only a few inches thick and has a uniform thickness for a horizontal distance of 10 to 50 yards; the edges of the mud bed thin abruptly and turn slightly upward. Cross-bedded sandstones inclose these mud pans above and below.

Along the Straight Cliffs, southeast of Escalante, the conglomeratic Dakota (?) sandstone is underlain unconformably by variegated maroon and gray sandy shale, cross-bedded sandstone, and conglomerate. Massive, hard, cliff-forming grits, such as those that occur along the Colorado River, are not prominent in the vicinity of Escalante but are present on the northeast side of the Kaiparowits Plateau, farther southeast.

Along the Waterpocket Fold the general character of these beds seems closely to resemble the beds along the Colorado south of the Kaiparowits Plateau.

In places the Morrison is prominently cross-bedded and consists in large part of coarse grit and conglomerate that contain pebbles 4 inches or less in diameter. The conglomerate appears in very massive beds that grade into coarse grit or cross-bedded sand and in lenses and streaks. The lower part of the formation is commonly somewhat finer grained, though in places there are prominent beds of conglomerate in the upper part.

In Rock Creek Valley an unweathered surface of massive sandstone from which an enormous slab had recently been broken by frost action was examined in some detail. The 40 feet of rock consists of four lenses of conglomerate, one horizontal, the others inclined at angles of 6°, 13° and 28°, and three nearly horizontal lenses of sandstone. It is rusty brown throughout and contains iron nodules and iron coating on some pebbles. The pebbles in the conglomerate, named in order of abundance, are yellow-buff shale, red, green-gray, and white sandstone, chert, quartzite, and quartz. All grains and pebbles are poorly rounded, and thin, flat chips of shale attain lengths of more than 10 inches. With varying degrees of weathering the chips and irregular pebbles of friable sandstone and clay shale are firm or crumbling masses or entirely absent, where the rock has a porous appearance. In talus blocks some of the spaces left by the removal of these less resistant fragments are as much as 2 feet long and 4 inches in diameter.

A microscopic analysis of massive white Morrison sandstone 50 feet below the Dakota (?) at Little White Rock Canyon revealed clear quartz 97 per cent, decomposed feldspar 1 per cent, biotite and tourmaline 1 per cent, calcite fragments (from the cement) 1 per cent. The grains are poorly sorted; about 35 per cent range in diameter from 0.30 to 0.50 millimeter; the remaining 65 per cent grade downward to powder. The larger grains are well rounded, the smaller ones angular. The cement is calcite and some ferrous iron. Hand specimens show small flattened lozenges of deep-red ferrous clayey material. The pale-green color of some specimens comes from ferrous iron, which is generally associated with the gypsum that forms the cement.

STRATIGRAPHIC SECTIONS

The following sections show the arrangement of beds in the Morrison and the relations of the formation to the Dakota (?) sandstone above and the San Rafael group below. Other sections are given on pages 80–88.

Section of Dakota (?) and Morrison formations near south line of sec. 4, T. 41 S., R. 6 E., on west side of Little Red Valley, Kane County, Utah

[Measured by Raymond C. Moore]

	Ft.	in.
Dakota (?) sandstone:		
40. Shale, brown, carbonaceous, sandy (at top).		
39. Coal	4	½
38. Bone		3
37. Coal	1	7
36. Shale, black, carbonaceous and bone	1	6
35. Sandstone, carbonaceous	1	
34. Shale, red		2
33. Conglomerate, coarse, gray to nearly white, locally brown, ferruginous; upper part contains abundant fragments of petrified wood and logs as much as 4 feet in diameter, more or less cross-bedded with white and pinkish sandstone	20	
32. Conglomerate, coarse pebbles 3 inches or less in diameter; contains some layers of cross-bedded coarse sandstone	60	
Total Dakota (?) sandstone	88	6½
Unconformity.		
Morrison formation:		
31. Shale, green, sandy	3	
30. Sandstone, red, shaly	4	
29. Shale, red, with green bands	3	
28. Sandstone, white, soft, coarse-grained, massive	45	
27. Sandstone, gray, soft; contains bands of green shale	3	
26. Sandstone, coarse-grained, white	11	
25. Sandstone, light-brown, soft; contains streaks of shale	3	
24. Shale, green, with red streaks	3	
23. Sandstone, brown, hard	15	
22. Shale, green		10
21. Sandstone, light-colored, coarse-grained	11	
20. Shale, green		10
19. Sandstone, shaly		10
18. Shale, red	1	
17. Sandstone and shale	47	
16. Shale, green		10
15. Sandstone and shale	37	
14. Shale, green		6
13. Sandstone and conglomerate, coarse	10	
12. Shale and sandstone, red	5	
11. Sandstone, brown, coarse-grained to conglomeratic	45	
10. Sandstone and shale, red, with greenish bands	8	
9. Shale, red	6	
8. Sandstone, coarse to conglomeratic, massive	55	
7. Sandstone and greenish shale	3	
6. Shale and sandstone, red	2	
5. Sandstone, coarse-grained, with cross-bedded conglomerate	20	
4. Sandstone, with thin beds of red shale	15	

Morrison formation—Continued.

	Ft.	in.
3. Sandstone, coarse-grained, massive, conglomeratic, with thin band of green shale at top	35	
2. Shale, red		10
1. Sandstone, coarse, with fine conglomerate; weathers in cliffs	25	
Total Morrison formation	419	8

Base covered.

Section of the Morrison formation on Croton Creek Fork of Last Chance Creek, Utah

[Measured by Raymond C. Moore]

	Feet
6. Sandstone, hard, thin-bedded, light yellowish gray	70
5. Sandstone, like bed above but more massive	50
4. Sandstone, yellowish, soft, cross-bedded, somewhat shaly; forms slope or weak cliffs	90
3. Sandstone, variegated dark red and gray; lenticular masses, irregularly bedded	115
2. Sandstone, white, massive	10
1. Sandstone, white; irregularly bedded; base not exposed	80
	415

Section of Cretaceous beds in front of Kaiparowits Plateau south of Tenmile Spring, about 15 miles southeast of Escalante, Garfield County, Utah, in middle part of sec. 4, T. 37 S., R. 4 E.

[Measured by Raymond C. Moore]

	Feet
Cretaceous:	
Tropic shale: Shale, bluish, sandy, grades downward to soft fossiliferous sandstone	400
Dakota (?) sandstone: Sandstone, conglomeratic, buff to almost white, the sandstone coarse to medium-grained, containing lenses of conglomerate with pebbles up to 3 inches diameter, irregularly cross-bedded; forms cliff and prominent bench	90
Cretaceous (?) and Jurassic (?):	
Morrison and Summerville (?) formations—	
Shale, red and light brown, sandy, interbedded with sandstone similar in color, forms slope partly concealed	55
Sandstone, light brown and yellow, fine grained, cross-bedded in part, occurs in massive layers and forms bench	70
Shale and sandstone, red and gray, interbedded, mostly covered	12
Sandstone and shale, red, gray and drab, in thin alternating beds, considerable variation in color and texture	60
Total Morrison and Summerville formations	197
Jurassic: Entrada and Carmel formations	1,250
Jurassic(?): Navajo sandstone.	

Section of rocks exposed in lower prominent bench southeast of Tenmile Spring on Harris Wash, southeast of Escalante, Garfield County, Utah

[Measured by Raymond C. Moore]

	Feet
Cretaceous:	
Tropic shale—	
7. Sandstone, light yellowish brown; rather soft but forms ledge; contains *Ostrea* and other fossils	10–12
6. Sandstone, brown, flaggy	1–2
5. Shale, bluish drab	30
Dakota(?) sandstone—	
4. Sandstone, light bluish gray to yellowish brown; finer and softer in lower part; coarser, harder, and flaggy at top; middle part conglomeratic	50
Cretaceous (?) and Jurassic (?):	
Morrison and Summerville (?) formations—	
3. Shale, alternating bands of reddish brown and gray, sandy, soft	59
2. Sandstone, light creamy yellow, soft; in massive beds 2 to 10 feet thick; upper 22 feet coarse grained and carries lenses of fine conglomerate; locally slumps down to soft sand	81
1. Shale, reddish brown and light gray, in alternating bands, sandy, soft	60
Total Morrison and Summerville formations	200
Jurassic:	
Entrada sandstone; base not exposed	128

MORRISON-DAKOTA(?) EROSION INTERVAL

Throughout the Kaiparowits region the Dakota(?) sandstone rests with more or less marked unconformity on the Morrison or on Upper Jurassic sandstones. In some places this unconformity is indicated by the wedging out of beds beneath the Dakota(?), in many places also by marked irregularities in the surface covered by the Dakota (?) sediments, and, in general, also by a marked change in the character of sedimentation at the base of the Dakota (?) sandstone.

At several places along Wahweap Creek the surface of the fine-grained green-white or white friable sandstone is cut by narrow channels and swales 5 to 15 feet deep; immediately above the sandstone and filling the depressions in its surface lie massive beds of firm gray-brown conglomerate that is composed of pebbles as much as 4 inches in diameter.

Most of the initial Dakota(?) deposits consist of coarse well-rounded gravel that is now tightly cemented and forms a prominent conglomerate bed. It is clear that the deposition of Upper Cretaceous sediments in this region was preceded by a fairly widespread interval of erosion. Some of the phenomena observed require for their explanation no great change in conditions of deposition, but in general it seems that the materials of the Morrison and the Dakota(?) have been derived from different sources and laid down under different conditions. The impression gained from a study of numerous exposures in the Colorado plateau province is that a long period of erosion, which involved the removal of a considerable thickness of strata, preceded the deposition of the Dakota (?) sandstone.

DAKOTA(?) SANDSTONE

LITHOLOGIC FEATURES

The stratigraphic division that is here designated the Dakota (?) sandstone is marked by rather persistent peculiarities in lithologic character, topographic expression, and stratigraphic relations to adjoining rock divisions. The irregularly bedded sandstone includes sandy and carbonaceous shale, poor coal, and locally conglomerate. The pebbles in the conglomerate consist mainly of quartz, quartzite, and chert of various colors; sandstone, hard limestone, vein quartz, and ironstone are not uncommon; and in some places there are rather numerous pieces of compact clay, most of them well rounded, though some have only rounded corners and edges. Most of these pieces of clay are smaller than a hen's egg, but a few are 4 to 6 inches in diameter.

The sandstone is commonly coarse to medium grained, brown or buff, and more or less cross-bedded. Some beds are thick and massive, but most of the individual layers are irregularly lenticular. Some beds are soft, shaly, and rather fine grained and weather readily, but others are tightly cemented and form projecting ledges or rim rocks. The shale is uniformly sandy, and in many places it is dark from included carbonaceous matter.

Thin coal beds, interbedded with streaks and lenses of bone, are very characteristic. Most of them range in thickness from a few inches to about 2 feet. In a very few places the coal is of good quality and forms beds as much as 3 feet thick. Macerated plant material, poorly preserved leaves, lignite, and silicified wood are common. North of Last Chance Creek the amount of petrified wood in the conglomerate at the base of the Dakota (?) is very unusual. In addition to abundant fragments, many logs 2 to 4 feet in diameter lie scattered here and there. The exposed portion of one log measured 90 feet in length. No roots were found in place, and probably the logs that make up this petrified forest drifted to this place and were buried in the gravel of an ancient stream.

The Dakota (?) west of Cannonville includes chunks of shale 4 to 8 inches in diameter and long thin lenses of exceedingly fine grained green-white sandstone within which are embedded pieces of light-green mud shale. These materials are identical in composition and structure with the marly parts of the "McElmo formation" along the San Juan River but are unlike those of the rocks beneath the Dakota (?) along the Paria River.

STRATIGRAPHY

In most parts of southern Utah the Dakota (?) sandstone and the Tropic shale are readily separated, in spite of the fact that they are conformable and that both include sandstone. The even-bedded yellowish-brown friable rock that contains more or less abundant marine fossils, which commonly forms the base of the Tropic, is unlike most of the sandstone in the Dakota (?) formation. But in parts of the upper Paria Valley alternating brown sandstone and sandy shale together with impure coal beds extend upward more than 200 feet from the basal zone of coarse sand and conglomerate that corresponds to a part of the Dakota (?) sandstone of other localities. A number of the beds, some of them almost at the base of the series, contain abundant marine fossils that are typical of the Tropic shale. The clastic lignitiferous deposits evidently represent merely a basal phase of Colorado deposition in this area—an oscillating change from near shore continental deposition to marine sedimentation. In this area a rather arbitrary division of the lowermost Upper Cretaceous strata has been made; the sandstone, coal, and shale below the lowest marine fossil-bearing beds are classed as Dakota (?), and the beds above them, including sandstone and coal, are referred to the Tropic shale. (See section, p. 99.)

In the Cretaceous beds on Willis Creek a few miles southwest of Cannonville, where Mancos fossils were found below the lowest coal, only 6 feet of sandy conglomerate seems referable to the Dakota (?) formation. (See section, p. 99.)

At the head of Rock Creek the beds assigned to the Dakota (?) include 33 feet of cross-bedded coarse sandstone arranged in lenses, above which lie in succession 23 feet of light-gray arenaceous shale that carries scattered quartzite pebbles and thin lenses of sandstone, and at the top 7 feet 8 inches of very impure coal and carbonaceous shale. The carbonaceous shale is conformably overlain by 6 feet of yellow-buff coarse sandstone that contains plant impressions and abundant marine fossils like those in the basal part of the overlying Tropic shale. This fossiliferous sandstone is accordingly referred to the Tropic.

Along Last Chance Creek excellent exposures of the Dakota (?) sandstone show a number of thin beds of lignite. The average thickness of the formation is about 50 feet, but the lithologic subdivisions are very discontinuous; sections less than a mile apart show large differences in detail. The section given on page 96 is fairly typical of a dozen or more measured sections in this vicinity.

On the northeast branch of Croton Creek the conglomerate at the base of the Dakota (?) sandstone has locally a thickness of nearly 100 feet. The pebbles are unusually large, and the lens of conglomerate has every appearance of occupying the channel of a large and vigorous stream.

On the Dakota(?)-capped plateau benches north of Warm Creek coal-bearing sandy shale and sandstone are underlain by massive conglomerate that appears to rest unconformably on thick beds belonging to the Morrison. However, the upper part of the formation has been stripped back a considerable distance, so that, as in the vicinity of Rock and Croton Creeks, the basal conglomerate of the Dakota(?) sandstone is united with the underlying massive Morrison beds to form an extended bench, from which the overlying weaker upper Dakota (?) rocks have been stripped.

On Wahweap Creek good exposures of the Dakota (?) and of adjoining stratigraphic divisions appear in the vicinity of Cottonwood Spring. In general character the formations are like those on Warm Creek and on the Paria, a few miles farther west. The basal conglomerate of the Dakota(?) sandstone is locally as much as 50 feet thick and consists of well-rounded pebbles that have an average diameter of 1 to 2 inches. It rests on an irregular surface carved in Morrison sandstone, and the contact of the dark conglomerate with the nearly white sandstone is very striking.

On the Paria River, about 6 miles below the mouth of Cottonwood Creek, the Dakota(?) sandstone forms a prominent bench that overlooks lowlands carved in soft Upper Jurassic rocks to the south. Some of the thin sandstone divisions here are hard and platy and form strong rim rocks. Near the top there is approximately 5 feet of coal, about half of which is of fairly good quality. The basal conglomerate of the Dakota (?) here is similar to that on Wahweap Creek, except that it is much thinner.

On the northeast face of the Kaiparowits Plateau, in the vicinity of Escalante, the Dakota(?) sandstone consists dominantly of hard massive sandstone and conglomerate, which form prominent benches that extend a mile or two outward from the main line of the Straight Cliffs. (See section on p. 94.)

Along the Waterpocket Fold the Dakota(?) sandstone is well developed in most places and exhibits characters more or less similar to those described for other parts of the Kaiparowits region. Coal beds that are found in parts of the outcrops near the Bitter Creek divide are not preserved elsewhere, and it appears that in some places the Dakota(?) is missing altogether. The section on page 98 shows the character of these beds near the Burr trail, 7 miles north of the mouth of Muley Twist Creek.

The following sections of the Dakota(?) sandstone are representative of many that were measured in the Kaiparowits region:

Section on north side of Last Chance Creek in NW. 1/4 sec. 4, T. 42 S., R. 5 E. (approximate, unsurveyed), Kane County, Utah

[Measured by Raymond C. Moore]

	Ft.	in.
Cretaceous:		
Tropic shale—		
22. Shale, bluish drab to nearly black, clayey, soft; weathers in slope; locally fossiliferous in lower part	650	
Dakota (?) sandstone—		
21. Shale, grayish brown	3	
20. Coal, fairly good grade, bright luster		4½
19. Sandstone, carbonaceous		1
18. Shale, gray to dark, carbonaceous	3	
17. Sandstone, yellowish brown, shaly, rather soft but makes slight projecting rim; fine grained	1	6
16. Shale, brown to gray, clayey	5	
15. Coal, very poor quality, dull luster, dirty; contains thin streaks of light lignite		9
14. Coal, fairly good quality, bright luster, blocky fracture		4½
13. Shale, dark gray, carbonaceous, hard	1	
12. Sandstone, brown, medium grained, cross-bedded, irregular; weathers in hard platy fragments that make a rim	1–2	
11. Shale, brownish gray, very sandy; contains thin beds of sandstone and streaks of brown ironstone	5	3
10. Sandstone, light yellowish brown, medium grained, massive, soft at top; makes a ledge; 330 yards west this sandstone is 8 to 10 feet thick and very massive	5	6
9. Coal, very poor; grades into bone		5
8. Shale, dark gray or dull black, carbonaceous; upper 4 feet very hard and dense	6	
7. Coal, poor quality, dull luster; a few thin streaks of bright coal		7
6. Coal, good quality, shiny luster, subconchoidal fracture, blocky joints		11
5. Shale, dark drab to nearly black, very hard; breaks with subconchoidal fracture; very dense and fine grained; near top grades into very carbonaceous hard rock that resembles bone; contains fragments of plants at top and thin irregular seams of coal	7	6
4. Shale, brown, very sandy	2	
3. Sandstone, bright yellowish gray to almost white, irregularly bedded, soft, friable	1	
2. Conglomerate, very coarse and gravelly, with small amount of cementing material and sand; pebbles 3 inches or less in diameter, average size about three-quarters inch; a single massive brown hard ledge; weathers somewhat readily and makes loose gravel	1–3	
Total Dakota(?) sandstone	46	

Cretaceous (?):

Morrison (?) formation—

1. Sandstone, yellowish gray, medium to coarse grained, irregularly bedded, massive; in part conglomeratic but does not contain large or numerous pebbles; in part irregularly cross-bedded, fairly hard; weathers in cliffs; top exposed; this bed forms the box canyon of Last Chance Creek below this point.

Section of Dakota (?) sandstone and associated rocks about 5 miles above mouth of Warm Creek, Utah

[Measured by Herbert E. Gregory]

	Feet
Cretaceous:	
Tropic shale—	
9. Sandstone, thin bedded, gray, lenticular, with stratum 1 foot thick chiefly of coquina, shells of *Gryphaea* and *Ostrea*—the "oyster beds"	4
Dakota (?) sandstone—	
8. Coal, about half of good quality	2
7. Shale, drab, calcareous; plant impressions	4
6. Coal; lower 2 feet good quality	4
5. Shale, like No. 7	2
4. Sandstone, brown, coarse; a few quartz pebbles and mud balls irregularly placed; cross-bedded; stub-ended and web-shaped lenses; surfaces of a few shale lenses ripple marked, sun dried, and strewn with root prints; some iron concretions; at the base is a lens 3 feet thick and about 80 feet long of dark-red shale with wavy lower surface	13
3. Conglomerate and sandstone, gray-yellow; essentially a series of lenses of coarse sandstone that is traversed irregularly by strings of subangular white quartz pebbles and short lenses as much as 4 inches thick of quartzite, chert, sandstone, and limestone pebbles; full of unconformities, porous; is a water-bearing bed	15
Total Dakota (?) sandstone	40
Cretaceous (?):	
Morrison (?) formation—	
2. Shale, green-yellow and red-brown; arenaceous and calcareous, irregularly bedded, foliation surfaces sun dried and cracked	10
1. Conglomerate and coarse sandstone, all cross-bedded, and some fine sandstone, yellow-brown; arranged as thick lenses that extend for several hundred feet and short stubby masses; many unconformities; in conglomerate lenses occur pebbles of quartz and quartzite of various colors, red chert, sandstone, limestone, and petrified wood, as much as 3 inches in diameter, smooth but not well rounded; beds of fine sandstone, ripple marked; rock porous, probably from weathering of clay lumps and balls of friable sandstone; some impressions of plants	120
Total Morrison (?) formation	130

Unconformity.

Jurassic:

Sandstone, green-white, friable, in beds 6 to 15 feet thick.

Section of part of Dakota (?) sandstone on east side of Paria River 6 miles below mouth of Cottonwood Creek, SW. ¼ sec. 21, T. 42 S., R. 1 W., Kane County, Utah

[Measured by Raymond C. Moore]

	Inches	Ft.	in.
Cretaceous:			
Tropic shale—			
6. Sandstone, yellowish brown, medium-bedded, very fossiliferous; contains *Gryphaea* and *Ostrea*.			
Dakota (?) sandstone—			
5. Sandstone, brown, grades downward into bluish drab; thin bedded, shaly; contains a few zones of clay shale with abundant fibrous gypsum in irregular seams		15	
4. Sandstone, brown, nodular, irregularly bedded, strongly pyritiferous		6	
3. Coal and bone—			
Coal, fair quality, bright to dull luster, but contains very numerous flat nodules of pyrite and lenses of sand as much as 4 inches in thickness	18		
Coal, good quality, bright luster, hard, subcubic cleavage, middle part (5 inches) somewhat bony	19		
Bone	3		
Coal, fair grade but containing thin streaks and lenses of bone	13		
Bone	6		
		5	8
2. Shale, dark, carbonaceous and sandstone at base		35	
1. Covered		20	
Total Dakota (?) sandstone		81	8

Section of lowermost Cretaceous strata on west side of Paria River in SE. ¼ sec. 12, T. 37 S., R. 3 W., about 1½ miles north of Cannonville, Garfield County, Utah

[Measured by Raymond C. Moore]

	Ft.	in.
Cretaceous:		
Tropic shale—		
19. Shale, bluish drab, soft; thickness several hundred feet, not measured.		
18. Sandstone, yellowish brown, hard, massive; forms capping ledge of prominent bench	8–10	
17. Sandstone, brown to nearly black, carbonaceous	6	
16. Shale, carbonaceous, upper part gray, middle and lower portions nearly black	8	
15. Shale, sandy, bluish gray, rather hard	5	
14. Shale, clayey, extremely fossiliferous; in places composed almost wholly of the partly broken remains of oysters	3	
13. Sandstone, bluish to brownish gray, carbonaceous; massive but weathers shaly	2	
12. Shale, brown, carbonaceous, sandy, rather hard		4
11. Coal, impure, poor grade		6
10. Shale, black, carbonaceous; lower part in places a carbonaceous sandstone	2	

	Ft.	in.
Cretaceous—Continued.		
Tropic shale—Continued.		
9. Shale, bluish gray; in places contains fragments of shells	1	6
8. Sandstone, bluish gray, hard; grades into beds above and below	1	8
7. Shale, bluish gray, hard, sandy, very fossiliferous; contains chiefly oysters	2	
Total Tropic shale	40+	
Dakota (?) sandstone—		
6. Coal, hard, impure, but rather even in texture; breaks in angular fragments; not highly lustrous except in few thin streaks	1	9
5. Shale, bluish gray, sandy	3	
4. Sandstone, brown, massive, irregularly bedded	8–10	
3. Coal, poor quality		6–8
2. Shale, yellowish, sandy, soft	20	
1. Sandstone, yellowish, soft, partly covered; contains shaly portions and irregular discontinuous thin streaks of coal	25+	
Total Dakota (?) sandstone	58+	
Covered.		

Section of Dakota (?) sandstone near Burr trail, on the Waterpocket Fold, a few miles north of the mouth of Muley Twist Creek

[Measured by Herbert E. Gregory]

	Feet
Cretaceous:	
Mancos shale; includes "oyster bed" 92 feet above the base.	
Dakota (?) sandstone—	
5. Conglomerate, brown; contains three thin lenses of sandstone; subangular pebbles, mainly chert, quartzite, and quartz, which average three-fourths inch in diameter	10
4. Shale, arenaceous, and thin sandstone, yellow-brown, cross-bedded, lenticular; contains impressions of plants	15
3. Sandstone, coarse, in overlapping lenses; quartz and chert grains well worn but not round; contains scattered pebbles one-half inch or less in diameter and a few iron concretions	14
2. Shale, sandy, and thin sandstone, red-brown; foliation surfaces sun cracked and ripple marked; some worm tracks; abundant iron in grains and black patches	15
1. Conglomerate (75 per cent) and very coarse sandstone (25 per cent), a series of short thick lenses and thin irregular beds, all strongly cross-bedded; pebbles one-eighth inch to 2 inches in diameter of white, red, and black chert, lesser amount of quartzite, quartz, and jasper, some igneous (?); some petrified wood; chunks and balls of compact green-white clay and of calcareous sand, irregularly distributed, weathering of which gives rock a porous appearance; iron concretions in form of pancakes, lozenges, and bolt heads	38
Total Dakota (?) sandstone	92
Unconformity.	
Shale and sandstone, red and green-gray.	

TROPIC SHALE

PHYSICAL AND STRATIGRAPHIC FEATURES

The stratigraphic division that is here designated the Tropic shale consists predominantly of uniform dark-drab clayey shale and fine-textured sandy shale, thinly laminated and soft, which breaks down readily to form slopes and broad, gently undulating flats. (See pl. 14, *B*.) The upper third of the formation is more or less sandy and in places contains thin beds of sandstone. Gypsum is uncommon, but crystals of selenite occur in many places on the weathered lower slopes.

Except in steep cliffs the shale is generally covered by a thin layer of very fine, loose porous débris, which supports a scanty cover of vegetation, and in many places the shale surface is quite bare. In traversing the outcrop a horse may sink above the fetlocks or even to the knees or may find firm footing.

Because this weak formation ranges in thickness from about 600 to 1,400 feet it exerts a profound influence on the topography in the area where it is exposed. Everywhere it has been stripped back so as to form a broad bench, which is underlain by the hard rocks of the Dakota (?), Morrison, and San Rafael formations. The shale composes the moderately steep slopes that lead from the bench to the overlying sandstone cliffs, and in places it forms broad saucerlike valleys. The several hundred feet of uniformly soft dark shale between persistent prominent sandstones, which are distinguished by very uniform and rather striking lithologic characters, by topographic expression, and by distinctive fossils, make this stratigraphic division one that can not be confused with any others in the region.

The base of the Tropic shale is characteristically sandy and highly fossiliferous. In most places, as along the southern bench of the Cretaceous plateaus and along the Straight Cliffs, this basal sandstone ranges in thickness from 1 to 15 feet. It is yellowish brown, friable, and rather evenly bedded and is in most places readily distinguished by its lithologic character and its fauna from the underlying sandstones of the Dakota (?) formation. Along the Waterpocket monocline also the basal sand of the corresponding shale division is very well developed.

In the upper Paria Valley the lower part of the Tropic consists of fossiliferous shale and sandstone which are somewhat similar to the beds seen elsewhere but which contain alternating beds of coal that extend upward as much as 200 feet from the base of the formation. The following section on lower Willis Creek, southwest of Cannonville, shows clearly the character of the lower part of the Tropic as here developed:

Section of lower part of the Cretaceous on Willis Creek near center of sec. 12, T. 38 S., R. 4 W., Garfield County, Utah

[Measured by Raymond C. Moore]

	Ft.	in.	Ft.	in.
Cretaceous:				
Tropic shale—				
14. Sandstone, fine to medium grained, massive and thin bedded; contains several lenses of shale; yellowish but weathers brilliant red in places; a middle bed about 2½ feet thick contains abundant fossil fragments, chiefly *Ostrea prudentia* and a few other pelecypods			75	
13. Coal, appears locally; poor grade and contains shale and sandy material			2	
12. Shale, gray; weathers soft; many fragments of *Ostrea*			20	
11. Sandstone, yellow-brown, middle part dark brown, cross-bedded; contains some fine conglomerate with here and there pieces of charcoal and bands of carbonaceous material one-sixteenth to one-eighth inch in thickness			20	
10. Shale, carbonaceous, upper 6 inches fissile; carries some sulphur			2	6
9. Coal, impure but black and glistening; contains much sulphur				2
8. Shale, gray, weathers soft, many fragments of *Ostrea*			3	
7. Coal, very impure and contains much sulphur; mostly a hard very carbonaceous shale				4½
6. Shale, like No. 14			8	
5. Sandstone, yellow-gray, hard, a single massive bed			1	6
4. Shale, like No. 14			33	
3. Coal—				
Coal, fair quality	2	4		
Bone		4		
Coal, good quality	1	10		
Sandstone, gray		⅝		
Coal, fair quality, contains some sulphur and gypsum	1	2½		
Sandstone, gray		½		
Coal, fair quality; contains sulphur and gypsum		10		
Sandstone, hard, clayey, fine grained, lenticular		2		
Coal, poor quality		4		
Clay		5		
Coal, fissile		3		
Coal, brown, impure, poor quality	1	1		
Shale, bluish, carbonaceous	2	6		
			11	4⅝
2. Shale, gray; weathers soft; many fragments of *Ostrea*			75	
Total Tropic shale			251+	
Dakota (?) sandstone:				
1. Sandstone conglomerate, yellow and white, hard, massive			6	
Unconformity.				
Jurassic: San Rafael group.				

In the broad, wide valley that lies between the Paunsaugunt and Table Cliff Plateaus and surrounds the village of Tropic, from which the formation is named, exposures of the shale are excellent. The maximum observed thickness is about 1,450 feet. However, much of the shale in this area is covered by agricultural soil, by gravel deposits, and by scrub timber. Southwest of Tropic the outcrop of shale is marked by gently sloping benches that extend toward the Paria from the base of the sandstones on the east flank of the Paunsaugunt Plateau, but the width of this belt is decreased by faulting. Southeast of Tropic the Tropic shale is well exposed near Henrieville and along the East Kaibab monocline in the Horse and Round Valleys and along Cottonwood Creek. (See pl. 21, *B*.) The Round Valley is a bowl-shaped depression carved in the Tropic shale where the dip of the beds is rather gentle, but farther south it is a longitudinal valley that is made narrow by the steep dip of the rocks.

The thickness of the Tropic shale at a point several miles north of the Paria River measured 900 feet, but along most of the south margin of the Cretaceous area the average thickness is about 600 feet. Eastward from the Paria River along the south face of the Kaiparowits Plateau, the Tropic shale is exposed as a fairly broad bench at the base of high sandstone bluffs. (See pl. 13, *B*.) Travel along it is fairly easy to Navajo Point, at the south tip, east of the Kaiparowits Plateau, where the bench is too narrow to follow. Beneath the Straight Cliffs the thickness of the Tropic shale ranges from about 550 to 750 feet. Though the width of the exposure is not great the sandy beds at the base extend outward a distance of 1 to 3 miles as a capping for the massive Dakota (?) and Morrison (?) beds. (See pl. 21, *A*.) In the valley of Halls Creek and eastward the Cretaceous shale that corresponds to the Tropic shale is thicker than in the Kaiparowits Plateau.

PALEONTOLOGY

Marine fossils are common in the lower part of the Tropic shale but rare or absent in the middle and upper parts. Locally the basal sandstone is especially rich in fossils. Oysters and Gryphaeas constitute nearly all the organic remains in the shaly beds, but in the sandstone they may be accompanied by other forms.

An oyster bed nearly 3 feet thick crops out near the base of the Tropic on the west side of the Paria River north of Cannonville and together with other fossil-bearing beds is found beneath coal beds. Parts of the oyster bed consist of shale with abundant fossils, but commonly there is little mud between the shells, and the rock might be called a limestone. The species identified are *Ostrea* sp., probably *O. soleniscus* Meek, *Gryphaea newberryi* Stanton, and *Serpula* sp. undet., probably new. The common fossils of the basal sandstone of the Tropic shale are *Ostrea prudentia*, *O. soleniscus*, and *Gryphaea newberryi*, and numerous specimens of these forms are found in most exposures at this horizon.

Some sandy layers in the upper third of the formation contain abundant plant remains.

Invertebrate fossils collected from the Tropic shale at several localities have been identified by John B. Reeside, jr., who has submitted the following report:

Tropic shale, 3 miles north of Henrieville, 100 feet above base. Lower Mancos fauna:

Trochocyathus or Paracyathus n. sp.	Exogyra aff. E. ponderosa Roemer.
Gryphaea newberryi Stanton.	Baculites gracilis Shumard.
Exogyra columbella Meek.	

Basal sandstone of the Tropic shale, from sec. 11, T. 42 S., R. 1 E. Apparently a Colorado fauna, brackish-water habitat:

Anomia propatoris White.	Corbicula? sp. undet.
Modiola multilinigera Meek.	Physa sp. undet.

Fossiliferous sandstone at base of Tropic shale in sec. 10, T. 42 S., R. 1 E. Lower Mancos fauna:

Ostrea prudentia White.	Exogyra aff. E. laeviuscula Roemer.
Gryphaea newberryi.	

East face of Kaiparowits Plateau south of Tenmile Spring and 14 miles southeast of Escalante, Utah. Sandstone in Tropic shale 30 feet above Dakota (?) sandstone. Lower Mancos fauna:

Ostrea soleniscus Meek.	Small gastropod case, undet.
Exogyra aff. E. ponderosa Roemer.	

Same locality as last above, but in shale above the sandstone. Lower Mancos fauna:

Gryphaea newberryi Stanton.	Tellina modesta Meek?

Halls Creek, east of Burr Creek, Garfield County, Utah. Sandstone in basal ("Tununk shale") part of Mancos shale:

Pteria gastrodes (Meek).	Tellina? sp.
Exogyra aff. E. ponderosa Roemer.	Siliqua huerfanensis Stanton?
Ostrea lugubris Conrad.	Mactra utahensis Meek.
Ostrea prudentia White.	Gyrodes depressa Morton.
Cardium trite White.	Mesostoma occidentalis Stanton?
Callista orbiculata (Hall and Meek).	Baculites sp.

Burr trail, Waterpocket Fold, Utah, "Oyster reef" above Dakota (?) sandstone. Lower Colorado fauna:

Barbatia micronema (Meek).	Baculites sp. undet.
Pinna sp. undetermined.	Cardium trite White.
Ostrea soleniscus Meek.	Cyrena securis Meek.
Ostrea prudentia White.	Tellina? sp.
Siliqua huerfanensis Stanton.	Spironema? sp.

Basal sandstone of Tropic shale near the head of Rock Creek. A fauna known at a number of localities in the lower part of the Colorado group in Utah:

Exogyra laeviuscula Roemer.	Cardium trite White.
Plicatula hydrotheca White.	Callista sp. undet.

Miscellaneous specimens from fine-grained light-gray calcareous sandstones in Tropic shale along Last Chance Creek. These species are chiefly those characteristic of the basal part of the Mancos shale in New Mexico and Colorado. Many of them have recently been found at the top of the Graneros shale of the Black Hills region, a suggestion that the beginning of marine sedimentation was appreciably later in Utah than in the Black Hills region.

Serpula sp.	Callista? sp.
Inoceramus sp., fragments.	Corbula nematophora Meek.
Gryphaea newberryi Stanton.	Lunatia n. sp. aff. L. concinna Hall and Meek.
Exogyra columbella Meek.	Turritella whitei Stanton.
Camptonectes platessa White.	Anchura n. sp.
Lima utahensis Stanton.	Baculites gracilis Shumard.
Anomia subquadrata Stanton.	Acanthoceras kanabense Stanton, n. var.
Modiola n. sp. aff. M. meeki Evans and Shumard.	
Veniella goniophora Meek.	

All these fossils appear to indicate the early Colorado or basal Mancos division of the standard Cretaceous section.

STRAIGHT CLIFFS SANDSTONE

PHYSICAL FEATURES

The Tropic shale is conformably overlain by massive sandstones that are very clearly different lithologically from the underlying rocks. In some places the drab-colored shale of the Tropic formation is overlain with rather abrupt change by massive brownish or yellow sandstone of the Straight Cliffs formation, but in general there are 100 to 300 feet of interstratified shale and thin sandstone which appear to represent a transition zone between the Tropic and Straight Cliffs formations. (See pl. 14, *B*.) In this zone the shale is very sandy and toward the top contains increasingly numerous thin beds of hard sandstone. It also resembles the overlying beds in color. Because of these features, which indicate that the change from mud to sand begins at the base of this zone, these intermediate beds are classed with the Straight Cliffs sandstone rather than with the Tropic shale.

The Straight Cliffs sandstone is characteristically composed of very massive beds of light-yellowish or buff-brown fine to medium-grained sandstone. Most of the hard, massive beds are 3 to 10 feet thick, but some that exceed 60 feet in thickness were noted. Where the formation lies essentially flat the sandstone forms nearly vertical unscalable cliffs that present somewhat irregular craggy surfaces. In some places alternations with softer strata and fairly uniform major bedding give evidence of general uniformity in deposition. A view of the Straight Cliffs from the plain a few miles distant on the northeast shows rather clearly this broadly even bedding of the sandstone. (See pl. 14, *A*.) Other exposures show few persistent, readily traceable divisions, and considerable irregularity occurs in both major and minor divisions. This high variability in the thickness and continuity of individual beds, the size of grains, the amount of cross-bedding, the distribution of the ferruginous cement, the degree of porosity, and the resistance to weathering makes detailed measurement of sections and especially comparison of parts of the formation in different areas rather difficult.

A noteworthy characteristic of the Straight Cliffs sandstone is the presence in several parts of this area of workable beds of coal. In some districts there are thin streaks of carbonaceous shale and poor coal at horizons that range almost from the bottom to the top of the formation, but in others there is no coal at all. The chief coal zone is the middle third of the formation, and this zone contains individual beds 15 to 20 feet thick. Some of the coal beds appear to be persistent over several square miles but pinch out in many places rather abruptly.

Much of the Cretaceous sandstone along Last Chance and Warm Creeks is altered by the natural burning of the included coal beds. The sandstone is altered to bright red, baked, and hardened, and the associated shale is changed to a bricklike dark hard argillite or to clinker. Bedding is so much disturbed that in many places it is impossible to determine the original attitude and composition of the strata.

In contrast to the underlying shale, the Straight Cliffs sandstone is resistant to erosion, and as the formation is several hundred feet thick it makes a broad plateau bench that is bordered by high, almost sheer cliffs. The long line of nearly rectilinear cliffs fronting toward the Escalante Valley is made by this division and suggests the name Straight Cliffs, which has been applied to it. Along the south margin of the Kaiparowits Plateau the escarpment formed by the Straight Cliffs sandstone is almost as prominent topographically, but it is very irregular in trend. Along the East Kaibab monocline this sandstone forms the western of the two high sharp-crested "comb" ridges that are made by the upturned Cretaceous sandstone. The canyons that cut through the sandstone are steep walled and in places have vertical sides. (See pls. 19, *B*; 20, *B*.)

In thickness the Straight Cliffs sandstone averages about 1,000 feet. In the Straight Cliffs escarpment it increases from about 900 feet near Escalante to about 1,200 feet at Fortymile Point. Near Wahweap Creek its measured thickness is 950 feet. At the head of Rock Creek it is 1,250 feet. On the east side of the Paunsaugunt Plateau, where its top has been removed by erosion, the remaining portions range in thickness from 700 to 1,200 feet.

STRATIGRAPHY

Because of the practically continuous unscalable escarpment along the Straight Cliffs it is very difficult to obtain detailed information concerning the composition of this sandstone in this part of the Kaiparowits Plateau. However, a section measured by Gregory on Collett Creek shows its character there. (See p. 109.)

At a point on Last Chance Creek where the thickness of the Straight Cliffs sandstone is more than 944 feet the formation consists almost entirely of sandstone with less than 10 per cent of sandy shale and only two or three thin lignite beds in the middle part of the formation. Marine and brackish-water fossils are found at several horizons in this area.

On the main Last Chance Creek, where the lower one-third of the transition beds of the Straight Cliffs sandstone, including the transition beds at the base, is accessible, the middle part of the formation is distinguished by numerous beds of lignite, some of which are as much as 20 feet thick, but as nearly all of this coal above a few feet from the bottom of the canyon is burned, and as the associated sandstone and sandy shale are much altered, neither the quality of the coal nor the composition of the sandstone could be satisfactorily determined.

On the Croton Branch of Last Chance Creek some of the very thin coals are now burning.

On Warm Creek the middle part of the Straight Cliffs sandstone contains thick coals which appear to correspond with those observed on Last Chance Creek. In this area as well as in the area to the east and north, all the coal is burned down to the beds that lie within a few feet of the bottom of the present stream valleys. The name Warm Creek is evidently due to the vapors from burning coal at points along the creek.

Along the upper west branch of Warm Creek the Straight Cliffs sandstone presents some features not shown elsewhere. In 615 feet of beds the thickest bed of massive sandstone is 60 feet thick; in the uppermost 300 feet only three individual beds exceed 20 feet in thickness, and in the lowermost 200 feet only one measured bed is thicker than 10 feet. Coal beds in this section begin 182 feet from the top and extend within 60 feet of the bottom. Within the intervening 373 feet lie 15 beds of coal of good quality, which have a total thickness of 28 feet 10 inches, and 12 beds of earthy lignite and coal mingled with shale.

Along Wahweap Creek excellent exposures of the Straight Cliffs sandstone reveal very few coal beds, and the few that are present are thin and of no value. Marine fossils are found at several horizons, but the distinctive zones that were recognized on Croton Creek were not found here. The same conditions appear to persist along the East Kaibab fold, where the sandstone is very well exposed in the westernmost of the two main Cretaceous hogbacks.

Along Henrieville Creek northeast of the village of Henrieville the entire Straight Cliffs formation is well exposed in a tilted position above the Tropic shale.

Beginning at the base, its large subdivisions and their estimated thicknesses are (1) buff coarse sandstone, of which about half the beds are 6 to 10 feet thick and the other half 1 to 3 feet thick, 160 feet; (2) argillaceous and arenaceous shale and coal, 60 feet; (3) sandstone, a series of shaly or thin beds within which are two or more strata of massive sandstone 10 to 30 feet thick, 120 feet; (4) sandstone, buff, coarse, irregularly bedded, in part cross-bedded and lenticular, in beds 15 to 80 feet in thickness, separated by discontinuous beds of shalelike sandstone, 450 feet. Except for the coal and associated shale of No. 2 and some thin coal beds in No. 3, the entire section, approximately 800 feet, consists substantially of sandstone, highly variable in thickness and continuity of beds, in size of grains, in amount of cross-bedding, in amount and position of iron as cement and concretions, in degree of porosity, and in resistance to weathering. The shale, especially that in the uppermost 400 feet, occurs essentially in lenses of thin-bedded sandstone, some of them as much as 10 feet thick and persistent for more than a mile; in other places the shale occurs in mere patches on uneven surfaces of massive sandstone beds. Argillaceous shale where present is inconspicuous. It occurs sporadically in thin sandstone and as irregular masses of hardened clay within the thick beds. The weathering of these masses has given some beds a cavernous appearance and provided exit for ground water.

A plane-table traverse along this creek shows a total thickness of the Cretaceous sandstone above the Tropic shale of 1,700 feet, but the Straight Cliffs sandstone was not differentiated from the overlying Wahweap sandstone.

The following selected sections show the composition and arrangement of beds in the Straight Cliffs formation of the Kaiparowits region:

Section of Cretaceous strata on south rim of Kaiparowits Plateau, near head of west branch of Last Chance Creek

[Measured by H. E. Gregory with the assistance of J. E. Doneghy]

	Ft.	in.
Straight Cliffs sandstone:		
39. Sandstone, massive, with many iron concretions and some iron cement; weathers to general red tone at base of small knobs and ridges; contains shark teeth; top of plateau	35	
38. Sandstone, coarse grained, buff-yellow, conformable beds 6 inches to 3 feet thick without shale partings	55	10
37. Shale with interbedded sandstone	16	4
36. Débris-covered slope, composed largely of irregularly bedded sandstone	67	6
35. Sandstone, buff-yellow, massive; fine, angular grained; calcareous cement; forms flat bench with vertical cliffs cut by strong vertical joints	83	5
34. Sandstone in thin even beds with stratum of calcareous shale 8 inches thick at base	6	3
Straight Cliffs sandstone—Continued.		
33. Sandstone, massive, largely of clean angular quartz grains	7	
32. Shale, arenaceous, with thin lenses of dark sandstone and of earthy coal	5	4
31. Shale, arenaceous and argillaceous; contains impressions of plants	2	4
30. Sandstone, coarse grained, porous, in even beds 6 inches to 1 foot thick; contains much iron in concretions and nodules; weathers red	27	10
29. Sandstone, massive, buff-yellow; coarse, angular grains	11	2
28. Sandstone with shale partings	1	7
27. Sandstone, buff-yellow, massive	38	7
26. Sandstone, buff, in regular beds 1 to 2 feet thick, interbedded with calcareous shale	17	6
25. Sandstone, yellow-gray; five beds	27	10
24. Shale, arenaceous, sprinkled with iron grains		8
23. Sandstone, fine grains, regularly bedded	2	7
22. Shale, like No. 24		6
21. Sandstone, buff, massive, calcareous and iron cement; coarser grains angular, slightly cross-bedded	41	3
20. Shale, yellow, arenaceous and argillaceous; contains streaks of calcareous material and a few fragments of carbonized wood	3	4
19. Sandstone, buff, composed of fine grains of quartz, most of them angular; calcareous cement; massive, resistant except for an irregular bed or lens of shale 3 inches thick near base	76	3
18. Sandstone and shale in alternating beds 3 inches to 2 feet thick; rich in organic matter; includes a few thin seams of coal	28	3
17. Coal; thin lenticular beds interstratified with carbonaceous shale	2	5
16. Sandstone, thin, and shale like No. 18	14	8
15. Shale and coal: (Ft. in.)		
Shale, arenaceous; contains impressions of plants — 6 in.		
Earthy lignite and lenses of sandstone and shale — 5 ft. 4 in.		
Coal, good quality — 10 in.		
	6	8
14. Sandstone, white, in thin even beds, medium grains of pure quartz, poorly cemented with lime; a few partings of arenaceous shale	9	4
13. Sandstone, white, massive, resistant, slightly cross-bedded, composed of very fine white coarse grains; no iron and no organic matter	29	2
12. Shale, arenaceous, and thin-bedded sandstone	4	2
11. Sandstone, buff, slightly cross-bedded; massive, except for 5 inches of shale 22 feet from the top; fine angular white quartz grains and some larger red iron-coated grains; cement composed of iron, lime, and gypsum (?); porous and gives rise to seeps of water at places where rocks are coated with gypsum	79	3
10. Shale, gray, and sandstone, unevenly stratified in beds and lenses 1 inch to 1 foot thick; shales rich in carbonized plant remains; fragments and impressions of plants also in sandstone	17	8
9. Shale, blue-gray, and earthy lignite	2	7

Straight Cliffs sandstone—Continued.			Ft.	in.
8. Sandstone, buff-gray, in wavelike beds but not cross-bedded; sugary texture; grains prevailingly angular, cemented by lime; few iron nodules			8	4
7. Shale and shaly sandstone, gray, in beds less than 10 inches thick, exceptionally regular; contains much iron, also lime and gypsum as cement and as disseminated particles; forms slope partly covered by landslides			23	
6. Sandstone, buff, in friable beds 1 to 6 inches thick; contains much crystalline gypsum; bottom 3 feet is red porous cross-bedded sandstone through which water seeps			10	5
5. Sandstone, gray, massive, hard, resistant; bottom 10 feet strongly cross-bedded; grains small, white, rounded, and well sorted; contains pebbles as much as 1 inch in diameter arranged in porous lenses and as scattered individuals			41	
4. Sandstone, buff-yellow, compact, cliff maker; grains well worn and assorted; includes five beds:	Ft.	in.		
Sandstone, in vertical cliff, separated into beds by thin lenses of sandy shale and lenses of ironstone containing broken fragments of *Inoceramus* and *Prionotropis*	23	2		
Sandstone, thin bedded, even bedded	8	10		
Sandstone or conglomerate, composed of interleaving lenses of white quartz pebbles 1½ inches or less in diameter	53	4		
Sandstone, fine grained, thin bedded, even bedded, with scattered large pebbles	5			
Sandstone, massive, cross-bedded, weathers porous, solution has produced "toe holes" and miniature caverns	22			
			112	4
3. Sandstone, buff-yellow, cross-bedded; beds 1 to 3 feet thick			20	
2. Sandstone, yellow-gray, irregularly separated into 4 beds			16	10
Total Straight Cliffs sandstone			954	2
Tropic shale:				
1. Shale, gray and slate-colored, and sandstone in beds less than 5 inches thick; shale increasingly more argillaceous, more abundant, and in thinner beds toward the bottom; surfaces of beds decorated with minute concretionary lozenges, plant impressions, and fossil shells			22	
Shale, slate-colored, abundant Mancos fossils.				

Through an accident to the pack train fossils collected from the beds analyzed in this section were lost. A notable feature of the section is the small amount of coal. At a place less than 2 miles distant the equivalent of beds Nos. 9 to 20 contains nine beds of coal, the thickest measuring 23 inches, and more than half of the coal is of good quality.

Section north of west branch of Croton Creek Fork of Last Chance Creek, from sec. 10 to northern part of sec. 27, T. 40 S., R. 5 E., Kane County, Utah

[Measured by Raymond C. Moore]

Straight Cliffs sandstone:	Feet
9. Sandstone, light yellowish brown, very massive, hard, somewhat irregularly bedded; forms prominent cliff and upholds the main Straight Cliffs escarpment; shaly zone 275 feet from the top contains an abundant marine fauna—oysters, gastropods, and other forms	300
8. Sandstone, yellowish brown, soft, more or less shaly, irregularly bedded; forms slope beneath cliff above	110
7. Sandstone, brown, massive, hard; forms prominent rim	25
6. Sandstone, soft, shaly, yellowish brown	20
5. Sandstone, light yellow, medium to massive bedded, moderately soft; weathers in large blocks and in rounded surfaces	160
4. Sandstone, light creamy yellow, very massive, hard; forms box canyons; locally contains very numerous large Inocerami; a ledge maker	115
3. Sandstone, light yellowish gray to light brown, soft, calcareous, medium bedded; weathers in angular blocks	220
2. Sandstone, brown, soft, shaly	30
Total Straight Cliffs sandstone	980
Tropic shale:	
1. Shale, dark drab to nearly black, uniform texture	500+

Section measured on north wall of Bryce Canyon, north part of sec. 5, T. 37 S., R. 3 W., Garfield County, Utah

[Measured by Raymond C. Moore]

Tertiary:	
Wasatch formation—	Feet
14. Sandstone, reddish brown to pink, calcareous; weathers in massive cliffs and fantastic erosion forms, very irregularly bedded; rests unconformably on slightly uneven surface of underlying rocks	100+
Cretaceous:	
Straight Cliffs sandstone—	
13. Sandstone, yellow, coarse and gritty, soft; interbedded with sandy shale and grades into shaly sandstone; in places weathers in slopes; elsewhere occurs in slopes and ledges	42
12. Sandstone, yellow, massive, medium fine grained; forms vertical ledge	17
11. Shale, blue, clayey to sandy; rather soft but in places forms vertical cliff beneath capping sandstone; contains fragments of plants poorly preserved	33
10. Sandstone, yellow and light creamy, fine grained, massive; forms prominent ledge	50
9. Shale, sandy, and yellowish sandstone; form slope with irregular discontinuous ledges	100

Cretaceous—Continued.

Straight Cliffs sandstone—Continued.

	Feet
8. Sandstone, yellow, very massive, somewhat irregularly stratified; weathers in large blocks and more or less smoothly rounded surface; a prominent cliff-making division	95
7. Shale, yellowish brown, sandy; grades into very soft shaly sandstone; forms a slope	28
6. Sandstone, yellow, massive, medium to fine grained, fairly hard; forms ledge, irregularly bedded	32
5. Shale, sandy, drab to yellow; forms slope	40
4. Sandstone, yellow, massive; irregularly bedded and with irregular contact with subjacent division, into which it grades	16–20
3. Conglomerate, sandy, brown, ferruginous; contains many pebbles as much as 1 inch in diameter; parts stained very bright red	27–30
2. Sandstone, creamy yellow, very soft and poorly cemented; weathers readily to loose sand, massive	55
1. Ironstone conglomerate, brown, very hard, a prominent ledge	1–12
Total Straight Cliffs sandstone	535+

Covered to creek bottom, 15 feet more or less.

Base of section undetermined but 100 feet more or less above Tropic shale.

PALEONTOLOGY

Marine and brackish-water fossils are found in many parts of the Straight Cliffs sandstone, and according to identifications by John B. Reeside, jr., all belong to the fauna of the upper (Niobrara) part of the Colorado group.

A very massive fine-grained sandstone about 250 feet above the base of the formation in the southeastern part of the Kaiparowits Plateau contains large numbers of big, thick-shelled *Inoceramus umbonatus* Meek and Hayden, which corresponds to *I. involutus* Sowerby of the European Emscher and Coniacian and in the western interior region is strictly limited to the Niobrara horizon.

A zone about 170 feet above the *Inoceramus*-bearing ledge contains fairly abundant specimens of *Ostrea soleniscus*, *Barbatia micronema* (Meek), *Modiola multilinigera* Meek, and *Ostrea* sp. undet., which also indicate Colorado age.

About 275 feet below the top of the formation on Croton Branch a marine fauna containing *Serpula* sp. undet., *Membranipora* sp. undet., *Ostrea soleniscus* Meek, *Modiola multilinigera* Meek, and *Turritella* or *Chemnitzia* sp. was found in several places. This assemblage is indicated by Reeside as belonging to the Colorado.

On the trail to the top of the Kaiparowits Plateau at the head of Rock Creek, from a bed in the sandstone 180 feet above the top of the Tropic shale, *Nucula coloradoensis* Stanton, *Ostrea prudentia* White, *Modiola* sp.?, *Cardium curtum* Meek and Hayden, and *Gyrodes depressus* Meek were collected, and from about the middle of the Straight Cliffs sandstone on the Coyote Holes trail *Turritella whitei* Stanton, *Ostrea* sp. undetermined, *Cardium pauperculum* Meek, *Plicatula hydrotheca* White?, and *Mactra arenaria* Meek. Both of these lots are referred by Reeside to the uppermost Colorado.

On the summit of the Kaiparowits Plateau, about 10 miles from the south end and within 100 feet of the top of the Straight Cliffs sandstone, pelecypod fragments and specimens of *Corbula perundata* Meek and Hayden were gathered. This species occurs in both the Colorado and Montana groups and is not distinctive.

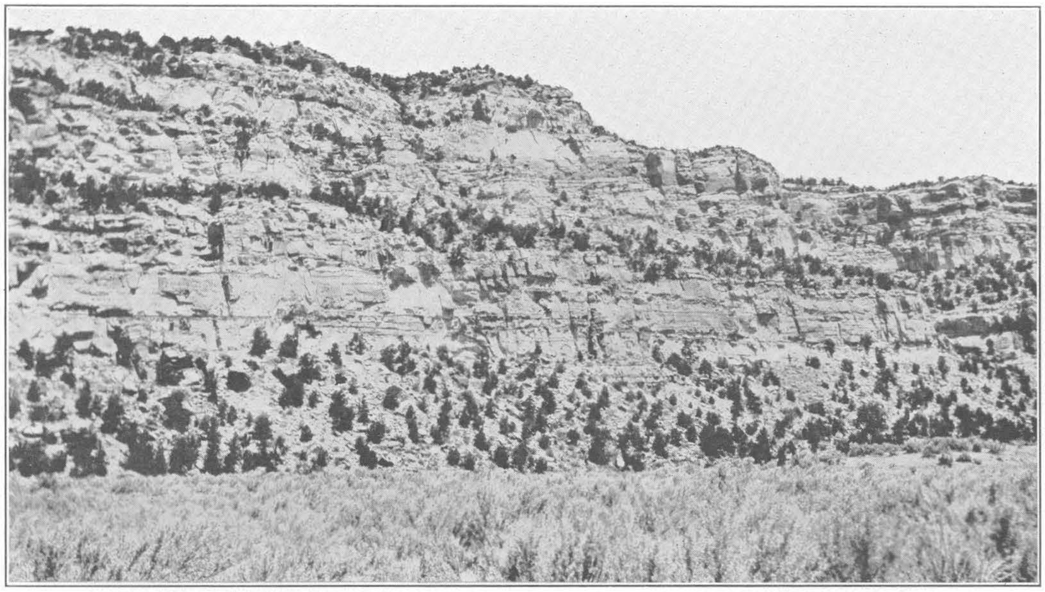
The distribution of marine fossils and coal beds seems clearly to suggest the general position, probably a varying one, of sea and land during the time of deposition of the sandstone in this area. Commonly where coal is well developed no marine fossils are found in the sandstone, but elsewhere, especially toward the east and northeast, marine invertebrates occur at several horizons.

WAHWEAP SANDSTONE

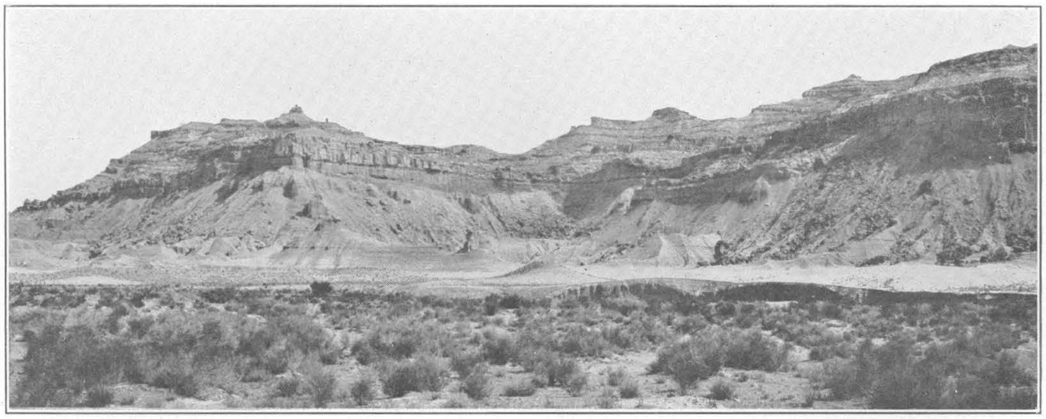
PHYSICAL FEATURES

The term Wahweap sandstone designates a series of sandy shale and massive sandstone that conformably overlies the Straight Cliffs sandstone and underlies the distinctive Kaiparowits formation. As a stratigraphic division the Wahweap is characterized by its topographic expression, the absence, so far as observed, of coal beds, and the scarcity of fossils.

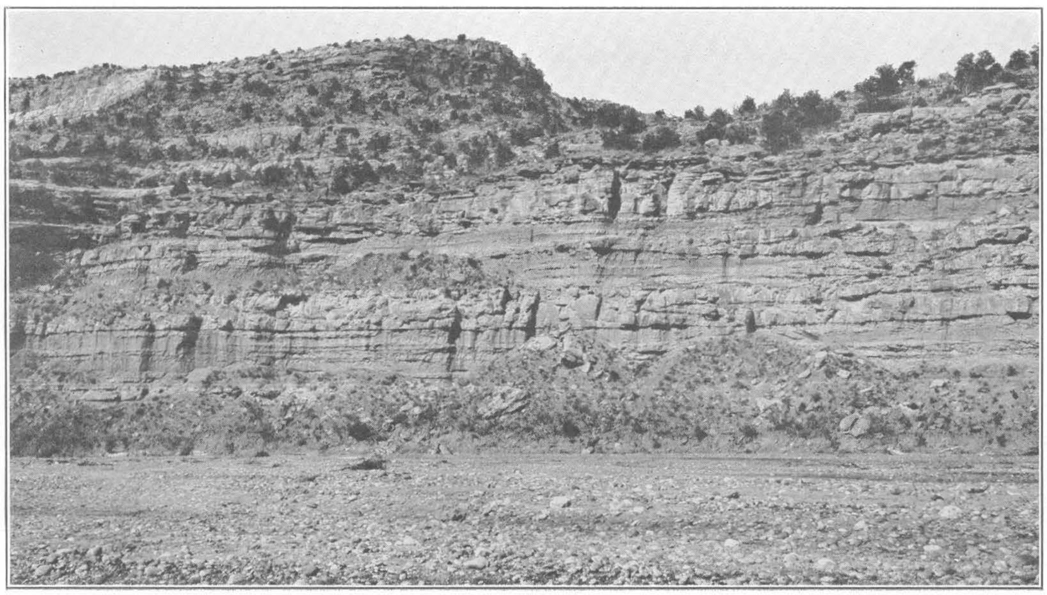
The lower and middle parts of the Wahweap formation consist of alternating groups of sandy shale and sandstone. Toward the top the amount of sandstone and the thickness of sandstone beds increase, and the upper third consists almost entirely of sandstone. In places the topmost bed forms a massive unbroken ledge 100 to 200 feet thick. This arrangement of relatively weak and thin beds underlying resistant thick beds has permitted a recession of cliffs on a large scale; the huge cliffs developed in the Wahweap stand several miles back of those in the Straight Cliffs formation. Where the beds are steeply inclined, as along the East Kaibab monocline, the relatively weak beds in the lower Wahweap mark the position of a longitudinal valley between two hogback ridges. Along the south margin of the Kaiparowits Plateau and in the canyons that dissect its surface the massive upper sandstones form almost vertical cliffs; the capping ledge in particular is an unscalable cliff. The lower sandstones make weak cliffs and benches separated by slopes formed of sandy shale.



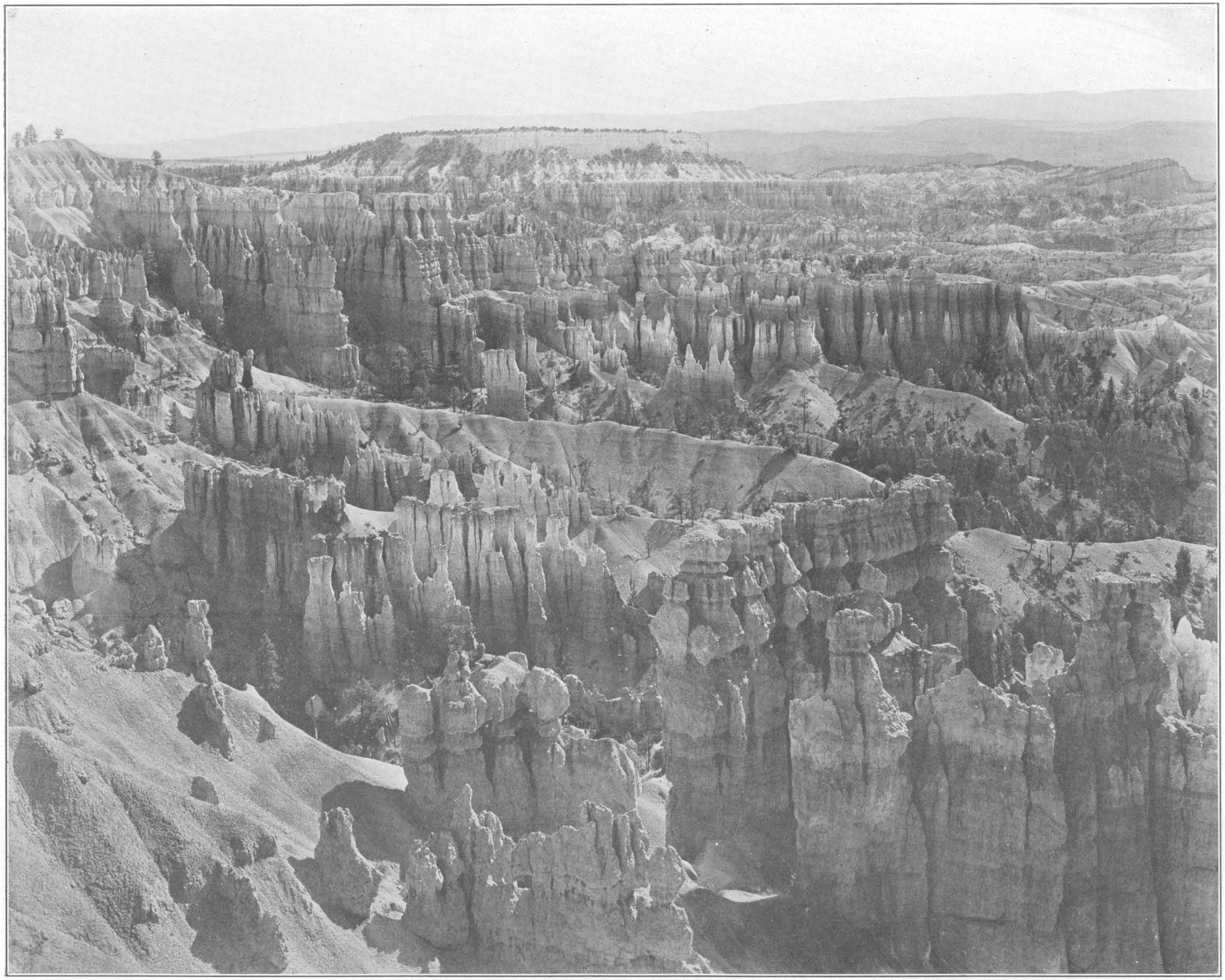
A. STRAIGHT CLIFFS SANDSTONE ON ESCALANTE RIVER WEST OF ESCALANTE



B. TROPIC SHALE OVERLAIN BY STRAIGHT CLIFFS SANDSTONE, WAHWEAP CREEK



C. WALL OF WAHWEAP SANDSTONE, WAHWEAP CREEK



BRYCE CANYON

Rain and running water have carved the partly consolidated varicolored Tertiary rocks of the Wasatch formation into a gorgeous fretwork of pinnacles, spires, and colonnades. Photograph by George L. Beam; used by courtesy of National Parks Association.

Lithologically the sandstone and shale of the Wahweap formation resemble those of the underlying Straight Cliffs formation. In color the sandstone is light creamy yellow or brownish buff; the shale is grayish to greenish brown. In general the bedding, especially that of the large units, is rather even, but many of the sandstone beds are notably lenticular, and the gradation from massive ledges to thin-bedded sandstone and on to very sandy shale is highly irregular. (See pl. 14, *C*.) Some of the sandstone is cross-bedded. In texture most of the materials are medium to fine grained, but in some places near the base of the formation lenses of conglomeratic sandstone were observed, some of which contain fragments of vertebrates.

Measurements of the thickness of the Wahweap sandstone at more than a score of places along the escarpment from the East Kaibab monocline to Last Chance Creek show an average thickness of about 1,250 feet. In the Paria Valley and also north of Henrieville, where the Wahweap sandstone is exposed in a monoclinal fold, the thickness seems to be considerably less.

STRATIGRAPHY

The following section shows the general character of the Wahweap formation:

Section of Wahweap sandstone at escarpment southwest of Last Chance Canyon, sec. 7, T. 40 S., R. 4 E., Kane County, Utah

[Measured by Raymond C. Moore]

	Feet
Wahweap sandstone:	
19. Sandstone, light yellowish brown, very massive, forming sheer cliff; caps plateau	210
18. Shale, brown, sandy	15
17. Sandstone, buff, medium to massive, fairly even bedding with thin shaly partings; forms broken cliff, practically continuous with that of the capping sandstone	60
16. Sandstone, light brown, medium to massive bedding, with alternating thin shaly sandstone divisions; forms steep slope with weak cliffs	130
15. Sandstone, brown, soft, shaly; forms slope	50
14. Sandstone, yellowish brown, massive; forms cliff	20
13. Sandstone, brown, soft, with irregular thin harder beds; weathers in slope	35
12. Sandstone like No. 14	25
11. Sandstone and sandy shale; resemble No. 16	45
10. Sandstone, light buff, medium bedded; forms weak cliff	15
9. Sandstone and shale, mostly covered	30
8. Sandstone like No. 14	40
7. Shale, greenish brown, very sandy, grading to soft sandstone and containing thin hard sandstone streaks; forms slope	145
6. Sandstone like No. 14	30
5. Shale like No. 7	125
4. Sandstone like No. 14	50
3. Shale like No. 7 with a few more prominent sandstone beds forming weak cliffs	185
Wahweap sandstone—Continued.	
2. Sandstone like No. 14	40
1. Shale like No. 7 with 5–7 feet of thin hard sandstone in middle part; in slabby cross-bedded sandstone near base a fish bone was collected	95
Straight Cliffs sandstone.	
	1, 245

Generalized section of the Wahweap sandstone on upper Coyote Creek, T. 41 S., R. 1 E., Kane County, Utah

[Measured by Raymond C. Moore]

	Feet
Wahweap sandstone:	
5. Sandstone brown to yellowish, many thin and massive beds with small amounts of shale; slopes are in large part formed of soft sandstone rather than shale; series is capped by a massive, resistant sandstone about 60 feet thick, which weathers in vertical walls	350–400
4. Shale, brown in lower part, with some gray in middle and upper parts, sandy and cross-bedded; contains many lenses of sandstone that occur very irregularly	300–350
3. Sandstone, brown, similar to other beds in the section; occurs in two beds with shale between	30
2. Shale, grayish brown	20
1. Sandstone, brown to gray, fine grained; exposed	15
	760±

In sec. 33, T. 39 S., R. 3 E., a fragment of a crocodile or turtle bone not certainly determinable was found about 600 feet below the top of the Wahweap sandstone. No fossil invertebrates were collected. In stratigraphic position the formation probably represents uppermost Mancos.

UNDIFFERENTIATED STRAIGHT CLIFFS AND WAHWEAP SANDSTONES

In the northern part of the Paria Valley, along the East Kaibab monocline north of the "Gut," on the east slope of the Paunsaugunt Plateau, and in the valley of the East Fork of the Sevier River and along some of its tributaries on the top of the plateau the Cretaceous sandstones include the Straight Cliffs and Wahweap formations. Southeast of Table Cliff a very complete section of the two sandstones is exposed. They were not separated in mapping, but plane-table measurements and projection of dips and trigonometric computation indicate a combined thickness of 1,700 feet. Similarly, a complete but unstudied section of the sandstones lies south of Widtsoe, but farther west pre-Tertiary erosion has removed the upper part of the Cretaceous so that the Eocene now rests on different parts of the Wahweap and Straight Cliffs sandstones. In Bryce Canyon only a little over 600 feet of the sandstone remains between the top of the Tropic shale and the base of the Tertiary. Where erosion has so largely reduced the original thickness of these sandy parts of the Cretaceous, the remaining rocks presumably belong chiefly to the Straight Cliffs sandstone, but no attempt was made to distinguish the formations, which are so clearly differentiated on the Kaiparowits Plateau. However, most of the study of the Cretaceous beds in the northern Paria Valley was undertaken before the mapping of the rocks on the Kaiparowits Plateau, and it is probable that more detailed field work would result in a separation of the two formations in this region.

On the Escalante-Widtsoe road in sandstone that corresponds to one of the two formations above the Tropic shale occurs a thick bed of well-rounded pebbles of quartzite and chert that range in diameter from half an inch to 5 inches and are of many colors. Associated with the conglomerates are thin, short gravel lenses, shale balls, and sandstones on the surface of which occur impressions of twigs and of a log nearly 3 feet in diameter. The significance of these observations with relation to studies farther south has not been determined.

KAIPAROWITS FORMATION

Most published sections of Cretaceous strata in northern New Mexico, northern Arizona, and southern Utah include representatives of the Dakota(?), Mancos, and Mesaverde formations of southwestern Colorado. Wherever present, the Mesaverde or in some places thick beds of sandstone in the Mancos give rise to prominent cliffs and form the surfaces of plateaus that are flanked by slopes of Mancos shale and rise high above surrounding platforms of Jurassic sandstone. At most places the latest Montana Cretaceous strata have been swept away by erosion or remain as inconspicuous hills and ridges. Along the headwaters of the Paria River, Wahweap Creek, and the west branch of Collett Creek beds appear that are younger than the Wahweap sandstone. At Kaiparowits Peak and Table Cliff these beds occupy the position between the Wahweap sandstone and the massive Wasatch formation. About 2,000 feet of the beds have been preserved where they are protected from erosion near the Table Cliff Plateau. For these beds, which constitute the topmost Cretaceous of southeastern Utah, the term Kaiparowits formation is proposed.

As viewed in the field, the Kaiparowits formation is strongly contrasted with adjoining formations. The Wahweap sandstone below is buff and resistant to erosion, and the outcropping edges of its constituent beds form cliffs that are difficult of ascent. The Tertiary (Wasatch) limestones above are a brilliant pink and likewise form practically unscalable cliffs. The Kaiparowits, which lies between, presents tones so dark that they appear in some lights almost black, and except for inconspicuous shelf-like benches it forms a series of inclined surfaces that unite on intervalley spaces to form a general slope from the top to the bottom of the formation. The rock is so friable that the water from the infrequent storms has cut a tangle of gullies and canyons, remarkable for their number and for the steepness of their sides. In dry weather the gentler slopes and the intertangled ridges may be traversed by carefully selected routes, but during showers the whole surface seems to move downward, and travel with horses is dangerous.

At a distance the Kaiparowits appears to consist of shale beds with here and there thin lenses of sandstone, but on closer examination the predominant rock proves to be fine-grained drab arkose sandstone, composed of quartz, orthoclase, albite, and biotite cemented by lime. Many of the feldspar grains are kaolinized and in contrast with the abundant biotite give the rock the appearance of a mixture of coarse pepper and salt. Most of the individual beds are less than 5 feet thick and die out within a few hundred feet. The few that were traced for a greater distance differ in thickness and in the arrangement of the prevalent cross-bedding. Within and between the sandstone beds lie thin, flat lenses and stub-ended lenses of slightly more firmly cemented sand grains, which are commonly of lighter color, some of them buff or yellow.

In addition to the sandstone, the Kaiparowits formation contains lenses, pancakes, flattened balls, and irregular beds, some traceable for as much as 100 feet, of brown, gray-green, and white sandy limestone. Some thin lenses are composed of nearly pure limestone—hardened calcareous silt sprinkled with sand above and below. The formation includes also lenses of limestone conglomerate composed of concretionary balls and irregular chunks of limestone, mingled with sand. From these lenses fossil shells and fragments of bone were obtained at several horizons. At Table Cliff the topmost strata of the Kaiparowits formation are less friable than those beneath; they include beds of coarse brown sandstone, lenses of sand firmly cemented by iron, and lenses of conglomerate composed of pellets of hardened limy mud and chips of arenaceous shale.

Along the upper tributaries of Wahweap Creek the Kaiparowits formation is widely exposed to view and constitutes rough badland slopes that are intricately cut by gullies and shallow canyons. At the east end of the narrow pass through the East Kaibab monocline, locally known as the "Gut," the following section of the lower part of the formation was measured:

Section of lower part of Kaiparowits formation in upper Wahweap Valley

[Strike of beds, N. 10° E.; dip, 2° E. Measured by Herbert E. Gregory]

	Feet
Cretaceous:	
Kaiparowits formation—	
17. Sandstone, general color drab or dark brown but unweathered parts are irregularly speckled dark and light, resembling a mixture of pepper and salt; numerous lenses of sandstone of uneven degrees of fineness, of hardened mud, and of sand and limestone interrupt the regularity of bedding; some beds contain cavities from which gray-green mud lumps have been weathered; sand grains are composed of quartz, orthoclase, albite, and biotite and are held together weakly by calcite and gypsum cement	36
16. Conglomerate composed of clay lumps, hard calcareous bullets, angular pieces of limestone and small bits of petrified wood in a sandstone matrix; contains impressions of plants and broken fossil shells	2
15. Sandstone, brown, calcareous; massive; resembles the limy mud walls of present valleys; bed extends about 300 feet	15
14. Sandstone, like No. 17	20
13. Sandstone, like No. 16	12
12. Limestone, brown, hard, sandy	2
11. Sandstone, brown, drab, and buff, very unevenly bedded, heterogeneous composition; two sections half a mile apart show different arrangement of beds; entire exposure appears as shale slopes that are separated by sandstone cliffs 6 to 15 feet high, but the "shale" thickens and thins and in places appears to sweep diagonally across horizontal sandstone beds; essentially the outcrop is formed by a series of sandstone beds, which continue for a few hundred feet to a few miles and are interrupted and interspaced with lenses of buff, spotted, and brown sandstone, some friable, some resistant; includes lenses of lumpy clay, of sandy limestone, and of conglomerate composed of lime balls; no continuous argillaceous beds were seen; iron-cemented masses that resemble lozenges, pancakes, and irregular lumps occur in many positions, also plant impressions, crushed shells, and fragments of bone	144
10. Sandstone, buff and green-yellow, arenaceous and calcareous, and mud shale, in irregular beds 1 to 8 feet thick, friable and slightly concretionary	50
9. Sandstone, brown; dense, cross-bedded; resistant, with a few lenses of friable sandstone	35
8. "Shale," compacted mud, and fine sand in poorly defined beds 4 to 8 feet thick that alternate with beds of friable brown sandstone 1 to 5 feet thick; contains a thin lens of earthy lignite	30
7. Sandstone, like No. 9	10
6. "Shale," like No. 8	30
Cretaceous—Continued.	
Kaiparowits formation—Continued.	
5. Sandstone, like No. 8	6
4. Sandstone, irregularly bedded; contains lenses of thinly laminated gray mud with patches of impure lignite, otherwise like No. 11	35
3. Sandstone, brown, resistant to weathering; contains lenses of conglomerate composed of hardened mud lumps; forms prominent bench	6
2. Sandstone, like No. 11	45
1. Shale, like No. 8	16
	495
Sandstone, buff, firm, massive, cross-bedded, considered top of Wahweap formation.	

The equivalent of the Kaiparowits formation beneath Table Cliff was described by Howell [27] as 1,200 to 1,500 feet of "gray arenaceous (and argillaceous) shales containing an elongated form of *Physa*, *Limea*, and two species of *Viviparus*, a single specimen of a small oyster, and some fragments of large bones." He assigned these beds to the Tertiary but recognized the difficulty of correlating them with other Tertiary deposits in Utah.

Fossils collected near Canaan Peak were studied by Reeside, who submits the following report:

> Unio sp., internal cast of much elongated species like U. danae Meek and Hayden.
> Unio sp., internal cast of short triangular form like U. brachyopisthus White.
> Unio aff. U. neomexicanus Stanton.
> Physa sp., cast of large species like P. reesidei Stanton.
> Viviparus panguitchensis White.
> Viviparus sp., cast of large rounded form like V. leidyi Meek and Hayden.
> Viviparus or Campeloma sp., small internal casts.
> Campeloma sp.
> Goniobasis subtortuosa Meek and Hayden.
> Goniobasis sp.
>
> This fauna seems to me to be nearest the fauna of the Fruitland formation of New Mexico; it is probably not older than middle Montana.
>
> At a horizon about 150 feet above the base of the Kaiparowits formation, in the northeastern part of sec. 27, T. 38 S., R. 1 E. (unsurveyed):
>
> Goniobasis? subtortuosa Meek and Hayden.
> Viviparus conradi Meek and Hayden?
> Bulinus subelongatus Meek and Hayden?
> Campeloma sp.
> Viviparus? sp.
>
> Suggests Judith River fauna or perhaps Fruitland; fresh-water habitat.
>
> In the lower part of the Kaiparowits formation in the central part of sec. 17, T. 39 S., R. 2 E. (unsurveyed):
>
> Unio sp., apparently a smooth oval species suggesting U. danae Meek and Hayden.
> Unio sp., apparently a smooth triangular species suggesting U. brachyopisthus White.

[27] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 271, 1875.

Age undeterminable. These fossils may be as late in age as the Fruitland formation of the San Juan Basin, which is upper Montana, and are probably not older than middle Montana.

Fragmentary vertebrate material examined by Prof. R. S. Lull includes the following forms:

Part of a turtle shell, Baena sp. Range: Judith River to Uinta.
Vertebra of ceratopsian dinosaur, cf. Triceratops sp.
Large Trachodon-like dinosaur. Distal end of left humerus and articular end of scapula.
Distal end of right tibia about two-thirds the size of Trachodon annectens.
Ungual, probably Trachodon.
Two or three unidentifiable bone fragments.
Dinosaurs probably Lance in age; turtle not debarred.

COMBINED SECTIONS

In addition to the sections describing the character of different subdivisions of the Cretaceous which have been presented above, measurements of two or more of the Cretaceous divisions were made at a number of places. For convenience, some of these combined sections, which afford a basis for comparison of the Cretaceous of the Kaiparowits Plateau with formations of that age in surrounding regions, are presented here. A section measured by Moore at the Bitter Creek divide, between the Circle Cliffs and the Henry Mountains, has been published.[28]

Section across Waterpocket Fold at Burr trail, 7 miles north of the mouth of Muley Twist Creek, east side of Circle Cliffs, Garfield County, Utah

[Measured by Raymond C. Moore]

		Feet
Cretaceous:		
Mancos shale—		
Blue Gate sandstone member—		
17. Sandstone, yellowish brown, massive; forms prominent escarpment that terminates in vertical cliff		276
"Blue Gate shale" of Gilbert—		
16. Shale, bluish drab, sandy, very uniform texture and color, soft, weathering in badlands		1,100
Tununk sandstone member—		
15. Sandstone, white, calcareous, cross-bedded, grading to yellow flaggy sandstone, soft and massive below; thin lignite bed 23 feet above base		65
"Tununk shale" of Gilbert—		
14. Shale, dark bluish to greenish drab, sandy; contains selenite crystals; two thin sandstones, 8 inches to 1 foot thick, dark brown, hard, flaggy, separated by 5 feet of shale, occur 300 feet below top; near middle part occurs thin soft sandstone that contains hard dark-brown concretions; at base lies 6 to 8 feet of soft brown calcareous sandstone with abundant marine invertebrates		950
Dakota (?) sandstone—		
13. Sandstone, light creamy yellow, soft, massive		12
Cretaceous(?):		
Morrison formation—		
12. Shale, light bluish, with thin bands of red, sandy, soft		230
11. Sandstone, shale, and conglomerate—	Feet	
Sandstone, yellowish brown, conglomeratic	5–7	
Shale, bluish drab and red, sandy	20	
Sandstone, reddish brown to light greenish, coarse grained, massive	5	
Shale, yellowish brown, sandy	15	
Conglomerate and coarse grit, reddish and light greenish gray, massive, hard, very irregularly bedded; forms prominent hogback	80	
		126
Jurassic:		
San Rafael group—		
Summerville and Entrada formations—		
10. Sandstone, red, thin bedded, soft, partly concealed, and white sandstone, grading downward to tan-brown, massive, soft, cross-bedded, weathering readily, partly concealed		1,430
Carmel formation—		
9. Shale, light red and greenish, gypsiferous; contains some beds of hard white sandstone and gypsum		170
8. Shale, maroon and light greenish, sandy, capped by hard, dense siliceous limestone, massive to flaggy		45
Jurassic(?):		
Glen Canyon group—		
Navajo sandstone—		
7. Sandstone, light yellow to white, medium grained, very massive, highly cross-bedded; the bedding etched in relief by weathering; crops out in high ridge or "reef"; near top is thin coffee-colored sandstone		1,260
Todilto(?) formation—		
6. Sandstone, brick-red; contains a few thin white and light-blue layers and lenses, thin bedded, cross-bedded, hard and soft; forms valley between Navajo and Wingate escarpments occupied by headwaters of Muley Twist Creek		214
Wingate sandstone—		
5. Sandstone, red, massive, rather fine grained, hard, prominently jointed; crops out as single massive ledge that forms sheer cliff; cross-bedded		260
Triassic:		
Chinle formation—		
4. Limestone and calcareous shale, light blue, mottled with lavender, in upper part; sandy shale and sandstone in lower part, darker colored, brown, purple, and blue		475

[28] Longwell, C. R., and others, op. cit., pp. 21–22.

Triassic—Continued.

Shinarump conglomerate— Feet

3. Sandstone, light bluish; grades to sandy bluish-green shale; does not form prominent escarpment 40

Moenkopi formation—

2. Sandstone and sandy shale, chocolate-brown and light yellow, thin bedded; thickness in part estimated 500

Permian:

Kaibab(?) limestone—

1. Limestone, arenaceous, yellow, dolomitic, fine grained, dense; bottom of exposure 70+

Section at Collett Canyon, beginning with lowest beds near mouth of canyon (dip 4° S.) and extending 5 miles south (dip about 1° S.)

[Measured by Herbert E. Gregory]

Cretaceous:

Straight Cliffs sandstone—

31. Sandstone in fine beds, not studied in detail, thicknesses estimated— (Ft. | Ft. In.)

	Ft.	Ft.	In.
Sandstone in beds 2 to 5 feet thick, lenticular; contains iron concretions; weathers red	30		
Sandstone, buff, massive, slightly cross-bedded; contains lenses of conglomerate	50		
Sandstone, thin bedded, irregularly bedded, and arenaceous shale, buff	60		
Sandstone, buff, massive	40		
Sandstone, thin bedded, and arenaceous shale	40		
		220	

30. Sandstone, buff, massive; fine quartz grains cemented by iron and lime and some gypsum; includes a few lenses of thin-bedded fine sandstone, of conglomerate with pebbles as much as 1 inch in diameter, and of arenaceous shale, with plant impressions and carbonized fragments 83

29. Coal and shale—

	Ft.	In.
Shale, drab, argillaceous; surface strewn with coarse sand grains	10	
Coal, earthy		8
Shale	1	
Sandstone, buff, imbricated, lenticular	2	
Shale, arenaceous	4	
Coal; contains shale partings	2	1
Shale, drab	4	
Coal, good quality	2	4
Shale, drab, contains impressions of plants	2	
Sandstone, buff; contains leaves, stems, and shells	1	
Shale, drab	8	
Coal, good quality	1	1

Cretaceous—Continued.

Straight Cliffs sandstone—Continued.

29. Coal and shale—Continued.

	Ft.	In.	Ft.	In.
Shale, drab, and thin sandstone	3			
Coal		6		
Shale, arenaceous, and earthy coal; many fossils	8			
Shale, drab, argillaceous		10		
Coal, good quality	2			
Shale, drab, argillaceous	5			
Coal, good quality	5	1		
Shale, drab	2	2		
Coal, good quality	4	2		
Shale, drab		6		
Coal, good quality, with a few thin shale partings	7			
			76	5

	Ft.	In.
28. Sandstone, buff, massive, cross-bedded; near top are strings, disconnected lenses, and chunks of black shale arranged in capricious manner	75	
27. Sandstone, buff, in beds 1 to 3 feet thick	15	8
26. Shale, gray-black; consists of hardened sandy mud, plant fragments, and earthy coal	8	6
25. Sandstone, buff, thin bedded; contains a few very irregular lenses of blue-black shale; sandstone is cross-bedded and shows ripple marks and tracks	17	7
24. Sandstone, buff, in general massive, essentially one bed, but includes lenses of thin-bedded sandstone and a few of drab shale, and 25 feet from the bottom strings of quartzite pebbles half an inch or less in diameter extend for several hundred feet, also a few lenses of coarser gravel; thickness estimated	80	
23. Sandstone, buff, in beds 2 to 4 feet thick, separated by beds a few inches thick; contains few lenses of buff arenaceous and calcareous shale and two of blue argillaceous shale, many fragmentary plant and shell fossils	22	
22. Shale, blue-black, argillaceous and gypsiferous; makes a lens that extends for about half a mile; forms impervious bed above which water emerges	13	
21. Sandstone, gray-buff, massive, slightly cross-bedded, fine quartz grains, calcareous cement; includes a few lenses of thin-bedded sandstone and streaks of clay shale	52	
20. Sandstone, gray, in irregular beds 6 inches to 2 feet thick	8	6
19. Sandstone, buff-gray, massive	10	
18. Shale, buff, sandy, lenticular; includes abundant impressions and fibers of plants and three thin lenses of impure coal	9	4
17. Sandstone, brown, imbricated, firmly cemented by iron and lime, strongly cross-bedded; at high angles rests on locally eroded surfaces of No. 16	10	7

	Ft.	in.
Cretaceous—Continued.		
Straight Cliffs sandstone—Continued.		
16. Sandstone, gray-buff, medium grained, some streaks of fine gravel, massive, cross-bedded except for concretionary nodules of iron and of lime	19	10
Total Straight Cliffs sandstone	721	3
Tropic shale—		
15. Shale and sandstone; at base slate-colored shale that carries gray sandstone lenses; in the middle lenses of sandstone and of shale, about equal amounts; at the top sandstone beds 2 to 4 feet thick, including some chunks and stringers of buff argillaceous shale; all beds differ widely in thickness and composition within short distances	25	
14. Shale, blue-black, blue-gray, or slate-colored, except for two red iron-stained beds near the top and two light-gray thin calcareous beds near the base; mostly thin bedded, uniformly argillaceous, except for three thin beds of fine clean-washed quartz sandstone and the calcareous beds, which range from almost pure limestone to calcareous clay shale; lime is probably present throughout; even densest blue-black specimens effervesce with hydrochloric acid; gypsum abundant, especially in the upper half, where it appears as crystals of selenite, as coating on foliation surfaces and joint cracks, and as disseminated grains; many foliation surfaces are lumpy, and small concretionary masses of lime are irregularly distributed; where protected by sandstone caps forms dark cliffs, elsewhere badland slopes, coated with spongy gypsiferous "marl"; measured 320 feet, estimated an additional 220 feet	540	
13. Sandstone, buff, thin-bedded, friable; quartz grains, mostly angular, cemented by lime, gypsum, and iron; at the top a brown lenticular cap of coarse sandstone that includes chert pebbles	18	10
12. Sandstone, buff, shaly, friable, highly calcareous; includes 2 feet of coquina essentially composed of fragments of *Ostrea*, *Exogyra*, and *Gryphaea*	6	
Total Tropic shale	589	10
11. Shale, buff-gray, or thin-bedded sandstones	8	4
Dakota(?) sandstone:		
10. Sandstone, buff, many angular quartz grains; at the top partly carbonized plant fragments form a layer 1 foot thick	3	
9. Shale, gray-black, uneven, lenticular	6	9
Cretaceous—Continued.		
Dakota(?) sandstone—Continued.		
8. Coal, earthy, upper 8 inches of good quality	2	8
7. Shale or shaly sandstone, gray, lenticular		8
6. Sandstone and conglomerate, gray-yellow, cross-bedded, in lenses that differ widely in thickness, extent, and texture; pebbles in conglomerate chiefly quartzite, chert, and hardened green clay; most pebbles angular and have smoothly worn surfaces; average long diameter of pebbles about 1 inch; about 10 per cent exceed 4 inches, and a few 6 inches	5	
Cretaceous(?):		
Morrison formation—		
5. Shale, purplish, unevenly bedded; includes three lenticular beds, each about 2 feet thick, of very resistant green sandstone; foliation surfaces lumpy, sun dried	18	8
4. Sandstone, gray-yellow, cross-bedded; contains a few lenses of conglomerate and scattered pebbles; much like No. 6	10	
3. Shale, gray-green and red, argillaceous and arenaceous	5	4
2. Sandstone (60 per cent), coarse, lenticular, cross-bedded, and conglomerate (40 per cent) composed of angular and subangular pebbles 3 inches or less in diameter; pebbles occur also in strings and as individuals in the sandstone; contains iron concretions; pebbles are of gray, white, yellow, brown, and red quartz, some attractively translucent; gray, red, mottled, and banded quartzite; gray and black chert; sandstone; green compact clay fragments; granite(?); rhyolite(?); all hard; forms resistant cap for No. 1, above which it is unevenly laid	45	
1. Sandstone, buff-gray to green-gray, soft, crumbly, very unevenly deposited, in part cross-bedded; beds 0.1 inch to 4 feet, many flat and stub-ended lenses of coarse sandstone with pebbles of quartzite and chert; strings of pebbles and isolated pebbles in sandstone; lenses, single balls, and aggregates of green compact clay lumps are conspicuous; resembles heterogeneous material deposited by present streams in near-by wash; coarser material at top	32	
Unconformity.		
Shales, red and green; base not exposed	20+	
	1,447	

Fossils from the drab shale that contains impressions of plants and the arenaceous shale and coal in the coal-bearing portion of this section (bed 29) were determined by Reeside as *Modiola laticostata* White, *Anatina* n. sp., *Corbula subtrigonalis* Meek, *Melania insculpta* Meek, *Amauropsis* n. sp., *Mytilus?* sp.—"species which occur abundantly in the Mesaverde of Book Cliffs" (upper Montana). From bed 23 *Inoceramus erectus* Meek, *Ostrea* sp. undet., *Cardium curtum* Meek and Hayden, *Callista* sp. undet., *Siliqua* sp., *Corbula nematophora* Meek, *Gyrodes depressus* Meek, and *Volutoderma* aff. *V. ambigua* Stanton were collected—"species whose affinities are with those of the Colorado group and which characterize a zone now believed to be the upper part of the Colorado group, * * * considerably older than the Mesaverde of the Book Cliffs region or than the typical Mesaverde of the San Juan region." In response to queries concerning some of these fossils and their stratigraphic significance, Mr. Reeside subsequently reexamined the collections and reports:

I find that in some manner some mixing of lots appears to have occurred, and one lot from Collett Creek had in it two very different lithologic facies—(1) a light-gray fine-grained sandstone containing a fauna of the same age as that of your Straight Cliffs sandstone but with more marine species; (2) a chocolate-colored sandy shale or very fine-grained sandstone with fossils that I identified as *Mytilus?* sp., *Modiola laticosta* White, *Anatina* n. sp., *Corbula subtrigonalis* Meek and Hayden, *Melania insculpta* Meek, and *Amauropsis* n. sp. This list is supported by a second lot from Collett Canyon, with identical lithology and without any suspicion of mixture. Now this list, on the face of it, is a good Book Cliffs-Mesaverde assemblage. Yet it may not mean all that it seems to mean. The *Mytilus*, *Anatina*, and *Amauropsis* may be dropped out of consideration. The *Corbula* I find has been recorded before (with question) from a Colorado horizon. The *Modiola* and *Melania* seem to be good identifications, and I have no previous record of their presence in pre-Montana beds. Nevertheless, if there is good reason to believe that the stratigraphic position is the same as that of the lots with *Ostrea soleniscus*, *Modiola multilinigera* and *Anomia propatoris*, I would prefer to say that the species listed at Collett Creek are longer ranging than has been hitherto supposed and that the beds belong together. Brackish and fresh water species do seem, for some reason, to have exceptionally long ranges, or perhaps it is better to say that very similar species seem to occur at quite different horizons.

Section of Cretaceous strata at head of Rock Creek, eastern Kane County, Utah

[Measured by Raymond C. Moore]

	Feet
Straight Cliffs sandstone:	
7. Sandstone, yellow, fine to medium grained, very massive, in irregular thick ledges	1,050
6. Sandstone, yellowish drab, shaly in upper part, massive in middle part and near base	200
Tropic shale:	
5. Shale, bluish drab, clayey, soft; weathers in slope, fossils in lower part	610
4. Sandstone, yellowish brown, massive, forms rim, very fossiliferous, contains Gryphaeas, oysters, and other forms	5–6
Dakota (?) sandstone:	
3. Bone and very black carbonaceous shale; contains one or two very thin streaks of coal	9½
2. Sandstone, gray to nearly white, with yellowish to greenish cast, massive, soft; grades downward into sandy shale, banded purple and gray; harder sandstone in beds 6 inches to 2 feet thick; reddish at base.	
1. Sandstone, massive; forms vertical cliff, reddish brown at outcrop (stained from wash above), gray, more or less conglomeratic; thickness not measured.	
	1,874+

CORRELATION

As indicated by the use of local names in describing the divisions of the Cretaceous in the Kaiparowits region, correlation with adjacent areas of described Cretaceous rocks can not be made with assurance. A comparison with standard sections in southwestern Colorado, in northwestern New Mexico, and in the Book Cliffs and the Wasatch Plateau in central-eastern Utah shows that the Cretaceous beds of southern and southwestern Utah were deposited much nearer the oscillating shore line of a basin of deposition than those so broadly distributed to the east and north. Accordingly notable differences may be expected between the deposits of this near-shore zone and those farther out in the basin. The Cretaceous in the Kaiparowits Plateau consists dominantly of sandstone and has approximately half the thickness of the Cretaceous in the Wasatch Plateau, where the rocks of this age, as also in regions farther north and east, consist dominantly of dark bluish-drab shale, so well exemplified by the Mancos shale.

Careful study of the Cretaceous in many widely separated areas has shown that the sandy divisions are by no means restricted to definite zones with equivalent time values. Where a sandstone has been traced laterally it not only differs in thickness from place to place by scores or hundreds of feet, but parts of it intergrade and intertongue with the contiguous shale, and in many places the whole sand body wedges out to nothing. It many places marine fossils are abundant; elsewhere they are rare or are not diagnostic. These assemblages of invertebrate forms indicate the presence of muddy sea bottoms and sandy sea bottoms and show repeated changes laterally and vertically from marine to brackish and fresh-water sediments. Because of these conditions the correlation of the sand bodies in the Cretaceous presents many difficulties.

Plate 5 presents typical sections of the Cretaceous in adjacent areas for comparison with the Cretaceous sections of the Kaiparowits region. This comparison shows that even the Cretaceous rocks of the exposures nearest to the Kaiparowits region are in many respects strikingly different. Thus in the Straight Cliffs there is less than 1,000 feet of shale, and approximately three-fourths of the Cretaceous section consists of sandstone. But in the Henry Mountains, only a little over 25 miles distant, there is nearly 3,000 feet of shale, and the interbedded sandstones constitute only a minor part of the Cretaceous.

As shown by Richardson [29] equally great differences mark the Cretaceous of the Virgin River region.

The fossils obtained from the Tropic and Straight Cliffs formations show that these divisions are of Colorado age and represent a large part of Mancos time. The overlying Wahweap sandstone has yielded no satisfactorily determinable fossil evidence, but on account of its position beneath the Kaiparowits formation, of very late Montana age, it probably corresponds to the lower part of the Montana group of other localities. It is also possible that the Wahweap represents a continuation of sandy deposition in Colorado time. The Kaiparowits formation obviously belongs to a very late part of the Upper Cretaceous, and as indicated by its vertebrate and invertebrate fossil remains it appears to correspond to the Fruitland formation of the San Juan region.[30]

As there are two main scarp-making sandstones in the Henry Mountains area, the Masuk sandstone above and the Blue Gate sandstone below, it is natural to regard them as equivalent to the two main scarp-making sandstones of the Kaiparowits Plateau, the Wahweap above and the Straight Cliffs below. (See pl. 18.) The Tununk sandstone of the Henry Mountains section is relatively less noteworthy, but with moderate certainty it represents the attenuated part of the Ferron sandstone of areas farther north, even though the Ferron attains a thickness of 800 feet. The Tununk sandstone is underlain by 1,000 feet of shale, which corresponds to a part of the Tropic shale. The upper part of the Tropic shale is represented in the Henry Mountains by the Tununk sandstone and possibly a small part of the "Blue Gate shale." The upper 400 feet of the "Blue Gate shale" yields a fauna of Telegraph Creek (early Montana) age and is therefore distinctly younger than the Straight Cliffs sandstone, from which Niobrara fossils are obtained. It follows that the Straight Cliffs sandstone in the Kaiparowits Plateau matches no sandstone in the Henry Mountains but corresponds to the lower part of the "Blue Gate shale." The Blue Gate sandstone is of lower Montana age. The stratigraphic position and apparent general correspondence of the Henry Mountains section with that of the Wasatch Plateau led Spieker and Reeside [31] tentatively to correlate the Blue Gate sandstone with the massive Emery sandstone, which occurs about 1,100 feet above the top of the Ferron sandstone and, like the Blue Gate sandstone, is separated by a shale interval from the Upper Cretaceous Mesaverde formation, which in the Wasatch Plateau is extensively coal bearing. The Emery sandstone contains Montana fossils.[32]

Although definite evidence is not available, it is very probable that the Masuk sandstone belongs to the Mesaverde formation, and it is so classified in reports on areas to the east and north. The shale beneath the sandstone is very sandy in the Henry Mountains, and there is an almost imperceptible gradation from the shale into the sandstone. In general lithologic character and thickness the Wahweap sandstone suggests equivalence to the shale and sandstone above the Blue Gate sandstone of the Henry Mountains. The shale in the Wahweap is more sandy than the "Masuk shale" of the Henry Mountains and contains numerous sandstone beds. Definitive fossils have not been found in the Wahweap, and its correlation is thus somewhat uncertain. Because the formation immediately follows the upper Colorado Straight Cliffs sandstone it probably belongs in the lower part of the Montana group and accordingly should be approximately correlative with the upper part of the "Blue Gate shale" and probably the Blue Gate sandstone. On this interpretation no strata that correspond to the "Masuk shale" and Masuk sandstone appear to be present in the Kaiparowits Plateau. Evidence of unconformities at the base and top of the Wahweap make this correlation, which is shown in Figure 6, less certain than for other parts of the section.

According to fossil evidence the Kaiparowits formation appears to correspond to the Fruitland formation of the San Juan Basin and evidently belongs very late in the Montana.

In two recent papers Spieker and Reeside [33] have recorded existing knowledge of the age and correlation of the Cretaceous formations of Utah. With particular reference to the Kaiparowits region Mr. Reeside has kindly written the following notes:

> An examination of some collections made by Spieker on the western side of the Wasatch Plateau, near Manti, shows that they supplement the collections that he and I made last year in Salina Canyon in such fashion as to give us an interesting

[29] Richardson, G. B., The Upper Cretaceous section in the Colorado Plateau, southwestern Utah: Washington Acad. Sci. Jour., vol. 17, pp. 464–475, 1927.

[30] Reeside, J. B., jr., Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin, Colo. and N. Mex.: U. S. Geol. Survey Prof. Paper 134, p. 24, 1924.

[31] Spieker, E. M., and Reeside, J. B., jr., Cretaceous and Tertiary formations of the Wasatch Plateau, Utah: Geol. Soc. America Bull., vol. 36, p. 439, 1925.

[32] Idem, p. 439.

[33] Spieker, E. M., and Reeside, J. B., jr., Cretaceous and Tertiary formations of the Wasatch Plateau, Utah: Geol. Soc. America Bull., vol. 36, pp. 435–454, 1925; Upper Cretaceous shore lines in Utah: Idem, vol. 37, pp. 429–438, 1926.

suggestion of the relations between the section in that region, the Coalville section to the north, and the Kaiparowits and Colob sections to the south. Each region has a basal unit of sandstone and conglomerate that contains the same pre-Carlile fauna, including coal near Coalville, in the Colob, and in the Kaiparowits. Above this basal unit in each region lies a marine shale with a fauna of Carlile age, and next in each a unit of sandstone and shale with a fauna of late Colorado (Niobrara) age, partly marine and partly brackish water. In the Colob the next higher unit is the fresh-water unit with the Fruitland-like fauna. It begins with a conglomerate. In the other regions the zone with this Fruitland-like fauna is members) of the eastern Wasatch Plateau, the unit of sandstone and shale above the marine shale of the western Wasatch Plateau and Coalville, the similar unit above the marine shale in the Colob region, and the Straight Cliffs sandstone in the Kaiparowits Plateau contain a late Colorado (Niobrara) fauna. We have not found this fauna in the Henry Mountains area, but it must certainly come in the lower part of the "Blue Gate shale." The beds immediately above this zone of Niobrara age have yielded few or no paleontologic data in the western Wasatch Plateau (where they form a series of conglomerate, sandstone, etc.) and in the Kaiparowits area, and their equivalent is apparently miss-

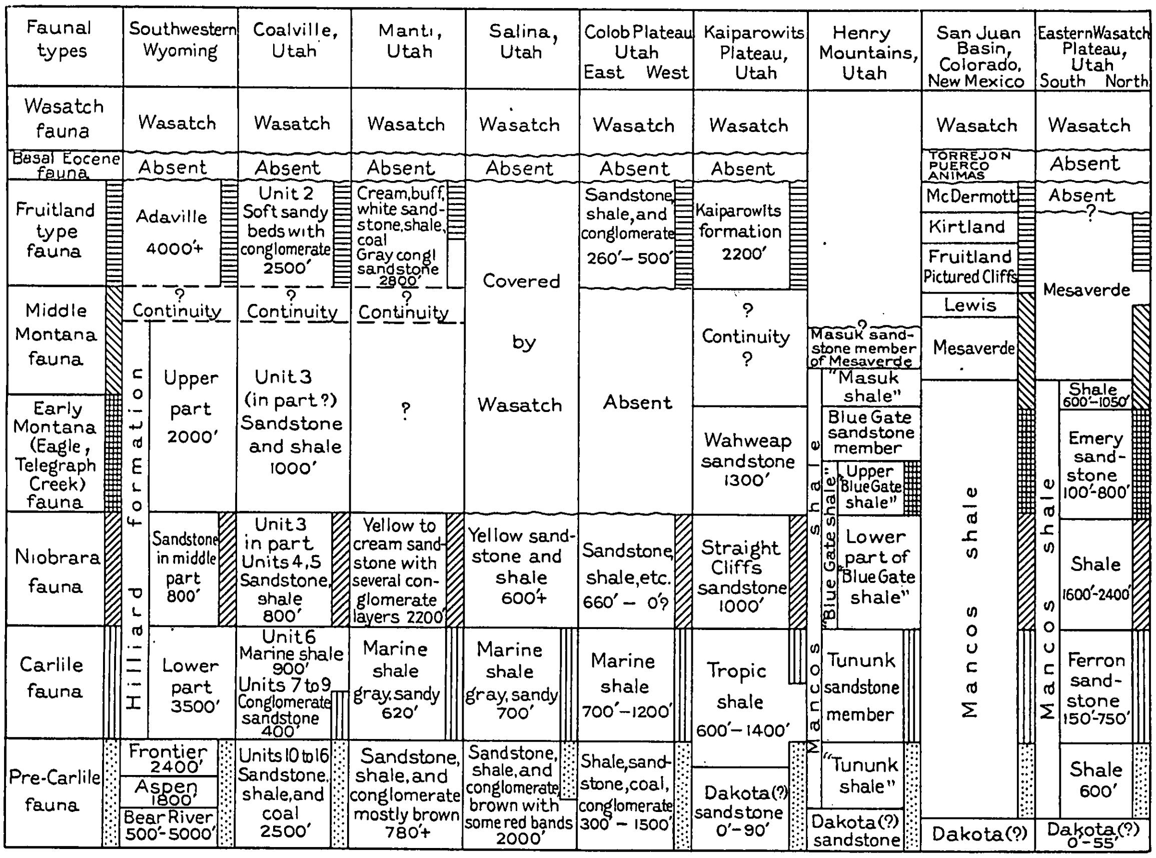


FIGURE 6.—Correlation of Cretaceous formations and distribution of faunas in Utah and adjacent regions

separated from the zone with the Niobrara fauna by other beds, which are probably of Montana age. I would not insist rigidly on these correlations or claim absolute equivalence of the units cited, but the similarities in the sections are much more striking than the differences.

The lower Mancos (pre-Ferron) of the eastern Wasatch Plateau, the basal part (sandstone and conglomerate) of the Colorado group of the western Wasatch Plateau and Coalville, the basal part of the Colob section, the "Tununk shale" of the Henry Mountains, and the lower part of the Tropic shale in the Kaiparowits region contain the same fauna—a pre-Carlile assemblage—and are nearly of the same age. The Ferron sandstone of the eastern Wasatch Plateau, the marine shale unit of the western Wasatch Plateau and Coalville, the marine shale of the Colob region, the Tununk sandstone of the Henry Mountains, and the upper part of the Tropic shale of the Kaiparowits region contain a Carlile fauna. The middle Mancos (between Ferron and Emery sandstone ing in the Colob region. In the eastern Wasatch Plateau the Emery sandstone contains a basal Montana fauna, as does also the upper part of the "Blue Gate shale." I would expect to find it also in the Blue Gate sandstone and believe that this sandstone and the Emery are more or less equivalent. It seems likely also that some part of the Wahweap sandstone would belong here. The Wahweap would also seem to include an equivalent of the "Masuk shale" and the Masuk sandstone of the Henry Mountains and some part of the late Mancos and early Mesaverde of the eastern Wasatch Plateau. The Kaiparowits formation seems to find its equivalent in the highest beds under the Wasatch formation of the Colob region, the highest beds of the western Wasatch Plateau and Coalville region, and the higher Mesaverde of the eastern Wasatch Plateau (Price River formation).

The Evanston region in southwestern Wyoming may also be compared with the areas cited above, as shown in Figure 6.

TERTIARY ROCKS

WASATCH FORMATION (EOCENE)

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

Beds of early Tertiary (Eocene) age are continuously displayed in the magnificent escarpments that border the Paunsaugunt, Table Cliff, and Aquarius Plateaus. They appear also in the broken slopes of Canaan Mountain, an outlier of the Table Cliff Plateau. For many miles around the heads of the Paria and Escalante Valleys they stand as an upper tier of a great amphitheater—a broken wall composed of square-fluted columns of high proportions. From below the Table Cliff Plateau they are seen to consist of a mass of limestone 1,000 feet thick with flat top and vertical sides resting on a sloping dull-colored base. It is surprising to find so enormous a block so symmetrically carved and so delicately colored, but similar large-scale erosion features occur wherever these limestones are exposed—all about the Paunsaugunt Plateau, in the walls of the Aquarius Plateau, and at Canaan Peak. Detailed erosion features are likewise striking and unusual. The maze of columns, pinnacles, and tables splashed with color that makes Bryce Canyon attractive is repeated many times in the eroded walls of the southern High Plateaus. (See pl. 15.) All the Tertiary beds that are recognized in this region are now assigned to the Wasatch formation.

PREVIOUS STUDIES

Dutton [34] describes the Paunsaugunt as a "tabular block of lower Eocene beds, exceedingly simple in its structure," which aside from its "marvelous color and sculptural forms presents little matter for special remark." He mapped the top of the Paunsaugunt and also that of the Aquarius and Table Cliff Plateaus and of Canaan Peak (Kaiparowits Peak) as limestone of Tertiary age, here and there overlain by lava. In Dutton's view "the Tertiary system of the plateau country is lacustrine throughout, with the exception of a few layers near the base of the system which have yielded estuarine fossils." From a maximum thickness of more than 8,000 feet in the vicinity of the Wasatch and Uinta Mountains "the deposits originally laid down in an enormous Eocene lake, which must have had an area more than twice that of Lake Superior and may even have exceeded that of the five great Canadian lakes combined," decreased in thickness southeastward and southwestward to shore lines in New Mexico and Nevada.

Dutton noted that the Eocene beds of the southern plateaus, Markagunt and Paunsaugunt, were to be correlated with the "Bitter Creek group" of Powell,[35] but that these southern plateaus included only part of the series exposed in the Uinta Mountains. The composition and thickness of the component members of the "southern Bitter Creek" were recognized by Dutton as shown below:

	Feet
Upper white limestone and calcareous marl (summit of series)	300
Pink calcareous sandstone	800
Pink conglomerate (base of the series)	550
	1, 650

The Pink Cliffs * * * are exposures of the fine-grained calcareous sandstone forming the middle member of the Bitter Creek.

The following generalized section he considered representative of the Tertiary sediments in the cliffs of "the eastern and southern margins" of the Paunsaugunt Plateau:

	Feet
Gray calcareous sandstone	180
White limestone	160
Red marly limestone and calcareous shale	300
Red pinkish limestone	450
Conglomerate, with small pebbles of gravelly sandstone	190
	1, 280

During his reconnaissance of 1872 Howell [36] examined the Tertiary at Last Bluff (Table Cliff Plateau). His published section, "measured in part and in part estimated," is quoted below:

	Feet
4. White to gray fresh-water limestone, containing *Helix* and *Physa bridgerensis*	500
3. Pink fresh-water limestone with bands of blue toward the base, containing *Physa*	850
2. Purple and light-colored marls with conglomerate toward the base	300–600
1. Gray arenaceous and argillaceous shales, containing an elongated form of *Physa*. [In the lower part] *Limea* and two species of *Viviparus*, a single specimen of a small oyster, were seen, and some fragments of large bones	1, 200–1, 500
Total thickness of Tertiary beds	2, 850–3, 450

As treated in the present report subdivisions Nos. 2, 3, and 4 of Howell's section are Tertiary; subdivision No. 1 is Cretaceous.

Howell remarks [37] that the Tertiary beds "to the north * * * are mostly soft calcareous shale and marls" and that "southward there is an increase in the limestone, and at the most southeastern exposure, the Last Bluff, there are over 1,200 feet of more or less compact limestone."

[34] Dutton, C. E., Report on the geology of the High Plateaus of Utah, pp. 12, 251–256, 292, 297–298, 158–159, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[35] Powell, J. W., Report on the geology of the eastern portions of the Uinta Mountains, p. 162, U. S. Geol. and Geog. Survey Terr., 1876.

[36] Howell, E. E., op. cit., pp. 270–271.

[37] Idem, p. 266.

STRATIGRAPHIC AND LITHOLOGIC FEATURES

Sections of Tertiary beds, here classed as Wasatch formation, were measured at a number of places. In a broad sense the three subdivisions outlined by Dutton and Howell may be recognized, but the features of the members are not persistent, and the thickness of the individual beds and of the entire series differs widely from place to place. At the south point of the Paunsaugunt Plateau the Wasatch measures 735 feet, at Bryce Canyon about 1,300 feet, and at Table Cliff about 1,500 feet. At Canaan Peak only about 300 feet remains. Where it is not protected by lava the upper beds are much reduced by erosion. No two exposures are alike in arrangement of beds and resistance to erosion. Variation in color, composition, texture, and structure is characteristic. Common features include prominent, narrowly spaced vertical joints; irregularly placed lenses of relatively resistant materials that give the appearance of cross-bedding; brecciated masses; dense masses of limestone embedded in calcareous shale; and strings of conglomerate. (See pl. 15.) At all places the color of the unweathered rock is white or pale pink, but on weathering a strong pink tone is produced, giving at a distance the remarkable appearance that has made these exposures famous. To the observing Piute, they are Unt-saw-ar Mu-kwan-kuut—" the high standing rocks that shine." In general each series of beds in the southern Utah Wasatch has a top of white limestone, lumpy, slightly brecciated, and dotted with cavities lined with calcite crystals. At Canaan Peak this cap bed includes smooth egg-shaped pebbles of limestone and scattered grains of basaltic ash. At each exposure, but in different stratigraphic positions, stand beds 10 to 30 feet thick of dense faintly pink limestone that makes a solid wall 100 to 300 feet high in which occur lenses of firm, dense gray limestone 2 to 6 feet thick and 10 to 100 feet long. Also at each exposure a series of shalelike limestones that have a total thickness of as much as 150 feet appear as evenly bedded silts mottled with dark-red, pink, and white blotches.

At the base of the Wasatch section lies a conglomerate quite unlike any other stratum in southeastern Utah. It consists of unusually well-rounded and smoothed pebbles of pink, gray, white, and red quartzite, some minutely banded and cross-bedded, black chert, rhyolite, porphyry, and many kinds of dense igneous rocks. About 50 per cent of the pebbles exceed 4 inches in diameter; a few exceed 10 inches. Because of concealing talus this conglomerate bed was seen in position only on the west slope of the Paunsaugunt Plateau, where it consists of 6 feet of quartz, quartzite, and rhyolite pebbles arranged in overlapping lenses and held together with calcareous cement. Lime shale covers its uneven surface, and its base is plastered on the irregularly eroded friable drab sandstone of the Kaiparowits formation. Doubtless because of its weak cement this conglomerate is not a cliff maker. Its characteristic boulders and pebbles cover the slopes at the base of limestone cliffs. To judge from this débris, the thickness and coarseness of the conglomerate differ considerably in different places.

The source of the igneous and metamorphic pebbles that make up this conglomerate is unknown. Their distribution in the Kaiparowits region suggests the presence of a land mass in central Utah that was exposed and eroded during very late Cretaceous time and then buried during Wasatch time. At places the pebbles are few or are represented by fine gravel; elsewhere the slopes are so coated with loose boulders as to make travel difficult, and the banks of the Little River, near its head in Canaan Peak, are composed of boulders that are piled to heights of 20 to 40 feet. Many miles farther south along the Paria River and Wahweap Creek pebbles from this bed are seen, and they are readily recognized in the gravel beds of the Escalante Valley.

At the divide between the Escalante and Sevier Rivers the lowermost Wasatch beds consist of a basal conglomerate that is composed chiefly of pebbles of quartzite, 2 to 6 inches in diameter, embedded in a matrix of sandy lime; pink limestone interbedded with white calcareous sandstone; and a massive bed of white limestone exceeding 100 feet in thickness. Fossils in the dull-colored friable sandstone beds below the conglomerate are those that are characteristic of the Kaiparowits formation. The Wasatch beds at " the dump" near the head of the Paria are eroded into tapering pillars and irregular columns that are crossed by broad bands of pink and cream-yellow. The material is chiefly limestone but includes a lens of conglomerate and thin beds of calcareous sandstone whose surfaces are covered with plant impressions.

Fossils are distributed sporadically throughout the dense and the brecciated limestone, but none were found in the shalelike beds. They occur chiefly in lenses and irregular masses of crushed or worn bits of shells or as shell forms filled in with calcite. An extended search resulted in finding only imperfect specimens, among which Dall[38] recognized "*Physa pleuromatis*, probably *Physa bridgerensis*, and a small discoid shell which may be a *Valvata* or possibly a *Planorbis*." He states: " There is little doubt of the Eocene character of the deposit."

At few places on the Paunsaugunt Plateau and Table Cliff does the thickness of the limestone exceed 500 feet, and at Canaan Peak it is about 200 feet. So far as known the beds that cap the southeastern extensions of the High Plateaus are of approximately

[38] Dall, W. H.; personal communication.

the same age as those farther north and northeast, and they are therefore all referred to the Wasatch. The difference in thickness is possibly the result of surface erosion and of the relief of the underlying Cretaceous beds, but the lowest beds are not lithologic equivalents, and the great differences in sequence, in composition, and in the proportionate amounts of limestone, shale, sandstone, and lignite make it possible that the Tertiary strata of Utah were deposited in several basins with here and there overlapping rims. It seems unnecessary to follow Dutton in assuming that such widely separated and unlike sediments as the carbonaceous shale and sandstone of the Price River, the dense pure limestone of Table Cliff, and the quartz sandstone and clay shale of Chuska Mountain in the Navajo country were laid down contemporaneously in a single large depression.

UNCONFORMITY AT BASE OF EOCENE

The well-known unconformity at the base of the Eocene beds in northern and central Utah has been traced to the Kaiparowits region along the face of the Paunsaugunt, Table Cliff, and Aquarius Plateaus. In places the beds above and below are parallel, and their separation is marked only by accumulations of gravel and by abrupt change from dull-colored marine shale and sandstone to pink or white fresh-water limestone. Elsewhere 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. At Canaan Peak the Eocene beds horizontally overlie the upturned strata of the East Kaibab fold, in which the youngest Cretaceous sediments are involved. Northward along the Aquarius Plateau the Eocene rests on progressively lower subdivisions of the Cretaceous and truncates the Dakota(?) and San Rafael beds that are upturned in the Pine Creek fold. Between Sand Creek and Boulder Creek only the lowest beds of the San Rafael group remain, and on the west flank of the Waterpocket Fold the Eocene rests on the Navajo sandstone. During the time interval thus indicated more than 5,000 feet of sediments were locally removed.

QUATERNARY DEPOSITS

The sediments in the Kaiparowits region that date from Quaternary time are chiefly alluvial deposits in valleys, on slopes, and on top of the higher plateaus. The accumulations of eolian sand are small and localized (p. 145), and incipient glaciation on the Paunsaugunt and Aquarius Plateaus has left only scattered boulders and inconspicuous remains. Swamp deposits appear along the northern headwaters of the Escalante River and about the glacial lakes on the Aquarius Plateau. During the last half century the alluvial fill of many valleys has been scoured out by the streams.

IGNEOUS ROCKS

Unlike other large parts of the plateau province, the Kaiparowits region is remarkably free from igneous rocks. No deep-seated masses, no dikes, and no volcanic cones have been found. The only products of igneous activity are lava flows on the Table Cliff and Paunsaugunt Plateaus—remnant outliers of much greater flows on the Markagunt and Aquarius Plateaus. As described by Dutton [39] these lavas are basalt and were erupted from widely distributed vents at different periods during Tertiary and more recent times. A flow in Johnson Canyon overlies alluvial deposits and has interfered with the course of the stream.

[39] Dutton, C. E., Geology of the High Plateaus of Utah, pp. 197–203, 295, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

CHAPTER 3. STRUCTURE

HISTORICAL SKETCH

On his memorable voyage down the Colorado Powell[1] noted the broad fold crossed by the river above the mouth of Trachyte Creek. He describes a monoclinal fold in Glen Canyon a few miles below the mouth of the San Juan as follows:

A few miles below the mouth of the San Juan River we come to an interesting monoclinal fold, where the dip of the rocks is in a direction a little north of east—that is, the beds are dropped down on the eastern side of the line, which trends nearly north and south, not broken off and dropped down but flexed, or bent, so that the beds on the western side of the line are found at an altitude many hundreds of feet above those on the east, and farther down the river the rocks exposed at the water edge are of greater age than those above.

The Echo monocline was also observed:

At the foot of this [Glen] canyon another monoclinal fold is seen, with the throw, or drop, also on the east side, or the uplift, if one is so pleased to term it, on the west side; and this brings up again Carboniferous sandstones and limestones.

A. H. Thompson[2] described the Waterpocket monocline as a "cliff forming the rim of Escalante Basin" and said of the Escalante monocline: "At the end of 20 miles this canyon valley was abruptly ended by a line of cliffs that stood directly across its course." A reconnaissance by Howell[3] along the east base of the Table Cliff and Aquarius Plateaus included a brief study of the major structural features. The East Kaibab fold was traced northward from Kaibab Plateau.

It was last seen a few miles to the east of Last Bluff (Table Cliff Plateau) and evidently does not extend much farther in that direction. Its drop at Paria is not far from 3,500 feet. * * * Between the Last Bluff and the Henry Mountains the rocks are folded and thrown into waves on a greater scale than elsewhere seen.

The uplift that underlies the Henry Mountains and its continuation northward into the San Rafael Swell is shown in section, and the Waterpocket flexure is described as two folds. He says:

The eastern fold, *A*, trends south-southeast, keeping an approximately straight course for 100 miles to the Colorado River and Navajo Mountain. * * * The fold *B* (about 12 miles west of fold *A*) approaches the fold *A* in one place so closely that the two form a perfect anticlinal. It spreads out rapidly again to the southward and soon afterward flattens out and disappears.

From a point on the south end of the Aquarius Plateau a third anticlinal fold about 16 miles west of fold *B* was noted. Between the mouth of Birch Creek and Last Bluff (Table Cliff Plateau) Howell records two other folds, as follows:

The first of these, *D*, is a monoclinal, with a throw of a few hundred feet only to the west. From this fold the beds rise at an angle of from 2° to 4° to the west-southwest, until the point *E* is reached, when they dip suddenly to the west again, at an angle as high in some places as 30°. After dropping about 1,500 feet they assume a nearly horizontal position and apparently continue to the Last Bluff with no further disturbance. These folds are both monoclinals * * * and were traced for 20 or 30 miles.

Fold *D*, or perhaps folds *D* and *E* combined, is the Escalante monocline, but the locations and dimensions given are too generalized to follow with assurance in the field. Howell mentions also the "Paria" (Echo monocline) and "Eastern Kaibab" folds, which were measured "just a little south of their point of intersection, where the combined throw of the two folds is about 4,000 feet." But his section, which extends from the Kaibab Plateau eastward across the Echo Cliffs and Kaiparowits Plateau bears little relation to the actual structure.

From observation points on the slopes of the Henry Mountains Gilbert[4] traced the course of the Waterpocket Fold and described and illustrated the major structural features of the portion north of the Masuk Plateau as follows:

It is far from following a straight line but, like most lines of orographic disturbance, swerves to the right and left, while maintaining a general trend. The amount of its "throw," or the difference in level between adjacent parts of the two blocks which it divides, is inconstant, its maximum being 7,000 feet. At some points the flexed strata are inclined at an angle of 50°, while at others their greatest dip is but 15°. Toward the north the flexure twice divides. One of its branches, the Blue Gate flexure, has a throw in the same direction and by its separation increases the throw of the main flexure.

Gilbert[5] also briefly described the Paria fold (Echo monocline) and directed attention to its stratigraphic significance.

[1] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, pp. 177, 178, 1875.
[2] Idem, pp. 137, 140.
[3] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 291–295, 1875.
[4] Gilbert, G. K., Report on the geology of the Henry Mountains, pp. 12–14, 1880.
[5] Gilbert, G. K., U. S. Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 51–52, 1875.

Dutton[6] has much to say of the structure of the Escalante Basin and the Kaiparowits Plateau as seen from distant viewpoints on the Aquarius Plateau. The Waterpocket Fold and the Escalante monocline are vividly described. He says:

The structure of the plateau is best studied upon the southern slopes [of the Aquarius Plateau]. Here the most striking feature is a large monoclinal, already alluded to as a companion to the Waterpocket Fold. It comes up from the southeast, crossing the lower end of Potato Valley, and trends along the slopes northwestwardly, disappearing beneath the lava cap. The throw of the monocline is to the westward. Upon its flanks the Cretaceous system is turned up and dips westward beneath the southwestward extension of the general plateau mass. The edges of its strata are truncated by erosion, and over them lies unconformably the Tertiary. The upthrow of the monocline heaves up the Jurassic white sandstone, which is seen rolling up in a huge wave 1,200 to 1,800 feet high across the lower end of Potato Valley. The position of this flexure relatively to the plateau mass is peculiar and very striking; indeed, at first sight it appears altogether anomalous. We are accustomed in the western regions to see the strata rolled up on the flanks of a mountain range like a great wave urged onward toward a coast and breaking against its rocky barriers. But the Escalante flexure is like a wave sweeping along parallel to the coast, the crest line of the wave being perpendicular to the trend of the shore. Its line of strike runs up the slope and disappears beneath the Tertiary near the summit of the plateau. A fine stream of water [Pine Creek] runs upon this monocline parallel to its strike, precisely as Waterpocket Creek runs upon and parallel to the course of that flexure.

The age of the Escalante monocline is evidently pre-Tertiary. It has been exhumed by the general erosion after having been buried beneath Eocene strata, and after these strata had been overflowed, in great part at least, by many hundreds of feet of lavas.

From Dutton's viewpoint only the northeast face of the Kaiparowits Plateau was visible. Accordingly the plateau appeared to be composed of strata "quite horizontal." The structural features within the mass were not observed.

Of the "Eastern Kaibab fault" and the "Paunsaugunt fault," Dutton[7] says:

The Eastern Kaibab fault [fold] * * * continues northward past Paria trending first north-northeast but gradually swinging in a curve around to the northwest, always preserving its true monoclinal form. As it approaches Table Cliff it dwindles as if about to die out; but opposite the southwest angle of the Aquarius Plateau it is joined by an important fault coming from the south-southwest. This is the Paunsaugunt fault, which lies near the eastern base of that plateau.

Dutton[8] thus describes the "Echo Cliff monocline":

It seems proper also to describe briefly the Echo Cliff monocline, since it is one of the most important in that great series of displacements which traverses the district from south to north. Everywhere it is a true monocline. It is known to extend more than a hundred miles south of the Colorado and certainly reaches 50 miles north of the river. * * * The total downthrow of the monocline varies greatly from place to place, but along those portions where it has been well observed, the total displacement ranges from 3,500 to 4,000 feet. Its age is Tertiary and probably very nearly coeval with the East Kaibab monocline—in other words, rather late Tertiary. The proof of Tertiary age is conclusive, since the flexure bends the Cretaceous beds wherever it approaches them, and its northward continuation involves the Eocene.

The Echo monocline has been described by Davis,[9] who considered it older than the Pliocene; by Robinson,[10] who thought it originated during the Eocene-Miocene interval; and by Gregory,[11] who presented evidence for believing it probably pre-Tertiary.

Prior to the work on which the present report is based no structural feature of the Kaiparowits region had been described on the basis of detailed field observations. Several of the features have not been previously recorded.

REGIONAL RELATIONS

As suggested by the wide, sensibly flat plateaus and long, even-crested escarpments the rock beds throughout most of the Kaiparowits region are gently inclined or nearly horizontal. This simple general attitude is interrupted in places by sharp monoclinal flexures, which trend in a general northerly direction and subdivide the region into large gently tilted blocks. In places minor undulations interrupt the otherwise regularly inclined beds between the monoclines. West and northwest of the Kaiparowits region northward-trending faults divide the plateaus into blocks not unlike those produced by the monoclines. In each of the three monoclinal folds that traverse central southern Utah the dip of the beds is eastward, and the rocks on the west are elevated and those on the east depressed. Along each of the faults the movement is in the opposite direction, the rocks on the east being elevated and those on the west dropped. The monoclinal folds affect all the rocks from the uppermost Cretaceous downward but do not involve the Tertiary, whereas the faults displace the Tertiary beds as well. The displacements of the two types are thus of different geologic age. Only one of the faults affects the Kaiparowits region. This, the East Paunsaugunt fault, trends northeastward along the east border of the Paunsaugunt Plateau.

Aside from the deflections that are due to the monoclinal folds, the general inclination of the beds in the southern part of the Kaiparowits region is northward, for the rocks here constitute the north flank of the

[6] Dutton, C. E., Report on the geology of the High Plateaus of Utah, pp. 286–295, U. S. Geol. and Geog. Survey Rocky Mtn. Region, 1880.

[7] Idem, pp. 32–33.

[8] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 205, 1882.

[9] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zoology Bull., vol. 28, pp. 140–141, 1901.

[10] Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, p. 36, 1913.

[11] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 115, 1917.

broad Grand Canyon upwarp in Arizona. Northeast of Table Cliff and Last Chance Creek—along the Straight Cliffs and in the Escalante Valley—the regional dip of the rocks is gently southwestward from the crest of the prominent Waterpocket Fold. These broad structural features are represented in the structure map of the region (pl. 16) and are also indicated in the structural sections shown on Plate 17.

METHOD OF DETERMINATION

During the course of plane-table surveys of most of the Paria Valley, the Kaiparowits Plateau, the Circle Cliffs, and Halls Valley altitudes of numerous beds were determined at hundreds of different points. By measurements of the thickness of formations in the parts of the area thus traversed, it is possible to construct a fairly accurate general structural map on a selected datum plane.

A structure map of the Circle Cliffs (fig. 8) was prepared with the top of the Kaibab limestone as a datum plane, but in making the map of the larger area shown in Plate 16 it was found that the representation of structure based on a stratigraphic horizon that in some places was more than 9,000 feet below the surface was subject to considerable error, chiefly because of unknown variations in thickness of the formations. Hence, the top of the Dakota (?) sandstone, or rather the base of the persistent and highly fossiliferous basal sandstone of the Tropic shale, which is a very widely distributed, well exposed, and readily identifiable horizon, was selected as a more suitable datum. It is approximately in the middle of the stratigraphic section.

In computing the altitude of the Dakota(?) sandstone in areas where older and younger rocks are exposed at the surface convergence maps were constructed for each of the main stratigraphic divisions. For example, an increase in thickness of more than 1,000 feet in the Triassic rocks between the Circle Cliffs and the San Juan River was taken into account.

Measurements of strike and dip were made in many parts of the region. This information, supplemented by observations of the areal distribution of formations and altitudes obtained from topographic maps, was utilized in drafting the structural map.

WATERPOCKET MONOCLINE

The Waterpocket monocline is one of the dominant structural elements in southern Utah. The ridges formed by the sharply upturned massive sandstone and the long, narrow soft-rock valley that marks its course may be traced for a distance of nearly 80 miles from the Colorado River northward to Thousand Lake Mountain. From Notom southeastward the jagged flanks of the Waterpocket monocline are particularly conspicuous.

The rocks in the monocline are steeply inclined to the east, and dips range from 15° at the south end of the fold on the Colorado River to 75° at some points east of the Circle Cliffs. (See pl. 19, *A*.) In several places a horizontal traverse of a little over 2 miles involves crossing all beds from the top of the Permian Kaibab limestone to the Masuk sandstone, near the top of the Cretaceous, a stratigraphic section of approximately 9,000 feet. (See pl. 18.) Near the head of Halls Creek the structural displacement is about 9,000 feet, but to the south the eastward inclination of the rocks becomes gradually less, the amount of the displacement diminishes, and a short distance south of the Colorado River the fold disappears. Where the Colorado River crosses the Waterpocket flexure the uppermost part of the Moenkopi formation is exposed for a short distance, and the overlying weak Chinle shale widens the canyon locally. (See pl. 26, *C*.)

Along the eastern flank of the Waterpocket monocline a longitudinal valley is carved in soft Upper Jurassic and Cretaceous rocks, and the more resistant strata stand on the floor of the valley as low hogbacks.

Southward from the vicinity of Muley Twist the steep west wall of the longitudinal valley consists of Navajo sandstone, which extends to the crest of the monocline and continues down its southwestern slope into the Kaiparowits downwarp. North of Muley Twist the Navajo forms a high hogback ridge separated by a narrow longitudinal valley from the sharp-angled sandstone ridge formed by the Todilto (?) and Wingate formations. In the middle eastern part of the Circle Cliffs the Wingate tends to form a series of triangular pyramids separated by eastward-flowing tributaries of Muley Twist Creek, which flows southward along the contact of the Navajo and Todilto(?) formations. The weak Triassic Chinle and Moenkopi rocks form a lowland on the west side of the sandstone ridges, but the underlying hard Kaibab limestone forms a dip slope that rises to the summit of the anticline, where an altitude approximately equal to that of the crests of the sandstone ridges of the plateaus farther east is reached.

The Waterpocket monocline involves all the stratified rocks below the Masuk sandstone, and the date of the deformation is therefore at least as late as the later part of the Cretaceous.

CIRCLE CLIFFS UPWARP

The Circle Cliffs upwarp is an elongated, very asymmetric anticline, somewhat more than 50 miles in length, bordered on the east by the Waterpocket monocline. The highest part of the upwarp has a domal form compressed from east to west and elongated parallel to the trend of the monocline. Here the top of the Kaibab limestone rises to about 6,500 feet above sea level, at a point near The Peaks. If the Dakota (?) sandstone were still present over the summit of the upwarp it would have an altitude of about 11,300 feet. Northward along the axis of the upwarp a relatively shallow sag lies between the high point in the Circle Cliffs and a second high point in the Miners Mountain swell. Southward the crest of the upwarp plunges gradually to about 6,500 feet a short distance south of the Colorado River. Southwestward the dip slopes on the hard Jurassic sandstone form a gentle descent, interrupted by low anticlines and synclines, that leads toward the Kaiparowits downwarp, whose lowest part is 30 to 40 miles distant. After crossing the belt of weak Upper Jurassic rocks in the Escalante Valley this dip slope continues to the hard sandstone of the Kaiparowits Plateau.

Erosion has breached the high part of the Circle Cliffs upwarp and produced a broad elliptical valley in the soft Triassic shale. (See pls. 8, *B;* 22, *B.*)

This depression, which is surrounded on all sides by inward-facing cliffs of massive Jurassic sandstone, is not hollowed smoothly into a basin but contains in its central part a broad, dome-shaped elevation that is upheld by the hard Permian limestone and surmounted in two or three places by outliers of hard Triassic conglomerate that reach an altitude as great as that of the top of the surrounding sandstone rim.

HARRIS SYNCLINE

In the central part of T. 36 S., R. 5 E., a southward-trending shallow syncline crosses Harris Creek, a tributary of the Escalante River. The structure is clearly shown in the basal sandy, gypsiferous upper Jurassic beds that overlie the Navajo sandstone. On the east side of the syncline the dip is 3° to 10°, but on the west it is as much as 20°. The southward plunge of the syncline is more than 150 feet to the mile.

COLLETT ANTICLINE

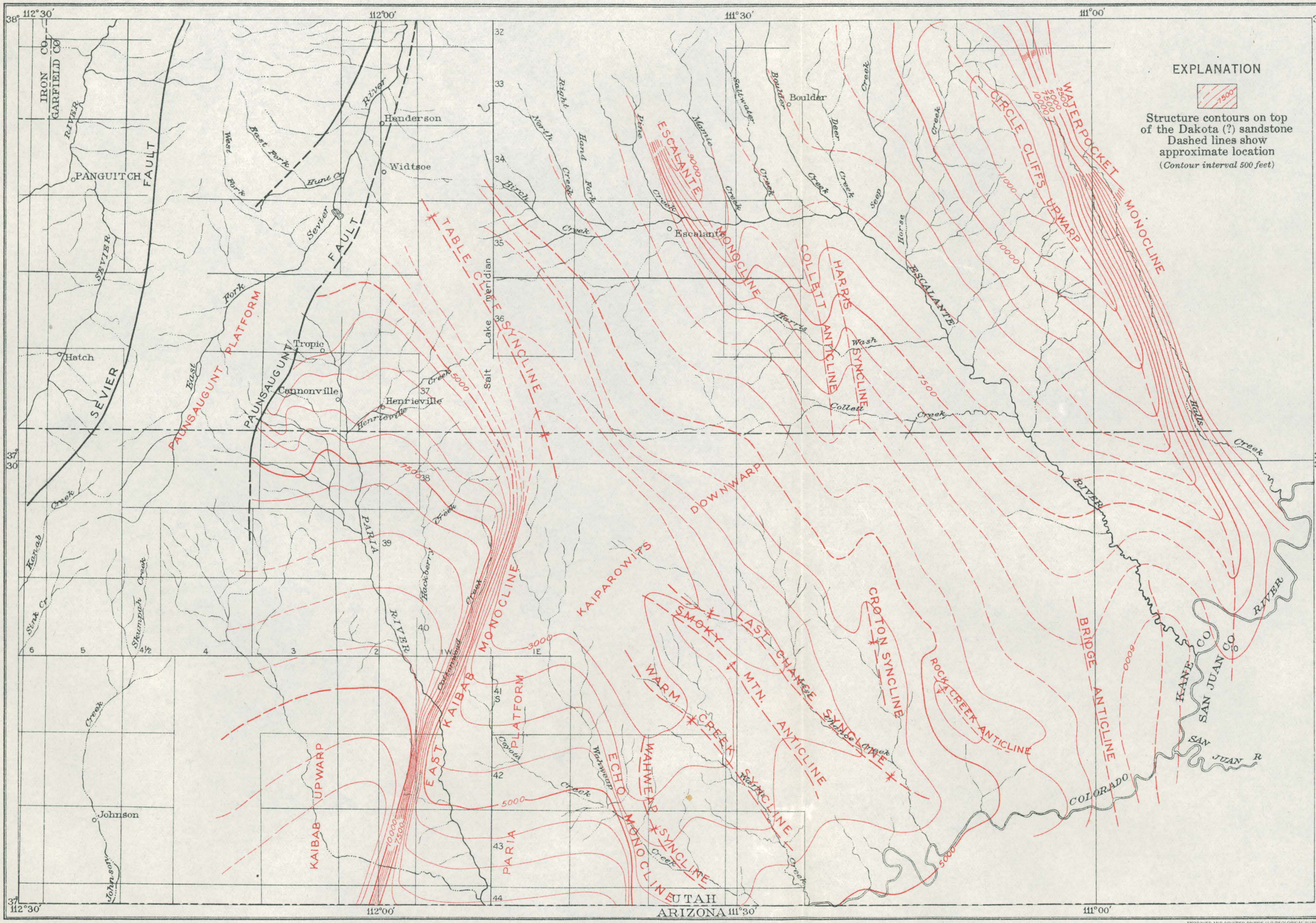
The Collett anticline is a minor elevation of the beds on the west side of the Harris syncline. It is locally rather prominent on account of the control it exerts in the distribution of the rocks at the surface, having produced a nearly continuous extension of the Navajo sandstone from the broad area of its outcrop north of Harris Wash to Collett Creek on the south. As measured in the stratified rocks that overlie the Navajo the inclination of the beds in the anticline is 5° to 20° on the east flank and 4° to 5° on the west flank.

ESCALANTE MONOCLINE

The Escalante monocline is locally a very prominent structural feature. As viewed from Escalante it stands as a wall of steeply upturned sandstone bordered by lower-lying surfaces of gypsum, shale, and alluvium, in the midst of which the village is placed. Directly across the wall the Escalante River has cut a deep, narrow trench, the beginning of a continuous canyon that leads to the Colorado River. The change in topography from a broad, open valley to a precipitous-sided trench is abrupt. South of Escalante the monocline plunges southward and seems to disappear within a few miles. Northward, however, its western flank for a distance of about 8 miles is exposed in the bank of Pine Creek. Farther north, on Sand Creek, the fold has been beveled by pre-Tertiary erosion, and as a series of truncated beds it disappears beneath the limestone and lava of the Aquarius Plateau. Unlike the beds involved in the Waterpocket flexure the Jurassic beds exposed in the eastern limb of the Escalante monocline have gentle dips that extend for but a few miles before becoming merged with the general regional structure. But the strata that form the westward flank dip sharply downward—30° to 36° along Pine Creek, 16° on Deadman Creek—and bring the Navajo sandstone (Jurassic ?) and the Straight Cliffs sandstone (Upper Cretaceous) into the same horizontal plane. The displacement amounts to more than 2,000 feet within a horizontal distance of about 2 miles. In its regional relations the Escalante monocline is an interruption of the general dip of the beds between the crest of the Waterpocket flexure and the base of the Aquarius and Table Cliff Plateaus—a huge wrinkle in an otherwise continuous westward-dipping sandstone.

KAIPAROWITS DOWNWARP

The great southward projection of the Cretaceous rocks that compose the Kaiparowits Plateau is explained by the structural depression of the plateau area. Northeastward from the base of the plateau there is an essentially uniform rise of the rocks to the summit of the Circle Cliffs upwarp, and there is consequently no real line of division between the areas designated downwarp and upwarp. A convenient and natural division, however, may be made along the line of the Cretaceous outcrops marked by the Straight Cliffs. On the south and southeast the rock beds rise gently toward the Colorado River, and there are no clearly defined structural limits of the downwarp in this direction. This part of the downwarp is characterized by gentle undulations, whose axes converge toward the center of the depressed area. Along Wahweap Creek the north end of the Echo monocline is a more prominent rock fold that marks out the Paria platform on the west from the structurally slightly lower area to the east. On the west the Kaiparowits downwarp is sharply bounded by the East Kaibab monocline, whose main axis, marked by the course of the House Rock Valley and Cottonwood Creek, trends north-northeast. North of the "Gut" this trend gradually changes to the northwest, and the dip of

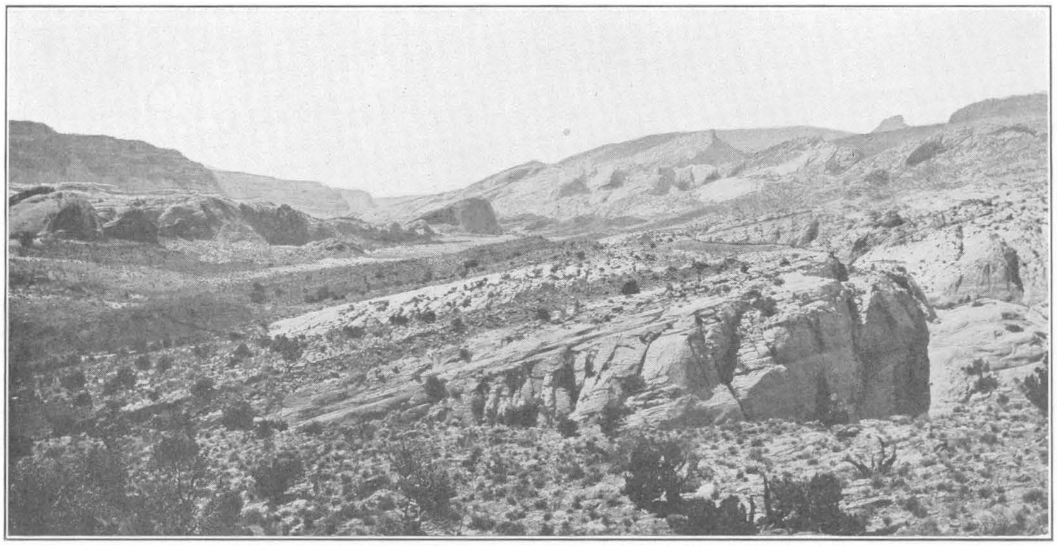


STRUCTURE MAP OF THE KAIPAROWITS REGION, SOUTHERN UTAH

Scale $\frac{1}{500,000}$

5 0 5 10 15 Miles

PANORAMIC VIEW (*A*) FROM CREST OF WATERPOCKET FOLD AND SKETCH (*B*) SHOWING SURFACE DISTRIBUTION OF FORMATIONS



A. VIEW LOOKING SOUTH ALONG HALLS VALLEY FROM A POINT JUST ABOVE MOUTH OF MULEY TWIST CREEK

The sandstone in the foreground and at the right is Navajo; dark soft strata of the Carmel formation and Entrada sandstone appear at the left. The cliffs in the left distance are composed of Summerville, Morrison, and Dakota (?) formations.

B. EAST KAIBAB MONOCLINE

Looking north from a point above Paria River. Navajo sandstone at left, Dakota (?) sandstone, Tropic shale, and Straight Cliffs sandstone, in order named, at right.

the rocks is notably less steep than farther south. The northern part of the downwarped area has a definitely synclinal structure, with an axis that trends northwest. As the axis of the syncline trends almost exactly beneath Table Cliff, it is called the Table Cliff syncline, although the Tertiary rocks of the plateau are not at all involved in the structure.

In most places the surface of the Cretaceous sandstone platforms accurately reflects the rock structure. From the crest of the Straight Cliffs a dip slope is gently inclined to the southwest. (See pl. 21, *A*.) This dip is locally much steepened on approaching the Table Cliff syncline, as indicated topographically by the development of hogback ridges on the Wahweap sandstone east of Table Cliff and Canaan Peak.

A view from any prominent point, such as the crest of the Cretaceous hogbacks on the East Kaibab monocline, shows clearly the gently basin-like structure of the central part of the Kaiparowits downwarp. The lowest parts of the basin in the vicinity of Canaan Peak and along the headwaters of Wahweap Creek are occupied by soft rocks of the Kaiparowits formation, and the maximum thickness of this formation lies where the underlying sandstone is most depressed. The dip slope on the top of the Wahweap sandstone rises gently but in a clearly defined manner on the northeast, east, southeast, and south. On the west lies the steeply upturned sandstone of the East Kaibab monocline.

The top of the Straight Cliffs sandstone forms a broad platform that extends outward from the Last Chance Cliffs. Except in part of the area along Last Chance Creek, where the rocks of this division have been extensively altered by the burning of the included coals and have been much dissected, the irregularities of the platform define the gentle anticlinal and synclinal warpings that are superimposed on the regional structure in this part of the downwarp. South of the Straight Cliffs escarpment the platform known as the Grand Bench, formed mainly by massive Morrison conglomerate, shows a continuation of structural features observed in the rocks farther north.

ROCK CREEK ANTICLINE

A prominent southeastward-trending anticline is observed on the headwaters of Rock Creek, about 6 miles north of the Colorado River, and intersects the Little Red Valley, a tributary of the Croton Branch of Last Chance Creek. Unlike many of the structural features of the plateau country, the Rock Creek anticline shows no steep dips, the maximum inclination being about 8° or 10°. The anticline has an elliptical dome shape that is striking because of its clear expression in the dip slopes of the Grand Bench and because of exposures of Navajo sandstone on Rock Creek and Wahweap sandstone in Little Red Valley that are entirely surrounded by younger formations. So far as known, the axis of the anticline is only 8 or 10 miles long.

CROTON SYNCLINE

The Croton syncline borders the Rock Creek anticline on the west and trends almost due north along the Croton Branch of Last Chance Creek. On the east side of the syncline the beds dip 8° or 9°, but on the west they have only a slight inclination toward the axis of the syncline, and within a short distance they reassume the regional slope toward the southwest.

LAST CHANCE SYNCLINE

Throughout almost its entire course Last Chance Creek follows the axis of a gentle but well-defined syncline, the east limb of which is formed by the general regional dip of the rocks, and the west limb by a gentle rise toward the crest of the Smoky Mountain anticline. Locally dips of as much as 5° are observed, but in general they do not exceed 2° or 3°. The axis of the syncline plunges northwestward at an average rate of about 65 feet to the mile, the direction of slope being opposite to that of the stream's flow.

SMOKY MOUNTAIN ANTICLINE

The gently rounded divide on the surface of the Straight Cliffs sandstone plateau and the Grand Bench defines an anticlinal axis that passes through Smoky Mountain. The anticline may be designated conveniently the Smoky Mountain anticline. Between the headwaters of Warm and Last Chance Creeks this axis is very sharply marked, and the dip slope from the top of the sandstone is very readily observable with the eye. Farther south the axis of the anticline is less clearly defined. Its trend is parallel to that of the synclines on each side, and like them it plunges gently northwestward.

WARM CREEK SYNCLINE

Warm Creek follows the central axis of a gentle synclinal depression somewhat similar to that of Last Chance Creek but broader and, especially to the south, less clearly defined. It is of interest chiefly on account of its relation to the position of the stream.

WAHWEAP SYNCLINE

The structurally depressed area on the east side of the Echo monocline may be designated the Wahweap syncline. The trend of this syncline is more northerly than the structural features that have been noted farther east, and there is here little structural differentiation from the Warm Creek syncline, which adjoins it on the east. For the most part Wahweap Creek does not follow the axis of the Wahweap syncline but flows in a course parallel to it, a short distance to the west.

TABLE CLIFF SYNCLINE

As defined by steep northeasterly dips at the head of the Paria Valley and by similarly steep southwesterly dips that are marked by the northwestward-trending hogback ridges along the headwaters of the Escalante, the Table Cliff syncline marks the bottom of the Kaiparowits downwarp. Its axis trends northwestward, and as indicated by a study of the Kaiparowits formation and the altitude of the top of the Wahweap sandstone, there is apparently a gentle plunge to a low point in the vicinity of Canaan Peak. The central part of the syncline is occupied by the Kaiparowits formation. The rocks are beveled off rather smoothly by erosion, so that above the axis of the syncline the Tertiary beds rest on beds high in the Kaiparowits formation, but a short distance to the east and west they rest on sandstone of the Wahweap formation, and farther away on lower beds down to the Navajo sandstone.

ECHO MONOCLINE

The sharp monoclinal flexure that is called by Gregory the Echo monocline is breached by the Colorado River at Lees Ferry. South of the river it is readily traceable for many miles in Arizona. Northward in Utah, where the flexure is much less prominent, it extends to the eastern part of R. 2 E., about midway between the points where the Paria River and Wahweap Creek cross the boundary. Near the State line the monocline is clearly defined by an eastward dip slope on the top of the Navajo sandstone, where dips of as much as 30° were observed. The displacement of any particular bed on the two sides of the monocline amounts to only about 1,500 feet, which is much less than at Lees Ferry and points farther south. Where Wahweap Creek intersects the monocline, 7 miles north of the State boundary, the dips average 12°–15° and the amount of displacement is somewhat less than it is to the south. Distinct easterly dips may be observed in the Cretaceous beds along Wahweap Creek as far north as Ty Hatch Creek, a tributary of Wahweap Creek in the southern part of R. 41 S. In this vicinity the fold plunges northward. The effect of the monocline on the distribution of rock formations is clearly exhibited on the geologic map of the area, for the border of the Cretaceous is about 6 miles farther south on the east side of the monocline than on the west side.

PARIA PLATFORM

The Paria platform is an area of gently northward-inclined beds between the East Kaibab and Echo monoclines. It is narrow at the north and widens gradually southward. It is structurally continuous with the great marble platform in which the Marble Gorge of the Grand Canyon is carved. Its maximum width in southern Utah is about 18 miles, but 20 miles north of the State boundary, where it passes into the undifferentiated parts of the Kaiparowits downwarp, it is barely 8 miles wide.

The gentle northerly dip slope is very well defined on the top of the Navajo sandstone in the Paria Plateau. East of the Paria River it forms the broad Clark bench, south of the Straight Cliffs escarpment. Upper Jurassic and Cretaceous rocks overlie and conceal the Navajo in most of the portion of the Paria platform that is included in the area here described.

EAST KAIBAB MONOCLINE

The East Kaibab monocline justly ranks as a major structural feature of the plateau country. It extends without interruption from the Colorado River northward to Table Cliff, a distance of about 120 miles, and defines the eastern border of the Kaibab Plateau. It raises the rocks on the west several thousand feet above those on the east, and through its influence in guiding erosion the present stratigraphic formations are so distributed that beds on the east side of the fold reach on the average about 40 miles farther south than corresponding beds on the west. Unlike the Waterpocket and Echo monoclines, the East Kaibab monocline trends east of north, but like theirs its steep dips are eastward. (See pls. 19, *B*; 21, *A*, *B*.)

The structural displacement along the East Kaibab monocline in southern Utah amounts to a maximum of about 5,000 feet. Along Kaibab Gulch it is possible to pass from the top of the Permian Hermit shale to the top of the Jurassic(?) Navajo sandstone in a horizontal distance of about 3 miles at right angles to the trend of the fold. The rocks on each side of the monocline slope gently north, so that successively younger rock divisions appear at the surface in passing from south to north. Along Cottonwood Creek and farther south the average dip of the rocks is about 40° E., but in places dips as steep as 65° have been measured. (See pl. 19, *B*.) In most places there is no observed evidence of faulting along the monocline, but south of the point where the Paria River crosses the fold there are indications of considerable fracturing of the massive Navajo sandstone accompanied by slipping and shearing. The extreme narrowness of the House Rock Valley near the point where Sand Wash crosses the sandstone escarpment indicates that a strike fault with downthrow on the east cuts out part of the soft Triassic beds that normally should be exposed at this horizon.

All the stratified rocks of the region up to the very top of the Upper Cretaceous Kaiparowits formation are involved in the folding, and the time of the deformation must therefore be at least very late in the Upper Cretaceous. It seems probable that the deformation took place at the end of Upper Cretaceous time and that the erosion represented by the pre-Wasatch unconformity may be referred to early Eocene time; represented by the Animas (Eocene?), Torrejon, and Puerco formations in the San Juan area, to the southeast. Evidence points rather strongly to a common age for the disturbances that produced the monoclinal folds of the plateau country. In several places rocks as young as the Mesaverde Cretaceous, which are included in the folding, are preserved from subsequent erosion, but in most places the pre-Wasatch or subsequent denudation has planed the surface down to rocks that are older than the Kaiparowits beds. Gregory [12] notes that very late Cretaceous rocks (the so-called Laramie beds of that area) are included in the deformation of the Defiance monocline in eastern Arizona, whereas in southern Utah the beveled Mesozoic beds are unconformably covered by Eocene beds. This indicates, then, that the general period of disturbance in the plateau country that produced the monocline is post-Fruitland in age and sufficiently older than the Wasatch to have permitted widespread and deep erosion of the underlying rocks.

KAIBAB UPWARP

The Kaibab upwarp includes the elevated strata on the west side of the East Kaibab monocline. The part of the upwarp that is included in southern Utah represents the northward-sloping border of the uplift, which reaches its greatest altitude far to the south, in the Grand Canyon district. The Kaibab limestone is exposed at the surface for about 10 miles north of the Utah-Arizona boundary, and beyond it successive outcrops of the younger beds appear in order. The Jurassic sandstone forms the eastward-trending escarpments known as the Vermilion and White Cliffs. The Cretaceous beds occupy the surface at the headwaters of the Paria Valley.

PAUNSAUGUNT FAULT

On the east side of the Paunsaugunt Plateau, but at a distance of 1 to 3 miles from the Pink Cliffs, which border the plateau, lies a prominent northward-trending fault with uplift on the east, known as the East Paunsaugunt fault. On the west side of the fault are Upper Cretaceous sandstones that belong to the Wahweap and Straight Cliffs formations, and on the east are Cretaceous beds that belong to the Tropic shale and the Dakota (?) sandstone, whereas farther south beds of the Upper Jurassic Carmel formation are found in contact with the Upper Cretaceous sandstone. Few places were observed where the total throw of the fault could be determined readily, but on Willis Creek the displacement apparently amounts to at least 1,500 feet. Where the Paria

[12] Gregory, H. E., op. cit., p. 111.

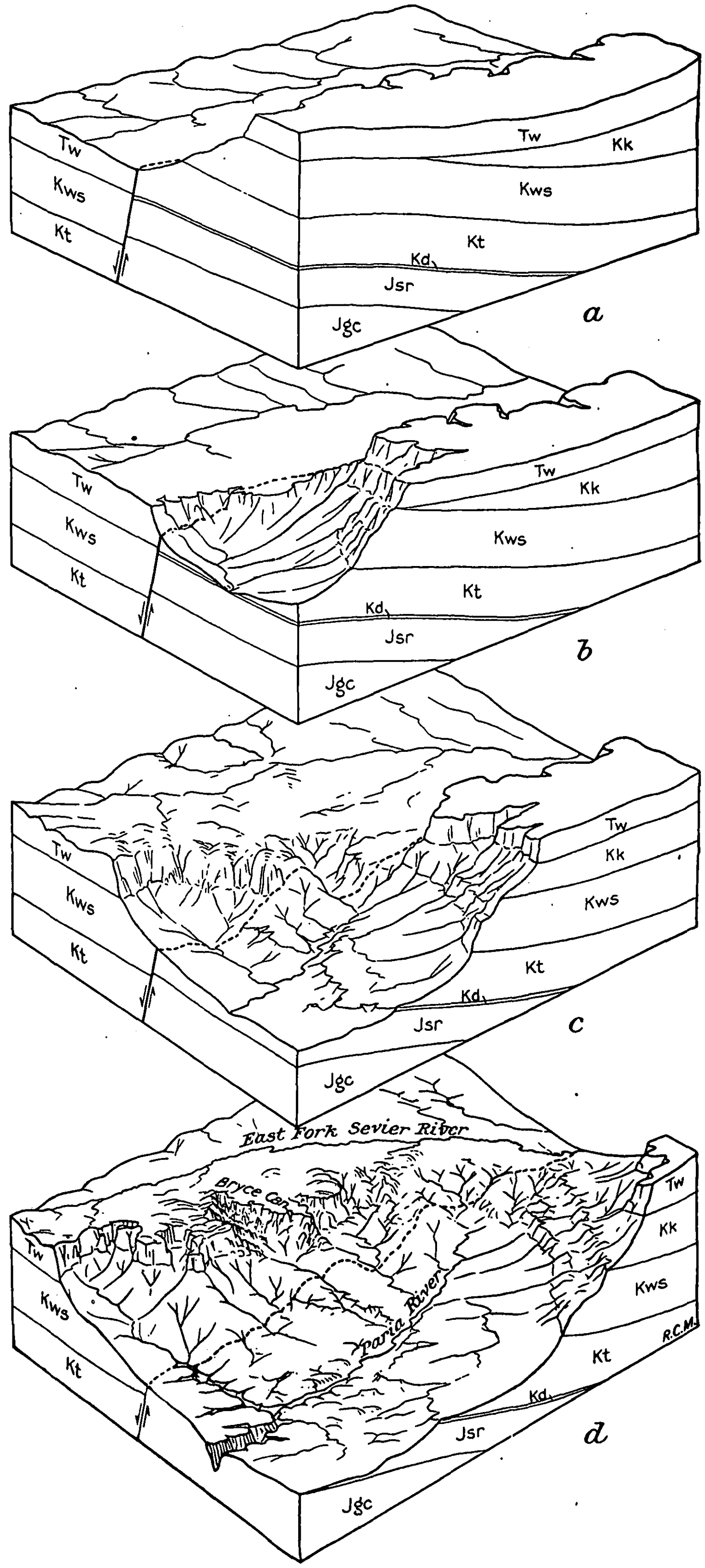


FIGURE 7.—Generalized block diagrams representing stages in the physiographic history of the upper Paria Valley. *a*, A short time after displacement of beds along Paunsaugunt fault; consequent northward drainage on the west (downthrown) side, and possibly also on east side. *b*, Recession of Tertiary cliffs on upthrown side through headward cutting of the Paria River drainage favored by steep gradient to the Colorado River and weak Cretaceous rocks below Tertiary. *c*, A later stage, showing erosion of the block west of the fault as well as further recession of cliffs on the upthrown block. *d*, Present stage. Not much headward cutting is needed for the Paria to capture the waters of the upper East Fork of the Sevier River. Tw, Wasatch formation; Kk, Kaiparowits formation; Kws, Wahweap and Straight Cliffs sandstones; Kt, Tropic shale; Kd, Dakota (?) sandstone; Jsr, San Rafael group; Jgc, Glen Canyon group

River crosses the fault Tertiary beds on the west are in contact with the Upper Cretaceous sandstones on the east, and the amount of the throw is apparently only 400 or 500 feet. As the fault affects the Wasatch Tertiary beds its age is post-Wasatch. In geologic time and in direction of dislocation of the rocks this structural feature is therefore entirely unrelated to the monoclines that have been noted in other parts of the area. The space between the Paunsaugunt fault on the east and the Sevier fault on the west, which is mainly occupied by the Paunsaugunt Plateau, may be designated the Paunsaugunt platform. As most of this area is covered by Tertiary rocks the structure of the underlying Mesozoic and older beds is not definitely known. Cretaceous sandstone that is exposed on the East Fork of the Sevier River lies practically flat, and it is probable that the older beds in this area have a gentle northward inclination similar to that of the Kaibab upwarp farther east. Topographically this platform has an altitude of somewhat more than 2,000 feet above the country to the east, which is a very interesting and physiographically significant feature, as the original effect of the Paunsaugunt displacement must have been to elevate the country on the east considerably above that on the west. This topographic inequality has since been reversed. (See fig. 7.)

Chapter 4. PHYSIOGRAPHY

REGIONAL RELATIONS

The Colorado Plateau province, of which the Kaiparowits region is a small but typical part, has long held special attraction for the student of land forms. For the province as a whole the topographic features are distinctive. In strongest contrast to the graceful outlines of humid climates, the plateau landscape is boldly rugged. The angled outlines of the land stand forth without protecting cover, but the naked landscape is decked in a maze of brilliant, fantastic colors.

The plateau province is essentially a country of broad cliff-edged mesas, more or less intricately trenched by narrow steep-walled canyons. In many places single platforms extend uninterruptedly for scores of miles. Commonly one wide plateau bench rises above another, and this in turn is surmounted by still others so as to form a series of broad, irregularly outlined steps, each hundreds or even thousands of feet in height. However, an outlook from almost any vantage point shows a sky line that is essentially horizontal; the breaks at the edges of successive plateaus appear quite insignificant, and the clefts carved by deeply intrenched drainage disappear almost completely. So well does the plateau surface on one side of a river appear to merge with that on the other that even the profound gorge of the Colorado becomes conspicuous only when its rim is closely approached. At a few points in northern Arizona and eastern Utah the general smoothness of the horizon is interrupted by laccoliths or volcanic piles—cone-shaped elevations like straw stacks in a broad field.

When viewed close at hand, each of the typical elements of the plateau landscape is bold and impressive. The surface of a plateau that at a distance seems a broad, smooth platform may prove to be intricately trenched by canyons hundreds of feet in depth, which make travel across it exceedingly difficult and in places all but impossible. The edge of each plateau is commonly marked by an imposing cliff, which surmounts a slope that leads down to the surface of the next lower platform. Many of these cliffs rise more than a thousand feet above the country below; from the floor of the Paria Valley to the top of the Table Cliff Plateau there is an almost unbroken ascent of more than 4,000 feet. Unnoticed details of the distant landscape on nearer approach stand forth as great buttes and towers.

Very noteworthy deviations from the normal subhorizontal elements of the landscape, and much more common than the irregularities due to igneous activity, are the long monoclinal ridges, many of them sharply serrate, which divide one section of the plateau country from another. Some of these walls extend almost without break and with little change in direction for more than 100 miles. Though these ridges are in general not lofty, they rise in places hundreds of feet above the adjacent plateaus.

As compared with other parts of the plateau province, the stratigraphic series of the Kaiparowits region are similar and the diastrophic movements are not unlike in kind and probably in time. The periods of igneous activity throughout the plateau country are probably more or less closely related. The establishment of the Colorado River drainage system and the development of the physiographic features that now distinguish its basin are chapters in the geologic history of Arizona, Nevada, and Colorado, as well as of southeastern Utah. The evidence from all these regions should be cumulative and accordant. Although the Kaiparowits region furnishes typical examples of nearly all the land forms of the plateau country and affords many interesting facts of physiographic history, the scope of this study is insufficient to make desirable the discussion of other than salient features. Interpretation of evidence concerning the physiographic history of the region is tentative and when correlated with future observations in this and in adjacent areas will doubtless be modified. Because of these considerations, the material presented in this chapter is largely descriptive.

FACTORS THAT INFLUENCE EROSION

CLIMATE

Southeastern Utah as a whole is arid. The average annual rainfall at six stations below the rim of the High Plateaus is 9.56 inches, and at few places on the High Plateaus does it exceed 12 inches. In parts of the Kaiparowits region it is probably less than 5 inches. The precipitation is subject to wide variation in time, in amount, and in place. The rain commonly falls in local torrential showers, and only at infrequent intervals are there general storms accompanied by widespread precipitation. (See p. 20.)

The sudden violence of the showers in a country almost barren of soil and vegetation results in a maximum amount of run-off, for little of the water soaks deeply into the ground. The falling rain gathers almost immediately into rivulets and gulleys, which carry it swiftly into the larger drainage channels. During heavy storms sheets of water cover much of the surface and roll along to some depression or plunge over the cliffs as a nearly continuous waterfall. In the canyons a turbulent, swollen flood of dirty, débris-laden water quickly appears, where before there may have been not even a trickle, and the waters may rise several feet in almost as few minutes. In narrow sections of the canyons the water may reach a height of 15 or even 20 feet above the canyon floor, and in many places it is dangerous to be caught during a heavy storm. To one not acquainted with the plateau country it is surprising to see the tumbling, noisy "wall of water" advance swiftly down a dry watercourse at a time when the immediately surrounding country is bone-dry.

During the passage of these floods the color of the water changes as one tributary after another contributes its load of waste. With the geology of the region in mind it is possible to determine the source of the materials, and thus the location of the storm, though many miles distant.

The run-off from a local shower may be insufficient in amount to reach one of the larger perennial streams, so that the water may deposit its load along the canyon as it sinks into the porous débris of the canyon floor. After the larger storms and during the rainy season, many of the tributary streams become through-flowing and contribute their mud and coarser land waste to the master stream.

If the rainfall in southern Utah were evenly distributed through the year the average flow of streams would be relatively small. It is even possible that evaporation and seepage into the materials of the valley bottom would more than counterbalance the small average surface flow; there would be little erosion. But the distribution of rainfall in sudden, hard showers, with consequent very rapid run-off, greatly facilitates erosion and the removal of large amounts of rock débris. A single flood may accomplish many times the amount of erosion that would result normally from months or even years of work by a small stream.

Evaporation tends to diminish the length and volume of streams, with consequent effects on transportation and deposition of débris. Gregory [1] has called attention to the seasonal and daily fluctuations of stream flow in response to evaporation, and Miser [2] ascribes some of the changes in volume of the San Juan to the periodic passage of hot dry winds.

[1] Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, p. 98, 1916.

[2] Miser, H. D., The San Juan Canyon, southeastern Utah, a geographic and hydrographic reconnaissance: U. S. Geol. Survey Water-Supply Paper 538, p. 17, 1924.

Frost is an active agent. The mesas and buttes that stand above the general surface level of the Paunsaugunt and Kaiparowits Plateaus are heavily coated with talus, and blocks pried from sandstone ledges are piled at the base of the higher cliffs and here and there along the canyon walls. Even on the gentler slopes frost supplies each spring a thin coat of material ready for removal by the torrential rills of summer.

VEGETATION

The collection of the rainfall in the stream courses of the Kaiparowits region is greatly accelerated by the generally scanty vegetation. The upper slopes and summits of the High Plateaus, above an altitude of about 8,500 feet, are fairly well forested. In places between the trees lie meadow-like glades carpeted with grass and dotted with thickets of shrubs. Here the run-off is retarded, and much of the precipitation sinks into the soil and underlying rocks. The lower slopes and the broad plateau surfaces at intermediate altitudes, such as the Kaiparowits Plateau, have a sparser covering of rather stunted trees, and the effect of vegetation in retaining moisture is considerably diminished. The lowest plateaus and valleys, at an altitude of around 6,000 feet and less, possess only a very scattered covering of small twisted cedars and scraggly piñons, with sagebrush, greasewood, and other plants in places between them. Each unit of the scanty vegetation tends to stand by itself, surrounded by bare soil, loose stony waste, or bare rocks. Over wide spaces not even a cactus has established a foothold in these inhospitable surroundings. Under such conditions the retarding effect of vegetation on active erosion is reduced to a minimum. For the region as a whole vegetation is a very subordinate factor in the control of run-off.

STREAM GRADIENTS

Owing to the comparatively short distance from the High Plateaus, where altitudes are 8,000 to nearly 11,000 feet, to Glen Canyon, where the altitude is less than 3,500 feet, most streams of the Kaiparowits region have steep gradients. The Paria River descends 7,400 feet in 75 miles, and even exclusive of its steep headwater tributaries, the lower 60 miles of the stream has an average fall of 43 feet to the mile. Similarly the Escalante River descends a little over 7,000 feet in about 80 miles, and the average descent below the steep headwaters is about 41 feet to the mile. Wahweap Creek, whose headwaters are in soft rocks that are underlain by a resistant sandstone platform, has an average gradient of 100 feet to the mile, and Last Chance Creek, in essentially similar surroundings, an average gradient of 70 feet to the mile. The shorter Warm Creek and Rock Creek have respectively average falls of 90 and 285 feet to the mile. In contrast with these streams the Colorado River in Glen Canyon has the exceptionally low gradient of about 2 feet to the mile.

There is an evident relation between the gradient of the streams and the character of the rock formations in which the valleys are carved. In portions of the valleys where soft rocks are exposed the stream gradient is relatively low, but where hard rocks are encountered the rate of fall is markedly higher. Thus, along most streams there is a succession of relatively gentle and relatively steep gradients. The interrupted profiles and steep gradients of the streams are indications of the rapid downward erosion that is taking place along their courses. Rapid erosion is indicated also by the characteristically large load carried by the streams. The flood waters sweep away enormous quantities of the finer sediments and push forward along the stream channels coarse rock waste, including large boulders. Much of the energy of some streams is utilized in transportation, with the result that vertical cutting is impeded, and there is a tendency to cut laterally and to develop meanders. The Colorado River in Glen Canyon is barely able to carry the load of waste supplied by its tributaries.

GROUND WATER

The predominance of high-lying plateaus and mesas bordered by lofty cliffs favors the emergence of ground water. Innumerable canyon walls provide an exit for water in bedding planes and zones of jointing, and much water seeps through the massive sandstones. Many rock surfaces are damp at night and on cloudy days, but in response to stronger evaporation during clear days only surfaces that are coated with efflorescence are moist. The local concentration of ground water along laminae of cross-bedding and on top of impervious beds has resulted in the production of rock-roofed recesses and alcoves. (See p. 144.) From walls of Navajo sandstone many seeps and springs emerge. Although continuous "spring zones" are not conspicuous features, most of the ground water in the Kaiparowits region reaches the surface at the contact of impervious and pervious strata. A few springs emerge at the top of the Chinle formation, from beds within that formation, and at the top of the Todilto (?) formation. The Morrison-Dakota (?) unconformity and the base of the Morrison is the site of several springs, and the sandstone overlying the Tropic shale is in many places saturated. The most numerous springs and seeps emerge at the base of the Tertiary, partly because the surface water supplied to these high-lying formations is relatively large and partly because the loosely compacted conglomerate that marks the Cretaceous-Tertiary contact is a capable water carrier. Along the base of the Paunsaugunt, Table Cliff, and Aquarius Plateaus a zone of moist rocks is almost continuous, and many patches of near-lying alluvium are saturated. The efficiency of ground water as a factor in erosion is further shown by landslides. (See p. 145.)

RELATIONS OF TOPOGRAPHY TO GEOLOGY

GENERAL RELATIONS

An outstanding feature in the topographic development of the Kaiparowits region is the control exerted by the composition, structure, and attitude of the rocks. It is readily observed that the surface of each broad bench or mesa is upheld by a rock mass that is resistant to erosion. From most benches the overlying weak rocks have been stripped away so that the present surface coincides closely with the top of the hard beds. The cliffed borders of plateaus and of canyons are likewise determined by hard rocks. In fact, the dominance of cliffs in the landscape is a reflection of the topographic influence of rock composition. Hard beds determine the broadly level plateau surfaces; where they are gently inclined, the surface is similarly inclined; and where they dip steeply the topography is mainly controlled by the sloping surface of the beds. Monoclines are represented in the topography by hogback ridges or by prominent lines of cliffs that are developed on the harder rocks. The surface exposures of weak beds are in general characterized by slopes or by gently undulating topography. Where the weak formations are disintegrated by weathering and by the corrasion of streams they strongly affect the configuration of valleys and the position of drainage lines. The relative thickness and position of the hard and soft beds involved in the Paunsaugunt fault has controlled the development of erosion forms in the upper Paria Valley.

The influence of geology on topography, including such structural features as jointing, stratification, and cross-bedding, is shown by the manner of the weathering of different stratigraphic units. The following will serve as examples:

The Dakota (?) sandstone, though of no great thickness, is exceptionally resistant to erosion, and where it is combined with the underlying Morrison it makes many prominent platforms that are bordered by high, almost vertical walls and crossed by sharp-cut narrow canyons Along much of the southwest flank of the Kaiparowits Plateau a Dakota (?)-capped bench is almost continuous. In places it is but a few hundred feet broad, but in the vicinity of Last Chance and Rock Creeks the rocks that overlie the Dakota (?) have been stripped back several miles and have formed Grand Bench—a great broad platform that terminates southward in cliffs nearly a thousand feet high. The Dakota (?) forms a hogback in the East Kaibab monocline (pl. 19, *B*) and caps low benches around Henrieville. On the east face of the Kaiparowits Plateau the Dakota(?) with the underlying Morrison forms a persistent bench that rises 200 to 600 feet above the adjacent lowland and extends 1 to 4 miles outward from the base of the higher cliffs.

Like the Dakota(?), the Shinarump conglomerate is represented in the topography by benches that are revealed by the stripping away of the less resistant overlying beds. In the Lees Ferry region the conglomerate serves as the cap for the persistent Moenkopi Cliffs. (See pl. 8, *A*.) In the Circle Cliffs it forms an inward-facing escarpment that is clearly differentiated from the higher cliffs and to it is due the preservation of the high mesas that overlook much of the surrounding country. (See pl. 7, *B*.)

The Todilto(?) combined with the underlying Wingate sandstone forms prominent benches in places where the overlying Navajo sandstone has been stripped away. In the Circle Cliffs these formations constitute a bench that defines the character of the topography on the border of the central depression. On the south and north, where the beds are nearly horizontal, the summit of this bench is nearly level. On the west and southwest, where there is a distinct inclination toward the Escalante River, strongly marked dip slopes occur at the top of the Todilto(?) formation. (See pl. 22, *C*.) Owing to radial drainage, consequent on the structure, spurs of this rock bench project along interstream divides toward the inner depression, and in a number of places where these spurs are partly broken down there are isolated buttes and towers.

The hard massive Wingate sandstone is affected by vertical jointing, which so controls the weathering of this formation that it forms uneven but practically continuous palisade-like cliffs. (See pl. 8, *B*.) In places slender projecting spires or needles of this rock have been defined by joint planes. The formation is cross-bedded, but because of the dense texture of the rock and its strong cementation the cross-bedding has practically no effect on the weathering of the sandstone or on the resulting forms. The overlying Todilto(?) formation is an irregularly lenticular, rather thin-bedded sandstone, which weathers characteristically in wide slabby benches. Individual layers of this formation are not notably softer than the Wingate, but the thinner uneven bedding associated with a few thin shale zones has a most striking effect on topographic expression at the outcrop of this unit. The succeeding Navajo sandstone is very massive and is traversed by few joint planes but is very prominently cross-bedded. The formation weathers characteristically in great sheer cliffs, rounded surfaces, domes, wigwams, and similar features, in which the wide-spaced jointing, extremely massive bedding, and irregularities of texture incident to cross-bedding, together with relatively weak cement, control the topography at its outcrop. (See pls. 4, *D*; 27, *C*.) The differences in these three sandstones are very characteristic and are persistently observable in the topography.

RELATION OF VALLEY FORM TO ROCK HARDNESS

The geologists of the Powell Survey repeatedly called attention to the influence of rock hardness on the gradient and form of valleys in the plateau province. This causal relation is indeed so remarkably close that with a general knowledge of the stratigraphy it is possible to predict the type of canyon in the area. In crossing one of the great rock platforms the explorer soon learns to select his route with reference to the extent and location of thin-bedded and thick-bedded formations. Even though no canyons are visible in a general view, experience teaches him that areas of Chinle, Carmel, Tropic, and Kaiparowits beds offer no serious obstacles to travel, that expanses of Moenkopi can be traversed without extensive detours, but that few routes across the Navajo, Dakota (?)-capped Morrison, Straight Cliffs, Wahweap, and Wasatch formations are practicable. To reach the opposite side of a narrow canyon in the Navajo sandstone may require a day of roundabout travel. Access to its floor may be impossible except by the use of ropes. Where hard rocks are exposed the gradient is steep and the valley is narrowly inclosed by precipitous walls; where soft rocks crop out, the gradient is gentle and the valley is open and has flaring sides.

The Kaiparowits region furnishes many illustrations of the marked contrast in the readiness with which hard rocks and soft rocks yield to the attack of erosion.

VALLEYS IN SOFT ROCKS

The relative hardness of rocks not only controls the development of the main topographic features but also very largely affects the manner of erosion by streams and accounts for the wide-stripped platforms that border Glen Canyon, the Escalante River, and other streams. Like the Tonto platform, which is developed on resistant Cambrian beds, and the "Esplanade," which is developed on the Supai formation of the Grand Canyon and Kanab Creek, the Glen Canyon platform, which has been made by stripping from the Navajo sandstone the weak overlying shale, is but the expression of the relative strength of the rocks; no earlier cycle of erosion is involved. (See pl. 21, *C*.) The weaker rocks tend to form slopes and to hasten the disintegration of the associated hard rocks; they also uniformly invite the main attack of stream erosion in the development of lowlands and valleys. Practically all exposures of soft rocks are therefore marked by more or less broad lowlands and valleys.

Fairly straight long valleys are carved in the upturned weak formations of the rock series that is involved in monoclinal folding. Thus Halls Creek is developed in the weak Upper Jurassic and Cretaceous shales of the Waterpocket monocline; Pine Creek, in the Upper Jurassic of the Escalante monocline and Cottonwood Creek, in beds of equivalent age that are involved in the East Kaibab monocline north of the Paria River. The House Rock Valley owes its position to the erosion of soft Moenkopi and Chinle formations, where these are brought to the surface by the East Kaibab fold.

The form as well as the location of these monoclinal valleys is obviously controlled by the structure and hardness of the rocks. Where the dip of the rocks is steepest, and the width of the soft-rock belt correspondingly narrowest, the valley is likewise narrowest, and where the dip is gentle the width of the valley or lowland is correspondingly increased. A deviation in the strike of the rocks is accompanied by a deflection in the position of the valley.

Where a stream traverses the outcrop of a zone of gently inclined or essentially flat weak strata, the width of the valley and the slope of its walls are dependent mainly on the size of the stream. Along larger drainage lines the already wide valley is commonly made still more open by the entrance into the soft-rock belt of several tributary valleys. The Escalante River above Escalante, the Paria River below Cannonville and near old Adairville, and several other main streams are examples. The saucer-like Butler Valley, in soft shaly San Rafael beds; the Round and Horse Valleys, in the Tropic shale southeast of Cannonville; and Sheep Flat, southwest of Cannonville, are broad, flat-bottomed, round valleys carved in soft rocks by a fan-shaped drainage system, the component parts of which are separated by divides too low to be noticeable. The broad, flat-floored bowl carved in the Cretaceous shale at the head of the Paria near Tropic is an exceptionally large "round valley."

In parts of southern Utah areas of soft rock are carved by streams into intricate badlands.

In the Kaiparowits region most of the channels of the streams in soft rocks are broad, shallow, flat-sided and moderately straight. During the times of ordinary flow the streams in them have an insignificant volume, and they commonly wind from side to side in channels that are too broad for their needs. During floods the whole channel is occupied by débris-laden water, and the stream is then much greater in width but shallower in depth than in adjoining hard-rock sections. Because of the wide cross section, erosion is less effective on the bottom of the channel, but there is a tendency to straighten the channel by wearing away projecting points. An irregular, highly meandering course seems to be abnormal under these conditions.

VALLEYS IN HARD ROCKS

In the Kaiparowits region areas of hard rocks are associated with narrow, very steep-sided canyons. The width of the stream channel is markedly reduced as compared with that in adjoining stretches of soft rock. The dominance of valley deepening over the gradual wearing down of the canyon sides has led to the cutting of the extremely deep, slitlike chasms that characterize the landscape of many parts of the plateau province. Some valleys tributary to the Colorado, to the Paria, and to the Escalante are several hundreds of feet deep but not more than a dozen feet wide at the bottom.

VALLEYS IN HARD AND SOFT ROCKS

Where the side walls of a valley consist of alternating hard and soft strata there is a corresponding alternation of strong with weak cliffs and of steep and narrow with wide and gentle slopes. The shape of the valley in cross section is determined by the relative thickness and position of the hard and soft strata that are exposed, and changes appear systematically in different parts of a stream course, dependent on the differences in the rocks above the stream channel. This distinctive physiographic character in the form of valleys of the plateau country was very well described by Powell[3] and Dutton[4] and more recently by Davis.[5]

Where local relief is great, weak rocks with interbedded hard layers may be carved into an amazingly intricate labyrinth of deep, narrow canyons, separated by irregular, in many places grotesquely sculptured knifelike divides. Where they are tinted vividly by varied colors, these valleys present very striking scenic attractions. Bryce Canyon shows these features in marvelous fashion.

EFFECT OF MONOCLINAL RIDGES

Essentially similar topographic features characterize all the monoclinal folds of the Kaiparowits region. (See p. 118.) Elongate ridges are formed by the hard rocks; long, narrow valleys are excavated in the soft beds; and each of the ridge-forming units presents an individual set of minor topographic characters. The Cretaceous sandstones commonly make very sharp-angled, serrate hogbacks not uncommonly crested with a projecting narrow comb that is inclined in the

[3] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, pp. 202–211, Washington, 1875.

[4] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 250–260, 1882.

[5] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zoology Bull., vol. 28, p. 40, 1901.

direction of rock dip. (See pl. 19, *B*.) The massive Navajo sandstone forms a lofty ridge with rounded outlines and irregular tumid swellings; its bare sloping back is deeply grooved by lateral canyons; and its upturned edge forms nearly sheer, unbroken cliffs or weathers with gigantic bouldery irregularities. The Wingate and its Todilto(?) cap forms a compact sharp-angled rocky ridge, and the dip slope of its upper surface is broadly smooth. The thin Shinarump conglomerate forms a narrow hogback ridge.

The Waterpocket monocline is marked on its east side by prominent hogbacks that are developed on the hard formations and by longitudinal intervening valleys. (See pl. 19, *A*.) Halls Creek occupies a monoclinal valley that has been carved in the weak rocks of the Waterpocket flexure and follows its trend. North of the low Bitter Creek divide the same structural valley is used by a northward-flowing tributary of the Fremont. The width of the valley depends on the thickness and angle of inclination of the weak Upper Jurassic beds, and as the dip decreases near the Colorado River, the valley becomes wider there than it is farther north. In two or three places, most notably at a point below the mouth of Muley Twist Creek, Halls Creek turns aside from its comparatively wide, open valley in soft rocks and plunges into a narrow, deep canyon in the hard Navajo sandstone. These departures from the easy pathway clearly mark local failures of the creek to adjust its course by shifting laterally in the zone of inclined soft rocks. (See pl. 24.) South of the Bitter Creek divide the Waterpocket Fold is practically unbreached below the top of the Navajo sandstone until the locally dissected area along the Colorado River is reached, and throughout this length of nearly 40 miles the upturned sandstones form a topographic barrier that can be crossed in only a very few places. The sheer walls of the Wingate sandstone cliffs are quite unscalable, and there are few openings through the Navajo. The only practicable passageway through the fold is afforded by the deep, narrow canyon of Muley Twist Creek, which cuts at right angles across the upturned Navajo in a tortuous defile in places not much wider than a wagon. (See pl. 23, *B*.) About 6 and 12 miles, respectively, north of the Muley Twist Gap it is possible with some care to get a horse down the steep slope on the top of the Todilto(?) rocks and through narrow, stream-carved gaps in the Navajo sandstone, but these passageways are hazardous. Near the Colorado River many short valleys rise on the east steep flank of the fold and extend to Halls Creek. Streams on the gently inclined west flank flow in deep, narrow gorges to the Escalante River.

The Circle Cliffs owe their interesting topographic features to weak Triassic rocks and structural dips. Most of the streams flow in a direction that coincides with the dip of the rocks, but some follow the outcrops of one of the weak formations parallel to the strike. The head portions of the streams are open, and the divides between them are not prominent, but the lower portions are narrow, deep canyons. (See pl. 23, *A*.) So clearly is the topography and drainage of this area controlled by geologic structure and rock hardness that there is no trace of a possible former drainage that was unrelated to the attitude and character of the Mesozoic rocks. If Tertiary beds once covered this area, as can not be doubted, all vestige of streams that flowed on the Tertiary surface has disappeared.

The bench that overlooks the Colorado River at the south end of the Waterpocket Fold is developed on the Todilto(?) and Wingate sandstones at a place where the Navajo sandstone has been stripped for a space of several miles. The surface of this bench descends to the level of the river in harmony with the eastward-dipping beds of the monoclines.

The effects of the Echo monocline are shown in the surface slopes of the Paria Plateau. In line with this fold the summit of the plateau descends sharply several hundred feet eastward. South of Cottonwood Springs, on Wahweap Creek, this broadly rounded slope is clearly seen descending along the top of the Navajo sandstone to a longitudinal valley that has been cut in the softer overlying beds. Northward along Wahweap Creek the flexure is marked by hogback ridges in the Cretaceous sandstone. The surface of the plateau inclines generally northward, and the bench that forms the top of the White Cliff is but a continuation of the bench that has been formed by the surface of the Paria Plateau, from which it is separated by the East Kaibab monocline. Both these gigantic platforms owe their form and position to the relative hardness of the Navajo sandstone and to the regional slopes that have been produced by monoclinal flexures.

The East Kaibab monocline is represented in the topography by very conspicuous hogbacks formed by the sharply upturned Mesozoic sandstones along the Paria River and Cottonwood Creek (pl. 19, *B*), by the House Rock Valley, which is carved in weaker rocks, and by the arched crest of the north end of the Kaibab Plateau. The resistant Kaibab limestone rises steeply from the House Rock Valley as a broad, smoothly curved surface and continues westward as the enormous flat arch of the Kaibab Plateau—structurally the Kaibab upwarp. The surface has the form given to it by tectonic movements.

Like the other folds of the Kaiparowits region, the East Kaibab monocline is a prominent topographic barrier, second only to the deep canyons. Travel is easy along the subsequent valleys that have been developed in the soft rocks but is almost impossible at right angles to the trend of the monocline. The only passage through the hogbacks that presents no special difficulties is near the abandoned village of Paria, where the Paria River has cut an oblique channel through the upturned hard rocks. (See pl. 26, *B*.) With some difficult climbing at one point, it was possible to cross the fold by ascending the canyon of Sand Wash. About 20 miles north of Paria a circuitous, constricted passageway, known as "the Gut," may be followed by a saddle horse or pack animal and is used at times by stockmen in traveling from Henrieville and Cannonville to the Wahweap country. Near Canaan Peak, where the eroded surface of the East Kaibab monocline is unconformably overlain by the Eocene sediments, the country is particularly rough.

RELATION OF STREAMS TO STRUCTURE

Many small streams and some large streams of the Kaiparowits region are obviously adjusted to the structure. Halls, Pine, and Cottonwood Creeks occupy valleys that have been developed in weak strata on monoclinal folds. In the Circle Cliffs dome the streams flow radially outward down dip slopes, and from the crest of the Waterpocket Fold streams follow tilted strata to Halls Creek and to the Escalante River. The East Fork of the Sevier River flows northward in accord with the inclination of the beds that compose the Paunsaugunt Plateau. Wahweap, Warm, and Last Chance Creeks, although they flow in a direction opposite to the dip of the beds, occupy shallow synclines. Some streams follow the slope of hard-rock platforms, and many of them have established short subsequent courses along the strike of easily eroded flat-lying or tilted beds or even on the crests of monoclinal folds.

But although much of the minor drainage is locally well adjusted to structure the larger streams are remarkably independent of structural control. They flow in and out of cliffs, cut through mesas, transect monoclines, cross faults from the downthrown to the upthrown sides, and make their way through tilted strata without regard to the direction of dip.

The Colorado River crosses the Waterpocket flexure without evident deviation and crosses the prominent Echo monocline almost at right angles and against the dip of the rocks. The Escalante River plunges directly through the prominent Escalante monocline and farther down its course has intrenched itself midway up the structural slope that extends from the Waterpocket monocline to the cliffs of the Kaiparowits Plateau. The Paria River flows southward almost opposite to the regional dip of the rocks and then turns slightly eastward and crosses at an oblique angle the sharply upturned beds of the East Kaibab monocline and nearer the Colorado River again flows practically against the inclination of the rocks. If the Escalante River were controlled by structure it should follow the belt of weak rocks in front of the Straight Cliffs, and the Paria River would have been spared the prodigious task of trenching the East Kaibab monocline and the Paria Plateau.

Powell, Gilbert, and Dutton repeatedly call attention to the discordant relations of the tributaries to the Colorado. Dutton [6] says:

> They rush into a cliff or into a rising slope of the strata as if they were only banks of fog or smoke. It matters not which way the strata dip, the streams have ways of their own.

This seemingly strange behavior was interpreted as evidence of antecedent drainage. Concerning the Green River and its tributaries that are intrenched in the folds of the Uinta Mountains, Powell [7] says: "The streams were there before the mountains were made * * *. The elevation of the fold was so slow that it did not divert the streams."

Dutton [8] thought that the Colorado drainage was inherited from a system of streams established on Tertiary strata which became folded and faulted at so slow a rate that the position of channels was little disturbed. The streams were antecedent to Tertiary upwarps, and the removal by erosion of Tertiary, Cretaceous, and Jurassic beds brought the drainage system to its present position without changing its pattern. On this interpretation the drainage of the Kaiparowits region might be described as superposed antecedent. Dutton says:

> The whole province is a vast category of instances of river channels where they never could have run if the structural features had in any manner influenced them. What, then, determined the present distribution of the drainage? The answer is that they were determined by the configuration of the old Eocene lake bottom at the time it was drained. Then, surely, the watercourses ran in conformity with the surface of the uppermost Tertiary stratum. Soon afterwards that surface began to be deformed by unequal displacement, but the rivers had fastened themselves to their places and refused to be diverted.

Dutton recognized, however,[9] that the Waterpocket and Escalante monoclines are of pre-Tertiary age; their beveled strata are overlain by Eocene sediments. He explained this "anomaly" by assuming that erosion prevailed in a part of the plateau province while deposition elsewhere was continuous. Gilbert[10] tentatively expressed the opinion that the Echo Cliffs flexure determined the course of the Paria River, but later concluded that "there is no ground for the

[6] Dutton, C. E., Report on the geology of the High Plateaus of Utah, p. 487, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[7] Powell, J. W., Exploration of the Colorado River of the West, p. 162, 1875.

[8] Dutton, C. E., Report on the geology of the High Plateaus of Utah, p. 17, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[9] Idem, p. 288.

[10] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 76, 1875.

opinion that the courses of Kanab and Paria Creeks were in part determined by antecedent folds." In a note written still later [11] he said:

The observations that form the basis of these reports were hurried in the extreme. The writer, for the most part, accompanied field parties which were specially equipped for rapidity of movement and were crowded to the utmost. Moreover, in a country almost unmapped the demand for geographical information was more urgent than 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 of facts. That many of these impressions should be erroneous was inevitable, and no one can be more conscious than I of the fallibility of what I have written. Still I am far from counting my labor lost; for the best presentations that have been given of western geology are not free from error, and I certainly have most honorable company in my imperfection.

More than a year has elapsed since the manuscript left my hands, and in that time I have again visited Utah. Partly as the result of my new work, and partly by facts which have been developed by others, I have been induced to change some of my ideas, and I avail myself of this occasion to make a few retractions.

On page 132, basalt is erroneously reported to occur near the town of Salina, Utah.

On page 44, it is stated that an orographic disturbance occurred in the northwest part of the plateau province "before the deposition of the Cretaceous." The unconformity which I observed I now know to have arisen after the deposition of the Cretaceous.

On page 116, the opinion is expressed that artesian water might be found along the eastern base of the Pahve t Range. Mr. Powell has since discovered a fault in the strata of the locality which greatly diminishes the probability.

It is asserted on pages 129, 130, and 525 that the San Francisco lava field is continuous with the great lava field of New Mexico. The notes of Dr. Loew show that this is not so.

There is no good ground for the opinions advanced on pages 76 and 81 that the courses of Kanab and Paria Creeks were in part determined by antecedent folds and that the Aubrey Cliff as a topographical feature antedates the Grand Canyon.

The unhappily large number of typographical errors in Part I are due in part to the fact that I was absent in Utah during the proofreading and did not see the pages until they had been stereotyped. In these few copies that I distribute myself I have corrected many of the errors in the margin. I have also restored in part some words and sentences that were suppressed in the manuscript after it passed my hands. Certain of the restored passages are necessary to the understanding of the context, and others are needed to prevent the impression that I disregarded through ignorance or discourtesy the work of other geologists.

It is difficult indeed to imagine the conditions under which the observed relations of deformed Cretaceous beds that unconformably underlie horizontal Tertiary beds can be accommodated to the supposed antecedent origin of the Colorado drainage system. There is no reason to doubt that Tertiary beds once covered all of the Kaiparowits region and extended far beyond its borders and also that the great upwarps and monoclinal folds are not only pre-Tertiary but were eroded to a surface of low relief before the deposition of the Tertiary beds. The known disturbances of the Tertiary beds consist of faults which postdate Eocene sedimentation and which probably developed after Tertiary and perhaps also Cretaceous and Jurassic beds had been removed from some areas north, south, and east of the Colorado River. The antecedent origin of the Colorado drainage system as described by the geologists of the Powell Survey is therefore highly improbable. It seems more probable that the Colorado and its main tributaries were established on a former, very widespread surface of Tertiary rocks. If the drainage was established as a consequent system on this old Tertiary surface the Colorado and its tributaries, on cutting into the older rocks, would obviously find themselves superposed indifferently on whatever formations and structural features chanced to underlie the Tertiary.

Even though the larger streams in the Kaiparowits region may in part owe their position to superposition of an original consequent system that was developed on Tertiary beds, their present trends and habits are adjustments to one or more surfaces of erosion of much later date. Remnant peneplains and abandoned meanders indicate an erosion surface of very low relief that bordered the main drainage channels and extended to some distance beyond. (See pp. 133–135.) On this erosion surface the Colorado River and its main tributaries could have been retained or established in essentially the position that they now occupy. If irregularities due to differences in rock hardness had been obliterated, the drainage lines established would be unadjusted to the underlying rock structure. When subsequently the region was uplifted and the streams began actively to deepen their valleys, the small, weak streams would be guided by structure, but the large, strong streams might retain their positions across obstacles that chanced to lie in their paths. Such superposition would presumably account for the existing discordance of streams and structure and for the resulting physiographic features. To use Gilbert's term, the streams are "superimposed by planation."

EXTENT AND RATE OF EROSION

The extreme ruggedness of the Kaiparowits region is due primarily to sculpture by streams. The lofty mesas and buttes have been carved out of extensive high-level plateaus, not lifted by locally active forces. The relief is a record of downward departures rather than upward departures from a former general surface. The amount of material removed by stream

[11] Idem, prefatory note in copies of vol. 3 personally distributed by Mr. Gilbert.

carving, however, is enormous; thousands of feet of rock have been stripped from a region tens of thousands of square miles in area. But the parts remaining are even greater than the parts removed; the amount of denudation yet to be accomplished in the present cycle far exceeds that already completed.

The present local base-level of erosion for streams in the Kaiparowits region lies at the head of Marble Gorge, where hard limestone greatly retards the downcutting of the Colorado River. Because of this barrier the river in Glen Canyon is no longer actively deepening its bed and seems unable to remove the rock waste that it has accumulated along its margins. The profile of the Colorado River through Glen Canyon and Marble Gorge is but a large-scale illustration of the adjustment to rock hardness that is shown by most streams of the Kaiparowits region.

As an aid in producing land waste, the Colorado River in its course between Hite and Lees Ferry exerts small influence, and until its load of waste is significantly lessened or Marble Gorge is deepened, it is likely to remain in that position. But the tributaries of Glen Canyon are not thus handicapped. Their gradients are steep, many of them precipitous; the floods that occur many times each year give them special strength. At present they are not only carrying the enormous amount of waste brought to them by smaller streams, but in many places they are deepening their channels and removing materials that were deposited during a former period of aggradation. Denudation in the Kaiparowits region is probably proceeding as rapidly as in any other part of the plateau province and more rapidly than in most humid regions. If the present favorable climatic conditions continue these relative rates seem likely to prevail throughout the present cycle of erosion.

EROSION SURFACES

REGIONAL DISTRIBUTION

On the Uinkaret, Shivwits, Kaibab, and Coconino Plateaus Dutton discovered remnants of old gently graded erosion surfaces which bevel across Permian beds—hard rocks and soft rocks alike—and which have been preserved by a protecting cap of basalt. This evidence of ancient cycles led to the significant generalization that before the beginning of the cutting of the present Grand Canyon and the other deep canyons of the region the plateau district was reduced essentially to a base-level of erosion and that the present cycle of active canyon sculpture was initiated by a pronounced uplift that strongly rejuvenated the streams. Dutton [12] says:

> At the epoch when the cutting of the present Grand Canyon began, no doubt the district at large presented a very different aspect from the modern one. The fact that the older basalts, wherever found, rest upon the same geological horizon, viz, the summit of the Permian, suggests to us the further inference that the region near the river was then flat and destitute of deep canyons and valleys, such as now exist there, and therefore destitute of great hills, buttes, or mesas. The meaning of this is a base-level of erosion. The rivers could not corrade, because they had reached, for the time being, their limiting depth in the strata. The work of erosion would then be confined to leveling the sculptural inequalities without the power to produce new ones or to augment the relief of old ones.

In addition to the peneplain remnants in the plateau province described by Dutton, others have been mapped by Huntington and Goldthwait,[13] Robinson,[14] and Gregory [15] and incidentally mentioned by others. Some of these erosion surfaces have been developed in Permian beds, others in Triassic beds, and the Hopi Buttes peneplain bevels successively Cretaceous, Jurassic, and Triassic beds. Although they stand at different altitudes between 4,000 and 7,000 feet, some of these fragmentary surfaces are probably comparable in age and history. In the Kaiparowits region old-age erosion surfaces appear at several places—conspicuous features in an area of vigorous youthful erosion.

CANNONVILLE EROSION SURFACE

In the upper Paria Valley the little Mormon town of Cannonville is surrounded by extensive remnants of an old erosion surface that planes smoothly across hard and soft Upper Jurassic and Cretaceous beds. In most places this erosion surface has a rather pronounced angle to the bedding of the stratified rocks. East of Henrieville and northeast of Tropic there are broad, little-dissected remnants developed on the soft Tropic shale. (See pl. 25, *B*.) A mantle of coarse, well-rounded water-borne materials protects the underlying weak rocks and has aided materially in preserving portions of the graded plain. Near Cannonville the erosion surface intersects the basal part of the soft shale and the hard sandstone at the bottom of the Cretaceous. To the west, overlooked by the high cliffs of the Paunsaugunt, the divides between the streams that are cutting actively headward into the High Plateaus are even-topped and very gently inclined toward the Paria.

In many places a lower surface is marked by a prominent bench that is subparallel to the upper erosion surface and about 200 feet lower. It is well developed in the Cretaceous shale area east of Tropic.

[12] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 223–224, 1882.

[13] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 226–237, 1904.

[14] Robinson, H. H., The Tertiary peneplain of the Plateau district and adjacent country in Arizona and New Mexico: Am. Jour. Sci., 4th ser., vol. 24, pp. 115–118, 1907.

[15] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 120–122, 1917.

Near Cannonville the erosion surface has an altitude of about 6,000 to 7,500 feet. In it the Paria River and its tributaries have carved valleys 300 to 1,000 feet in depth and are rapidly cutting deeper. Northward and westward along divides that have not yet been sharpened by recent erosion, the erosion surface continues as a fairly gentle slope that leads up to the summit of the higher plateaus. The borders of the Tertiary plateaus were doubtless slowly receding as the erosion surface was developing, but the slopes that surround the broad valley plains appear to have been rather well though steeply graded. The more active cutting, which was due to uplift of the region and rejuvenation of the streams, has merely served to sharpen the cliff profiles and to accelerate the retreat of the cliffs.

Southward the remnants of the Cannonville erosion surface merge with the gentle back slope of the massive sandstone that forms the White Cliffs. At the time when this surface formed the floor of the upper Paria Valley the White Cliffs escarpment rose hundreds of feet above the plain, and the Paria River crossed the sandstone in a moderately narrow valley, probably not unlike the present canyon except in depth. The outline of the White Cliffs has doubtless been somewhat modified, but there does not appear to have been much recession of the cliffs during the recent stage of active erosion that is now continuing.

Nearer the Colorado River, where traces of an older topography have been largely obliterated, it is not possible to recognize with assurance a former extension of the Cannonville surface. The gradient of the present Paria River is much steeper than that of the Cannonville stage, and accordingly, on approaching the Colorado, remnants of this older erosion surface, if present, would be at proportionately greater heights above the present valley floor. Some of the hard-rock surfaces of the plateaus northeast of the Paria River and of the Jurassic sandstone ridge along the East Kaibab fold exhibit suggestive traces of an older topography above 5,500 feet. On the hard-rock surface of the Kaibab Plateau the topography is notably more mature than that on the lower slopes along the House Rock Valley, and remnants of erosion surfaces bevel the softer rocks on the flanks of the East Kaibab uplift and extend in some places far out toward the Marble Gorge.

SURFACE OF KAIPAROWITS PLATEAU

In a regional sense the Kaiparowits Plateau is a thick mass of Jurassic and Cretaceous sedimentary rocks—the remnant of a mass that once extended throughout southeastern Utah and into neighboring States. Its preservation is due to its position in a shallow syncline and to the resistance of its capping Cretaceous sandstone. In general its surface is conformable with the attitude of its component rocks, but in places it is out of accord with the structure. Near Canaan Peak, at an altitude of about 6,500 feet, lie remnants of a smoothly graded erosion surface developed on the inclined beds of the weak sandstone and sandy shale of the Kaiparowits formation and cutting across harder and softer beds alike. From this surface gentle slopes lead evenly upward to the Tertiary limestone of Canaan Peak and thus duplicate the relations near Cannonville (p. 133). To the south and southeast the graded erosion surface merges with the broad, smooth slope of the Wahweap sandstone, which here has little relief. Migrating divides appear at several places where the headwaters of Last Chance and Wahweap Creeks, favored by steep gradients, are eating away the older topography.

The surface of the southeastern part of the Kaiparowits Plateau is distinguished topographically by open valleys and gentle slopes, together with some sensibly flat areas. Though some of the broad stream channels are deep, none of them reach the bottom of the capping sandstone. The topography as a whole seems distinctly more mature in this part than in other parts of the plateau surface. The upstream parts of many of the older valleys have been beheaded and their lower parts greatly steepened or cut off by erosion on the flanks of the plateau, indicating a considerable shrinkage in the size of the former graded upland. Obviously these features afford evidence of an old erosion surface.

The gently graded surface near Canaan Peak accords in general altitude and topography with the erosion remnants along the Paria. The somewhat rugged but maturely dissected topography of the southeastern part of the Kaiparowits Plateau is probably a part of the same old topography, and the more strongly developed relief is due to proximity to the Colorado, which is the master stream for both areas.

SURFACE OF PAUNSAUGUNT PLATEAU

The surface of the Paunsaugunt Plateau is gently concave. The bordering rim is uniformly higher than the central part, and the drainage is radially inward to the perennial East Fork of the Sevier River, which occupies the axial position. In direction of flow the main stream and its tributaries conform with the general inclination of the rocks.

In contrast to the deeply carved canyons of streams beneath the Pink Cliffs, the summit topography of the Paunsaugunt consists of mature slopes and gently graded flats. Land sculpture, so far as it can be accomplished by the gently sloping East Fork and its tributaries, has advanced far.

Between Red Canyon and Castro Canyon certain of the divides that separate the southeastward-flowing tributaries of the Sevier have a gentle southward slope that appears to mark a former graded erosion surface, and in places well-defined remnants of a graded slope lie between this upper one and the bottoms of the present stream valleys. Erosion by Castro Canyon has beheaded in a very interesting manner several of these southward-sloping tributaries and has cut off also the smooth interstream slopes from their continuation on the north. The southern part of the plateau, which rises to an altitude of more than 9,000 feet, is somewhat more rugged than the northern part, where wide alluvial flats cover the flanks of projecting hills. This contrast seems to be greater than the normal difference between the headwaters and the lower part of a stream course, and it is not unlikely that a geologically recent, slightly uneven northward tilting of this area has served to accelerate sculpture in the southern part and to bury the northern part of the river valley under extensive deposits of alluvium.

That the maturely eroded surface of the Paunsaugunt Plateau was once more extensive is shown by the form of the upper tributary valleys. Along the rim of the plateau that overlooks the Paria Valley the tributaries of the Sevier, which flow in valleys of very gentle gradient, come into competition with those of the Colorado, which flow in steeply inclined valleys. Many valleys on the plateau maintain their broad V form to the very edge of the Pink Cliffs, where they are cut off by the more favorably situated southward-flowing streams. Some streams from the lower lands have even reached the top of the plateau and have diverted drainage from the Sevier. Only a small amount of digging was required in the construction of the irrigation ditch that now leads water from the East Fork of the Sevier over the plateau rim to the fields at Tropic.

SLOPES OF AQUARIUS PLATEAU

A view toward the Aquarius Plateau from the high sandstone cliffs along the Waterpocket Fold shows very clearly a gently graded erosion surface that cuts obliquely and smoothly across the bedding planes of the hard Navajo sandstone. This slope extends from the upper plateau almost without break to the border of the Circle Cliffs. Along Pine Creek and Sand Creek the beds involved in the Escalante monocline have been truncated, and three remnant peneplains have been mapped. Tributaries of the Escalante are now cutting vigorously into the edges of the Aquarius Plateau and are gradually obliterating this slope, which remains only on the divides. Probably the interstream topography corresponds to similar features along the Paunsaugunt and Table Cliff Plateaus and represent the subdued outline of the Tertiary plateau during the stage of erosion that preceded the present cycle of canyon cutting.

A southeastward continuation of the profile from the Aquarius Plateau indicates that probably the excavation of the great bowl that is now bounded by the Circle Cliffs had been begun at this time, but erosion could hardly have advanced much farther than to establish the courses of the consequent streams that now carry part of the waters of this territory to the Escalante and Halls Creek.

EROSION SURFACES AT OTHER LOCALITIES

Along parts of the Waterpocket Fold and on some of the slopes that border the Henry Mountains clearly determinable remnants of old erosion surfaces now stand at altitudes between 5,000 and 8,000 feet. Some of the interstream erosion remnants bevel smoothly across a number of hard and soft Cretaceous and Upper Jurassic rock formations. As in the northern part of the Kaibab Plateau, some of the valleys of the Waterpocket Fold have a notably more open and more mature topography near their heads than farther downstream, where the valleys, though carved in the same formation, are extremely narrow and deep. Remnants of old erosion surfaces appear in the Paria Valley (pl. 27, *B*), in the Escalante Valley, and along Glen Canyon.

INCLOSED MEANDERS

Prominent features of many valleys in the Kaiparowits region are their tortuously winding courses. They appear in a few valleys carved in soft rock and are characteristic of valleys in hard rock. The high rock walls of big valleys and of little valleys follow each bend and turn in the stream course. (See pl. 21, *C*.) Through Glen Canyon the Colorado winds southwestward in and out around buttresses like a gigantic snake. Its tributary streams are even more sinuous. In the lower reaches of the Paria and Escalante Rivers and Wahweap, Warm, Last Chance, and Rock Creeks and in the canyons that enter the Colorado from the north and from the south closely pressed curves and almost right-angled turns mark the course of parallel canyon walls; straight sections are rare, and in few places is it possible to see both walls for half a mile ahead. Along the Virgin River, Kanab Creek, the San Juan River, and elsewhere in the plateau province the same phenomena occur.

Of the canyons in the Navajo country, Gregory[16] says:

> All the canyons are sinuous to a degree very much greater than indicated on topographic maps. Close-set meanders with horseshoe curves and goosenecks are common, and the traverse of many a canyon involves passing to right and left about towering buttresses with turns approaching 180°.

[16] Gregory, H. E., op. cit., p. 124.

The prevalence of these meanders along canyon courses is directly related to the kind of rock that forms the canyon wall. In the heavy beds, particularly massive sandstone, they are preserved; in shale and thin, soft sandstone they are absent or at least poorly represented.

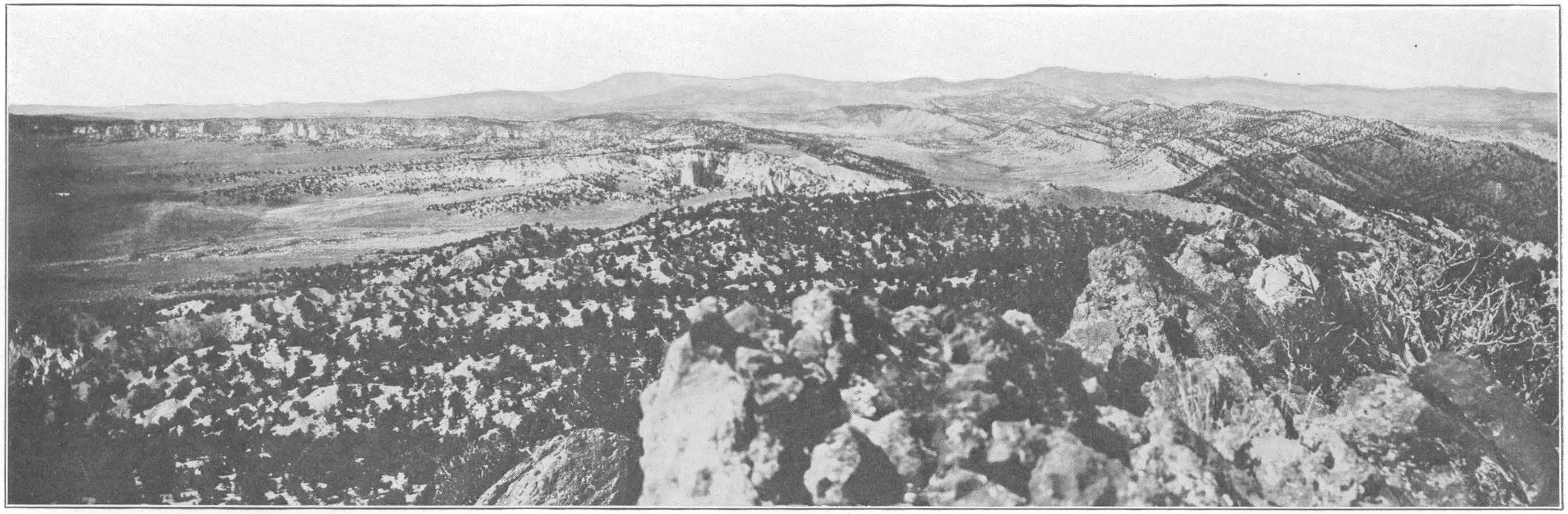
The Escalante River presents no unusual features in its upper course through Cretaceous strata, but from Escalante to its mouth the river follows a very sinuous course that is carved in sandstone of the Glen Canyon group. Wahweap Creek, Warm Creek, and other streams that drain the south side of the Kaiparowits Plateau show inclosed meanders in Cretaceous sandstone near their heads, but downstream they enter open valleys, and still farther downstream they again flow between high, closely spaced, intricately meandering walls. Where Pine Creek and Halls Creek flow through the Navajo sandstone they run in tortuous grooves that are difficult to follow; in the beds of the San Rafael group these valleys provide wide, open roadways.

The size and form of the inclosed meanders are related to the width of the canyon and the strength of the stream that occupies it. The meanders of Glen Canyon are broadly open curves with small arc and large radius. Most of the great swings are several miles in length, and their limbs are widely separated, but at Meskin Bar the river, after flowing 5 miles, returns to a point less than three-fourths of a mile from its former position, and at Lees Ferry a tunnel 4,000 feet long across a meander neck would eliminate 5 miles of channel. The smaller streams show many compressed loops that are made up of arcs of different degrees of curvature. Some turns are short, flat curves between nearly straight stretches and give the appearance of streams flowing around square corners. Some meander loops are so closely pressed that their bases are separated by less than 100 feet of rock, and the limbs of others have become united by the destruction of the intervening wall, which leaves an oxbow valley standing to one side. Meandering adds much to the length of the streams and thus decreases their average gradient and their power to erode. The length of Glen Canyon from Hite to Lees Ferry is 162 miles, and the water that passes through it falls 2 feet to the mile. If its meanders were eliminated the length would be 100 miles and the fall 3.2 feet to the mile. The lower Escalante maintains an unusually straight general course, yet because of its meanders within a belt only about three-fourths of a mile wide it flows 28 miles to cover a distance of 14 miles. Wahweap Creek flows 3.6 miles in a tortuous course to cover 2 miles, and Warm Creek flows 6.2 miles from Warm Creek Cabin to Glen Canyon, a distance overland of 2.8 miles.

An examination of the canyon walls that inclose the meander loops shows that some have undergone considerable changes and that others are in process of change but that many, especially those along Glen Canyon, probably have maintained both position and form during the whole period of canyon trenching. In other words, some of the existing meanders are the result of normal stream development within the present cycle, but others have inherited their pattern from a previous cycle of erosion. The chief characteristics of the inclosed meanders that are developed by the stream are the gradual slope—the "slip-off" slope—which appears toward the end and along the downstream margin of the spurs that project into the meander bends, and the well-defined steepening of the valley sides along the outer and downstream parts of the meander bends. Downward corrasion, combined with lateral corrasion, may so enlarge the minor irregularities in the direction of the stream's course that eventually the pattern is rather strongly meandering. (See pls. 22, *C*; 25, *A*.) Such inclosed meandering valleys, which are not inappropriately termed "ingrown" meanders by Rich,[17] are very common in the hard-rock formations of the Kaiparowits region. Their development in the normal course of downward corrasion appears to be the rule rather than the exception.

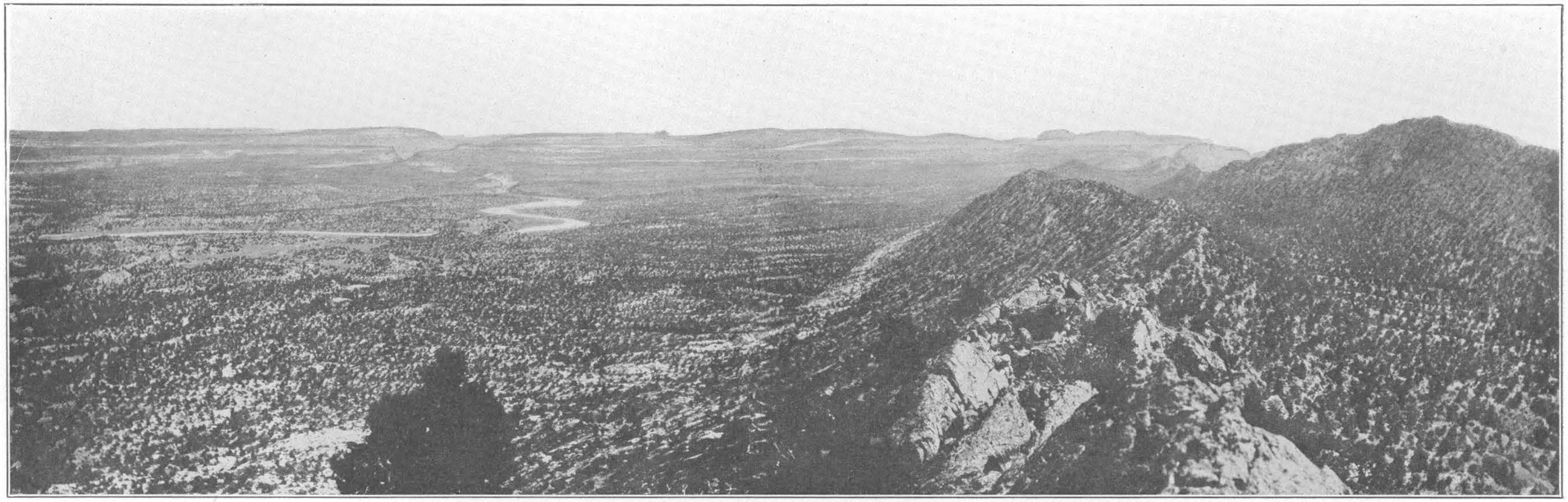
A traverse of the floors of the Paria and Escalante Rivers and Wahweap, Warm, Last Chance, Collett, Willow, and Halls Creeks shows that many meanders are normal features of land degradation under the conditions of load, rock hardness, and sudden changes of volume that prevail in the Kaiparowits region. Along these streams the intrenchment of meanders in a hard-rock formation is accompanied by a gradual obliteration of the meanders in portions of the valley where downward erosion proceeds in weak strata. On entering the hard rocks the width of the stream channel is constricted. During each freshet—and most of the run-off in the plateau country consists of floods that are occasioned by local torrential downpours—the sediment-laden waters, which roll cobbles and small boulders along the stream floor, are deflected alternately against the right and left walls of the narrow section of the canyon. The heavy load of material transported by the stream partly protects the bottom of the canyon while the rush of the water against the side walls and around the bends accomplishes what amounts proportionally to a very considerable sideward cutting. The concave portion of the meander curve is enlarged and moves progressively downstream, and slip-off slopes develop on the convex portions. The presence of a component in the

[17] Rich, J. L., Certain types of stream valleys and their meaning: Jour. Geology, vol. 22, p. 470, 1914.



A. VIEW LOOKING NORTHWARD ALONG THE EAST KAIBAB MONOCLINE

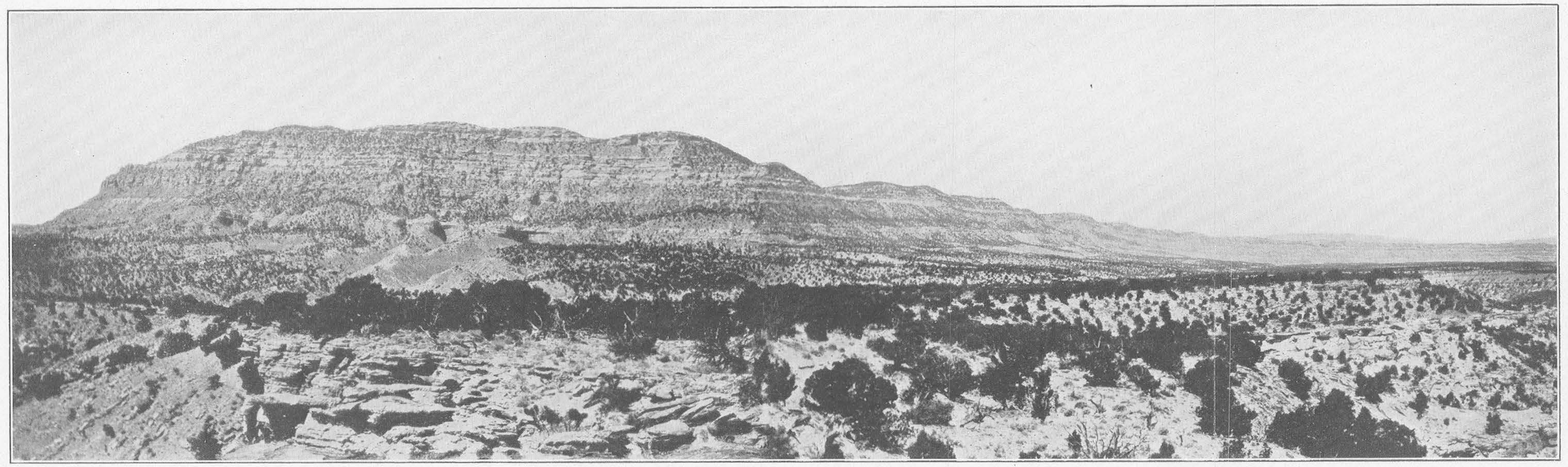
Butler Valley, at the left, is carved in weak San Rafael beds; it is rimmed by Morrison (?) and Dakota (?) sandstone. The valley in the central part of the view is carved in Tropic shale. Straight Cliffs sandstone and Wahweap sandstone make the prominent ridges at the right. Beyond these ridges may be seen peneplained Kaiparowits beds, partly dissected.



B. VIEW LOOKING SOUTHWARD ALONG THE EAST KAIBAB MONOCLINE

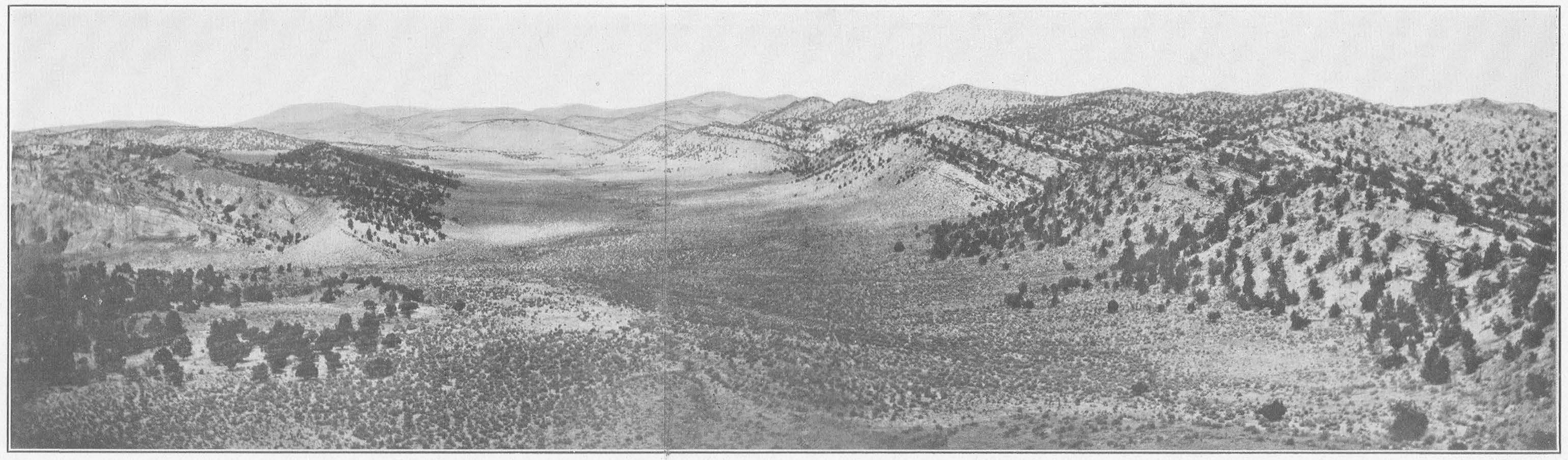
The canyon of Wahweap Creek is seen at the left and the upturned Cretaceous sandstones at the right. This portion of the Kaiparowits Plateau, upheld by the Wahweap sandstone, slopes gently northward, reflecting the dip of the rocks; the streams flow southward in ever-deepening canyons.

VIEWS FROM A POINT NEAR THE "GUT"



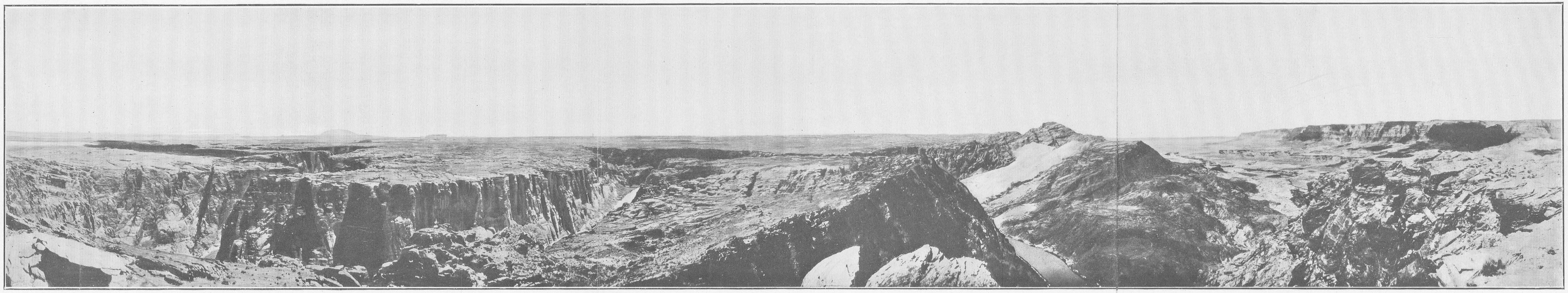
A. VIEW ALONG FACE OF STRAIGHT CLIFFS

View taken from a point about 14 miles southeast of Escalante. The sandstone in the upper part of the cliffs is the Cretaceous Straight Cliffs formation. Tropic shale forms a slope. The Dakota (?) sandstone makes the prominent lower bench.



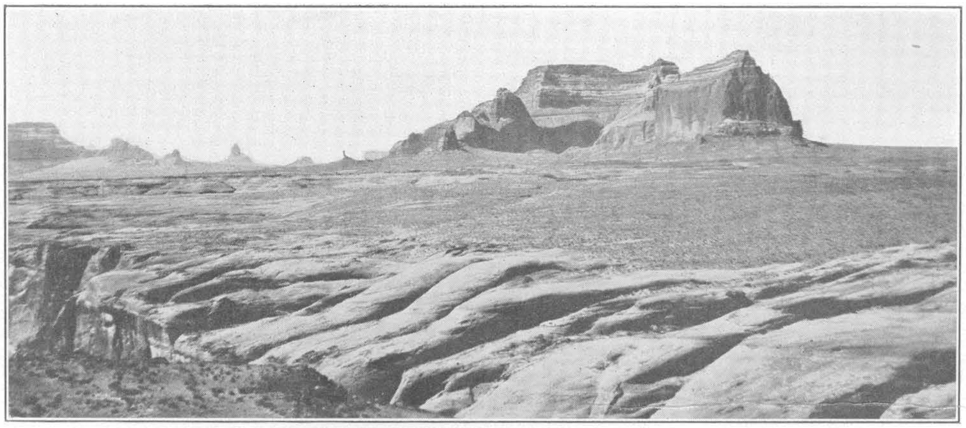
B. MONOCLINAL VALLEY IN TROPIC SHALE ALONG EAST KAIBAB MONOCLINE EAST OF BUTLER VALLEY

The hogback ridges at right are formed by overlying sandstones tilted by the East Kaibab fold. View looking north from a point near the "Gut," on the Kaiparowits Plateau trail southeast of Cannonville.



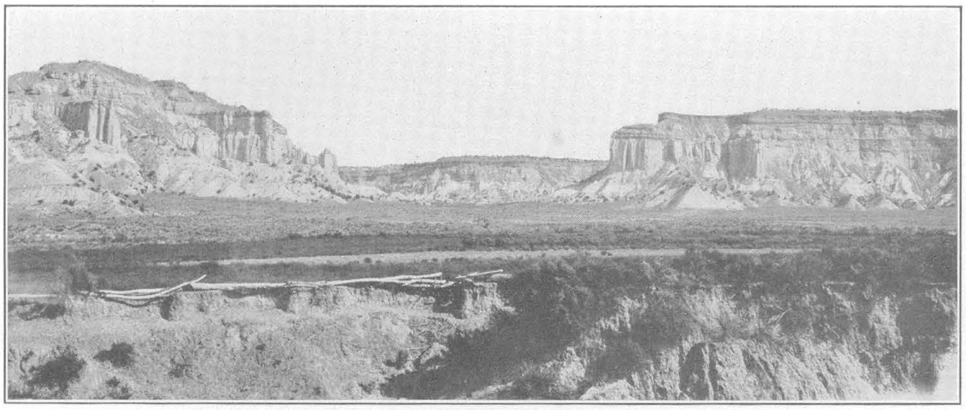
C. COLORADO RIVER FROM A PINNACLE ABOVE LEES FERRY

View looking south and east. Left, bare Navajo sandstone; Navajo Mountain in distance. Right center, monoclinal fold (Echo Cliffs), exposing Chinle. Right, Navajo, Shinarump, and Kaibab terraces; head of Marble Canyon.



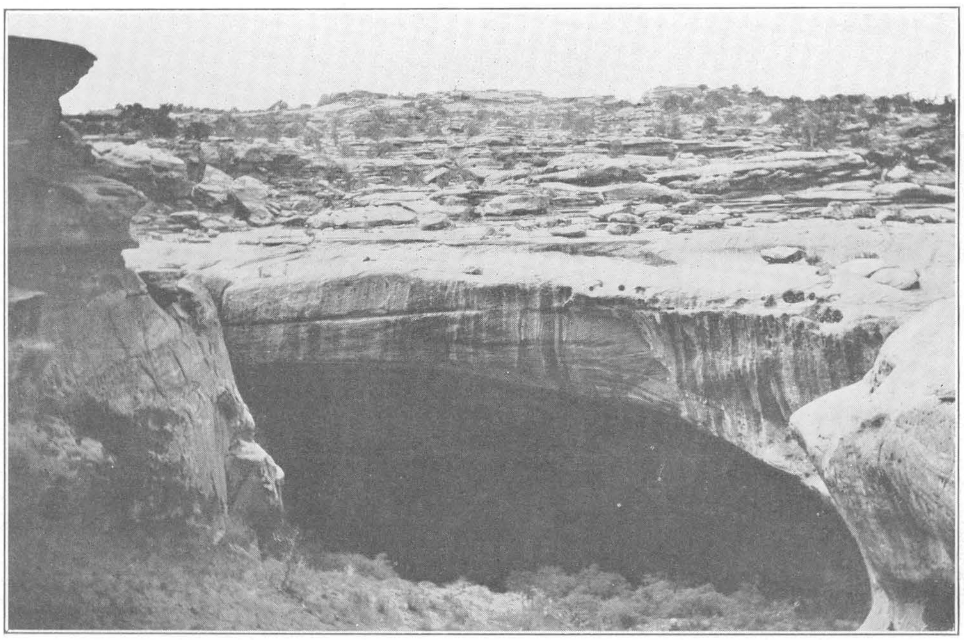
A. GLEN CANYON WEST OF MOUTH OF KANE CREEK

Monuments and buttes of hard sandstone (Entrada, Summerville, and Morrison formations) on a broad bench formed by erosion of weak strata (Carmel formation) overlying hard sandstone (Navajo).



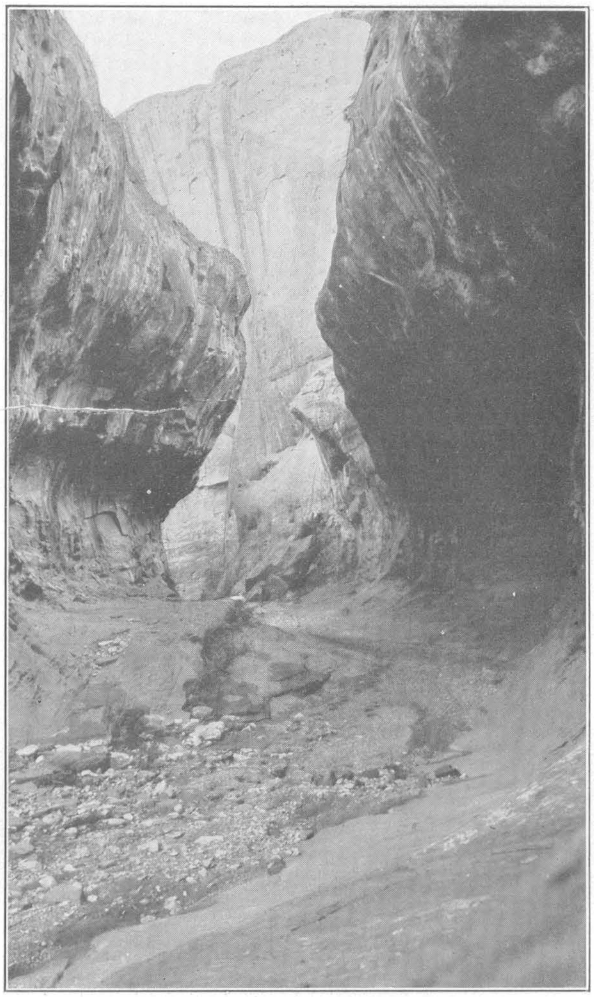
B. DRY VALLEY, A BOWL-LIKE DEPRESSION CUT IN THE SOFT STRATA OF THE SAN RAFAEL GROUP AND THE MORRISON (?) FORMATION

The stratified rocks are San Rafael group and Morrison (?) (light-colored), overlain by Dakota (?) (darker beds). The floor is covered by alluvial fill.



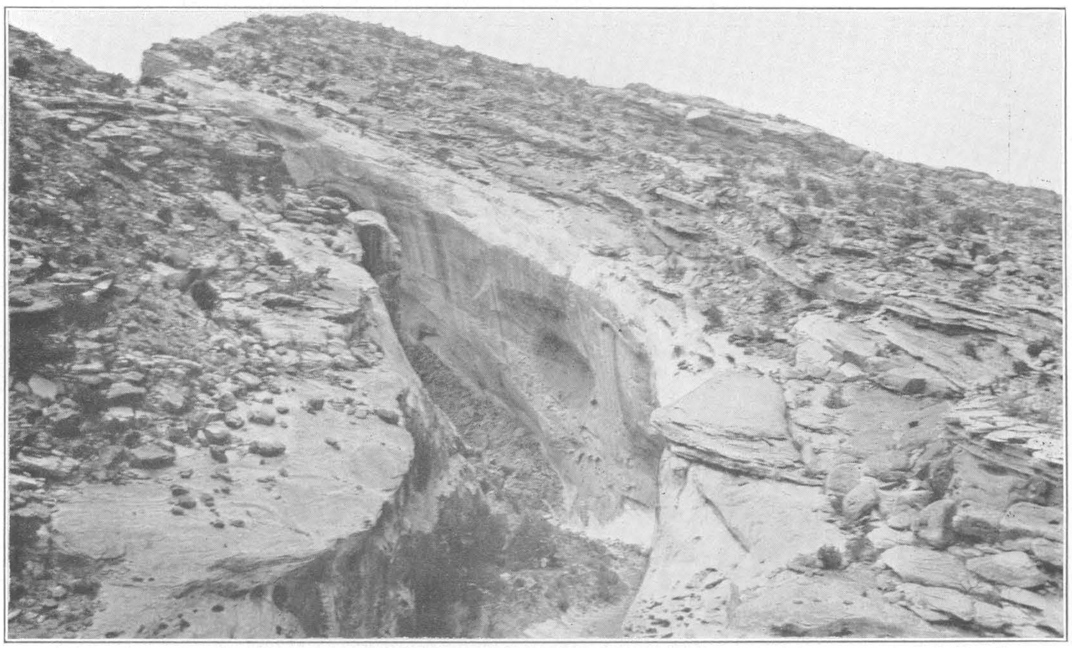
C. STRONGLY UNDERCUT MEANDER ON MULEY TWIST CREEK

The massive sandstone is Wingate, inclined toward the observer. The slabby sandstone is Todilto (?) formation.



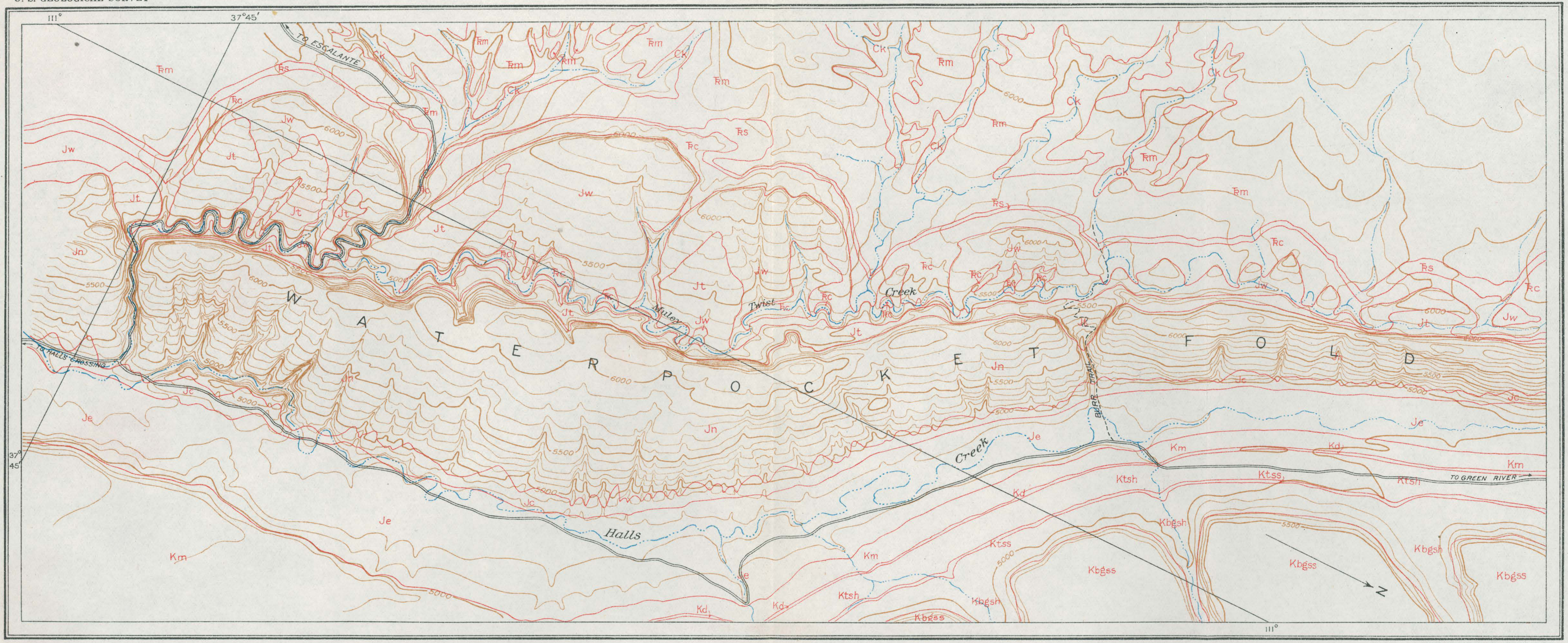
A. CANYON OF DEATH HOLLOW CREEK

The canyon is cut in Wingate sandstone.



B. CANYON TRIBUTARY TO MULEY TWIST CREEK

Steeply inclined Wingate sandstone overlain by Todilto (?) formation.



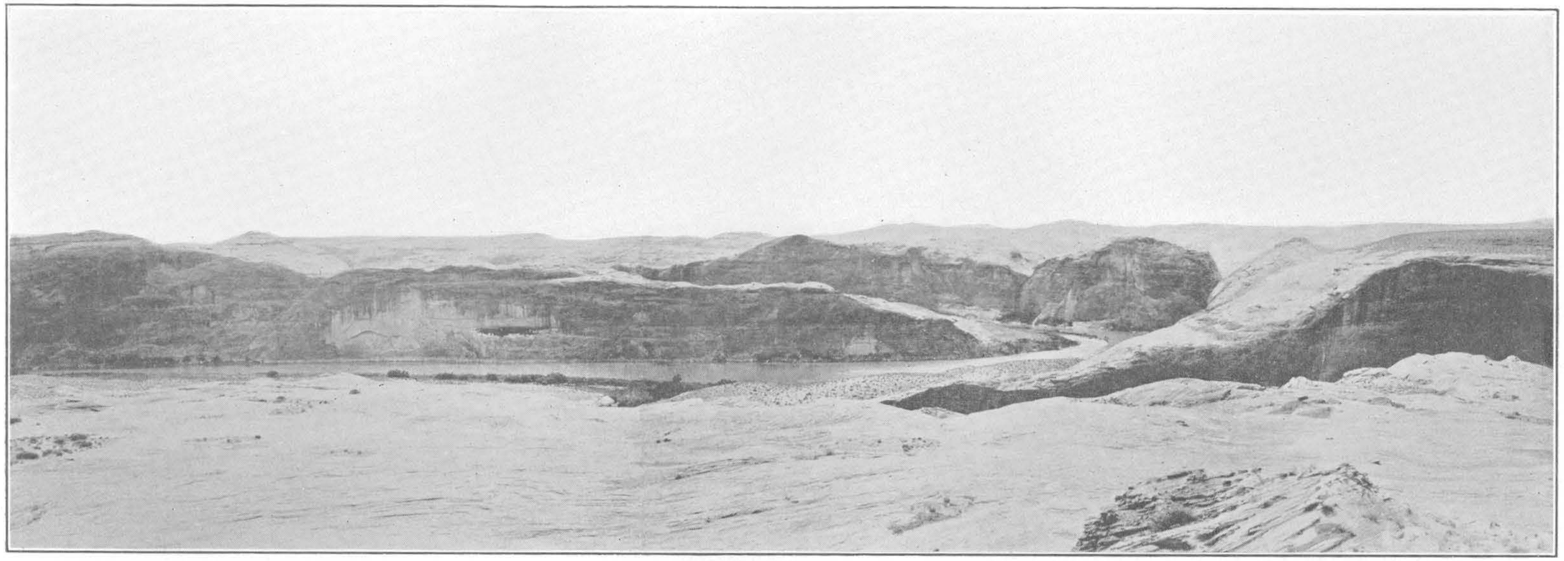
ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

TOPOGRAPHIC AND GEOLOGIC MAP OF A PART OF THE WATERPOCKET MONOCLINE, KAIPAROWITS REGION, UTAH

1 0 1 2 MILES

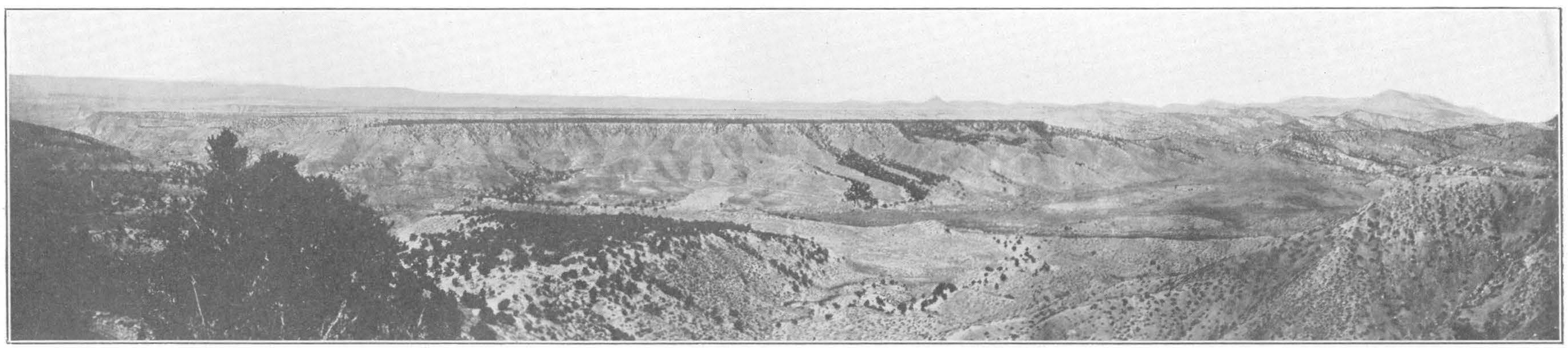
Contour interval 100 feet
Datum is mean sea level

Kbgss, Blue Gate sandstone; Kbgsh, "Blue Gate shale"; Ktss, Tununk sandstone; Ktsh, "Tununk shale"; Kd, Dakota (?) sandstone; Km, Morrison formation; Je, Summerville formation and Entrada sandstone; Jc, Carmel formation; Jn, Navajo sandstone; Jt, Todilto (?) formation; Jw, Wingate sandstone; ꞦTc, Chinle formation; ꞦTs, Shinarump conglomerate; ꞦTm, Moenkopi formation; Ck, Kaibab limestone and Coconino sandstone



A. COLORADO RIVER AT HALLS CROSSING

Shows undercut cliffs on outer and downstream sides of meander bends and slip-off slopes on spurs projecting into the bends. The country rock is Navajo sandstone, covered locally by Carmel strata.



B. CANNONVILLE EROSION SURFACE FROM POINT NEAR HEAD OF LITTLE CANYON

The Cannonville peneplain, partly dissected by tributaries of the Paria River, bevels the Tropic shale and higher Cretaceous strata.

erosion that tends to cut laterally is evidently the cause of the development of the meandering course. This lateral component appears to be due to proportionally large side cutting, where, during the active erosion of floods, the canyon floor is more or less protected by a carpet of cobbles and boulders that wear one another but retard erosion of the hard-rock floor. There is considerable sideward wear, especially along the outer and downstream margins of the stream curves, where rock materials in the rapidly moving water are flung against the walls of the constricted stream. (See pl. 23, *A*.) This lateral corrasion, combined with the vertical downward cutting, appears to be sufficient to modify the form of the valley and to shift the position of the stream in such a way as to form the meanders. A very influential factor appears to be the considerable load of coarse material that is carried by these streams in flood stage.

Where the streams have encountered soft rocks beneath a hard formation in which inclosed meanders have been formed, the slight resistance to sideward cutting permits rapid erosion of projecting spurs, which tends to widen and to clear out the valley. For a time the inclosing sandstone cliffs mays hold the stream essentially in its meandering course, but eventually they waste back and the valley becomes gradually more open. The cross section of the channel increases in width, and the sweep against projecting remnants of spurs tends to grind them away, giving rise downstream to a gently sinuous or even a fairly straight course. So consistent are these processes that the explorer soon learns to anticipate the position of deeply undercut banks and of slip-off slopes that may serve as guides for feasible routes from the floor of the canyon to its rim. As the canyon is deepened, the meander bends increase in width, and the stream pattern tends to become rapidly more complex.

If the thickness of the hard-rock formations is sufficiently great, the height of the rock walls and the consequent large volume of rock material to be moved for each unit of lateral cutting impose a natural limit on the development of these ingrown meanders. Where a considerable thickness of hard sandstone has been penetrated by the streams, definite "slip-off" slopes appear near the top of the canyon walls, whereas the lower walls on both sides of the canyon are steep or even vertical for tens or hundreds of feet. (See pl. 25, *A*.) This change in stream pattern from swinging curves accompanied by undercut banks and slip-off slopes to curves held tightly within hard-rock walls is well shown by the inclosed meanders on lower Warm Creek and lower Last Chance Creek. For similar features on Kanab Creek Gilbert[18] uses the expression "canyon within a canyon."

[18] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pl. 6 and p. 77, 1875.

Most of the smaller streams are vigorously removing meander spurs. In many places in soft rock the task has been completed, and even in hard rock it is well advanced. In the lowest 14 miles of Escalante Canyon six meander necks are each less than 500 feet across and have been reduced in height to less than 100 feet. One meander neck near the mouth of Willow Creek is 200 feet across and less than 20 feet high. Trenching of this low barrier would eliminate a curve 1½ miles long. Willow Creek has straightened its course by undercutting a meander spur, leaving it standing as an arch. (See p. 145.) In traversing smaller streams the route can be conveniently shortened by crossing low divides, where concave portions of meander bends come close together. In the process of down cutting in the hard rocks most meanders that have been developed at higher levels are destroyed, and in places remnants of them are perched high on canyon walls like the two-storied meanders of the San Juan described by Gregory.[19] It may be that the Ferry Swale, an oval trench that has been cut into the Navajo sandstone on the Lees Ferry-Wahweap trail, and El Rincon, opposite the mouth of the Escalante River, are abandoned high-level meanders of the Colorado.

Although many, perhaps most inclosed meanders in the Kaiparowits region require for their explanation only the normal vertical and lateral corrasion incident to the life history of streams, the meanders of Glen Canyon and of some of its larger tributaries call for a different explanation. (See p. 139.)

For Glen Canyon as a whole, horizontal shifting appears to have changed only slightly the outline of the meander bends and to have moved them only short distances downstream but not to have developed a new series of meanders from original small irregularities in the river's course. Field evidence leads to the belief that the Colorado was a meandering stream before the intrenchment that formed Glen Canyon, and that the essential features of the present meander pattern were developed as the normal expression of a graded condition on a former flood plain. If this conclusion is valid it appears that practically all the downward corrasion incident to recent uplift has been accomplished through hard rocks that were competent to preserve essentially the geographic plan of the earlier Colorado.

The position of the surface of erosion on which the Colorado developed its meandering pattern can not be determined with certainty. If the uplift that began the present cycle was uniform the relation is simple, but if uneven warping accompanied the uplift unknown factors are introduced into the problem. The minimum uplift is the present height of the Glen

[19] Gregory, H. E., op. cit., p. 127.

Canyon walls at Lees Ferry, about 1,800 feet. Unless the broad esplanade that extends backward from the canyon rim approximately marks its position, no evidence of the former surface of erosion exists in the vicinity of Glen Canyon. The esplanade is a structural platform that is upheld by resistant Navajo sandstone. The weak overlying Carmel strata permit considerable recession of cliffs and the destruction of erosion surfaces. Furthermore, if the ancient meandering habit had been established in resistant rocks above the Carmel the time required for cutting through this thin, weak formation probably would be insufficient to straighten the curves of the stream. With its pattern little modified the stream would be lowered to the top of the Navajo sandstone in a position to begin intrenchment within the present Glen Canyon walls. Obviously the depth of the canyon does not necessarily measure the difference in altitude between a former erosion surface and the present one. Although the evidence on which a definite measurement may be based is unsatisfactory and in some respects conflicting, a regional study of gradients, relations of meanders to rock type, and distribution of members of the stratigraphic series leads to the belief that the amount of uplift that began the present cycle of erosion was more than 1,800 feet and less than 2,000 feet. With this conclusion the evidence from remnant peneplains present here and there in the plateau province is not out of accord. (See p. 133.)

In developing meanders the streams have been assisted by the position and spacing of joint planes. Some bends in Paria Canyon correspond with the intersection of zones of jointing in the Navajo sandstone, and stretches of stream follow closely the base of walls that trend N. 50° W., parallel with zones of fracture. The influence of joints is evident in other crooked canyons; in parts of some narrow canyons it has substantially determined the position and size of meanders. For the region as a whole, joints have facilitated erosion, but in making meanders they appear as conditioning, not as controlling factors.

CYCLES OF EROSION

The remnants of old erosion surfaces in the Kaiparowits region and adjoining territory and the superposed relations of parts of the drainage bear evidence of one or more cycles of erosion older than the present. Inclosed meanders of the Colorado, the San Juan, and possibly those of some of the smaller streams mark courses inherited from a former well-advanced cycle. The maturely dissected, gentle slopes of the Paunsaugunt, Table Cliff, Aquarius, and Kaiparowits Plateaus, like those of the Coconino and Kaibab Plateaus, are out of harmony with the steep-walled canyons of the present cycle. They appear to represent an advanced state in a cycle of erosion, the beginning of which long antedates that of the present cycle.

The differences in altitude of the remnants of the old erosion surfaces and in the extent to which inequalities of hard and soft rocks were in different places obliterated make uncertain the correlation and even the number of erosion cycles. In the light of present knowledge it seems probable that the Colorado and its main tributaries were established as consequent streams on the surface of widespread early Tertiary deposits, scattered remnants of which now remain in southern Utah, northeastern Arizona, northwestern New Mexico, and southwestern Colorado. As the gradients of the ancient Colorado and its tributaries were reduced to a gentle slope, meanders developed and topographic inequalities were subdued. Whether the erosion cycle in which these characteristics of advanced denudation were developed was the first since the establishment of the Colorado system can not be affirmed, but it is the oldest for which there is clear evidence. At least one period of faulting in which the Tertiary beds were displaced, some of them many hundreds of feet, preceded the end of this cycle, for a large differential recession of the southward-facing cliffs had been effected in southern Utah, and in places the original topographic expression of the faulting had been obliterated and even reversed by erosion. The Colorado River seems to antedate the faulting, for the displacements have had little influence on the position of the stream.

The intrenched meanders along Glen Canyon and its main tributaries afford evidence of an old graded surface on which the meanders were developed. (See p. 139.) Conclusions derived from the study of many remnant erosion surfaces indicate that in the later part of the early erosion cycle the level of the Colorado River was about 1,800 feet higher than the present stream at the mouth of the San Juan River and nearly 1,900 feet higher at Lees Ferry. But it is obvious that if these inferences are even approximately correct, the surface of the plateau country at this time was by no means a peneplain. The cliffs that border the High Plateaus, though doubtless subdued in outline, stood approximately 5,000 feet above the adjacent part of the Colorado Valley, and the river in Grand Canyon was probably deeply intrenched.

Since the uplift of the plateau region, which renewed active stream erosion and commenced the present cycle of canyon cutting, corrasion has been dominant. To this cycle belongs all of the erosion that has formed Glen Canyon. Local peneplain remnants at relatively low altitudes in the Little Colorado Valley, on the San Juan River, and elsewhere south of the Colorado River, as described by Gregory,[20] and of erosion surfaces in parts of southern Utah north of the river, probably indicate minor movements of local base-levels. Aggradation and subsequent excavation of materials deposited in stream courses is recorded by gravel and alluvial terraces and in places by a recent change from depositing to vigorous cutting by the streams.

No definite evidence of the geologic age of the stages in the physiographic history of the plateau region is at hand. Dutton assigned the great erosion of this region to the Miocene and Pliocene. He believed that the outer gorge of the Grand Canyon was carved in Pliocene time and the inner gorge in Quaternary time. These conclusions, based on assumed climatic conditions during the Tertiary period, have not been substantiated. Robinson[21] places the peneplain cycle in the Pliocene and the erosion of the Grand Canyon in the Quaternary, basing these assignments on correlation with little-known strata and topographic forms in the country west of the Grand Canyon.

An outline of the probable main stages in the physiographic evolution of the southern Utah plateau region is as follows:

1. A period of widespread folding associated with regional uplift of the Cretaceous dates from the Cretaceous-Tertiary interval. The main structural features formed at this time are the Waterpocket monocline, the Circle Cliffs upwarp, the Escalante monocline, the Kaiparowits downwarp, the Echo monocline, the East Kaibab monocline, and the Kaibab upwarp.
2. A period of extensive erosion in earliest Tertiary time, during which the domes and ridges of Cretaceous rocks were reduced to a gentle surface.
3. A period of differential warping, which was probably associated with regional depression. On the long slopes and floors of the basins thus formed Eocene beds (Wasatch formation) of continental origin were laid down. Volcanism was active.
4. Post-Eocene uplift, accompanied or followed by extensive faulting.
5. A period of extensive and long-continued erosion, during which much of the Tertiary beds were removed, the present plateau blocks were outlined, and erosion surfaces of low relief were developed along the Colorado, the Paria, and other streams.
6. A regional uplift that revived the streams of the region and provided favorable conditions for cutting the canyons of the Colorado River and the many smaller streams.

The recent geologic history of the Kaiparowits region includes a period of aggradation, during which the bottoms of the rock canyons were filled with alluvium, and a period of degradation that was marked by the trenching of gravel floors of canyons and of alluvial slopes on plateaus.

[20] Gregory, H. E., op. cit., pp. 120–127.

[21] Robinson, H. H., op. cit., pp. 123–124.

FEATURES OF VALLEYS

GLEN CANYON

The characteristic features of Glen Canyon are the smooth high walls of sandstone; a series of meanders remarkable alike for number and form; and the gentle gradient and absence of steep rapids. Except at the Waterpocket Fold, where Chinle beds are exposed, Glen Canyon between the mouth of Halls Creek and Lees Ferry is carved in massive sandstone of the Glen Canyon group. From canyon floor to canyon rim the inclosing walls are the cut edges of these horizontal beds, which rise steeply, even vertically, from the river and reach in places heights of more than a thousand feet. Nearly everywhere the top of the Navajo sandstone marks the canyon rim, and in many places the entire wall is composed of that formation. Where the underlying Todilto(?) and Wingate sandstone appear they commonly form a continuous cliff with the Navajo. At the Waterpocket Fold, where the Navajo sandstone has been stripped back, the slabby Todilto(?) beds resting on the Wingate form the canyon rim.

Near Rock and Last Chance Creeks the Navajo sags to a low position, the top of the formation rising hardly 200 feet from the river level. In the upstream part of the sag the relatively weak beds above the Navajo have been stripped away many miles from the river, but at the downstream part, where these sandstones are unusually massive and hard and are capped by resistant grit that belongs to the Morrison formation, they form buttes that rise nearly sheer a thousand feet. Although separated from the inner Navajo sandstone cliffs by a narrow bench that is formed on weaker rocks, these upper sandstones closely hem the river. Below the Crossing of the Fathers these upper sandstone cliffs gradually recede and Glen Canyon regains its typical topographic features. Throughout its course in the Navajo sandstone Glen Canyon is narrow and straight-sided; in the weak Chinle beds its bottom is broadly flaring and its width considerably increased. (See pl. 26, *C*.) The Colorado River in Glen Canyon swings to the right and left in large symmetrically rounded curves that define a meander belt several miles wide. (See pl. 21, *C*.) The origin and physiographic significance of this remarkable assemblage of erosion features have been discussed by Moore,[22] who develops the evidence that they offer of a former erosion surface. (See also p. 138.)

In the sections of Glen Canyon between the Waterpocket Fold and the San Juan River and between

[22] Moore, R. C., Origin of inclosed meanders on streams of the Colorado Plateau: Jour. Geology, vol. 34, pp. 29–57, 1926; Significance of inclosed meanders in the physiographic history of the Colorado Plateau country: Idem, pp. 97–130.

Warm Creek and Lees Ferry most of the meanders of the Colorado River show no evidence of extensive lateral corrasion or sweep during downward intrenchment. Intervening sections show more or less definite evidences of horizontal shifting in the position of the river's course. In places slip-off slopes covered by patches of river gravel and undercut cliffs of the outer and downstream sides of the meander bends show clearly the operation of effective lateral cutting, but this work appears only to have slightly modified the meanders and not to have produced them.

The sudden termination of the intrenched meanders at Lees Ferry (pl. 21, *C*), where the river passes from the sandstone of Glen Canyon to the tilted limestone and older rocks of the Marble Gorge, does not indicate that the meanders were developed in Glen Canyon because of the obstacle afforded by the resistant rocks at the head of the Marble Gorge, for at the time the meanders were developed the Colorado River flowed in a course high above its present level at Lees Ferry and probably continued as a meandering stream across the weak beds which at that time covered the Kaibab limestone for a distance of 35 or 40 miles southwest of the Echo Cliffs. On this assumption the weak rocks were removed during active downward corrasion in the early part of the present canyon cycle, and the meanders of the Colorado River below Lees Ferry disappeared before the river's course began to be intrenched in the resistant Kaibab. It appears significant that two or three meander bends are preserved in Marble Gorge at about the point where according to hypothesis the old stream profile intersected the rising surface of the Kaibab limestone.

The gradient of the stream in Glen Canyon is about 2 feet to the mile and is little interrupted by rapids; boating is fairly easy and safe. On this low gradient the river is well adjusted to hard rock and soft rock alike; it is neither deepening its bed nor raising it significantly by building flood plains. The marginal accumulations of alluvium that appear at low-water stages consist mainly of mud and fine rock débris, with here and there a few cobbles.

So far as determined, the quickening of stream erosion that marked the beginning of the present erosion cycle affected all parts of the Colorado drainage system. As noted by Gregory,[23] the cutting of Glen Canyon and that of Marble Gorge represent an approximately equal amount of work, and accordingly the canyons are of approximately the same age.

The gentle gradient of the Glen Canyon section appears reasonably assignable to the lesser strength of the sandstone as compared with the very resistant Kaibab limestone and lower hard rocks encountered in the Marble Gorge and the rest of the Grand Canyon.

[23] Gregory, H. E., op. cit., p. 126.

Though the Colorado River in Glen Canyon is approximately graded with respect to rock hardness, it does not follow that deposition of flood-plain scrolls was lacking at stages before the canyon was sunk to its present level or that because of the barrier at Lees Ferry the formation of flood plains will gradually increase. As regards rock hardness the relation of Glen Canyon to the Marble Gorge has doubtless remained essentially the same since downward cutting began; the main result of deep carving is the gradual upstream migration of the hard-rock barrier at the head of the Marble Gorge. Under present climatic conditions continued denudation of adjoining lands would reduce the load to be carried by the river in Glen Canyon. The resulting increase in capacity would permit excavation and the formation of a more gently graded profile. However, it is probable that the slow deepening of the Marble Gorge just about balances the tendency to deposit materials in Glen Canyon.

WAHWEAP, WARM, LAST CHANCE, AND ROCK VALLEYS

From its source on the south flank of Canaan Peak to the Colorado River Wahweap Creek flows through rocks that are gently inclined in an upstream direction. It passes from weak Upper Cretaceous sandy shale across a sandstone platform, where for a few miles its banks are very low, and continues southward in an ever-deepening canyon until the high southward-facing escarpment is reached. Like the main stream, most of the tributaries of Wahweap Creek disregard rock structure—none of them flow northwestward in accordance with the dip of the rocks. The middle part of Wahweap Creek appears to be controlled by the local rock hardness and structure. From the mouth of Ty Hatch Creek, where the soft Tropic shale is first encountered, to Cottonwood Spring the stream follows the line of the Echo monocline. Southeast of the spring the creek swings away from the monocline and carves a pathway through northward-dipping Jurassic sandstone. The deflection from the monocline is readily understandable if this part of the course was established when the weak Tropic shale occupied this general position, as it must have at one stage during the erosion of the region. During a previous erosion cycle the portion of Wahweap Creek below Cottonwood Spring probably flowed on Straight Cliffs sandstone, for Tropic shale is found only near the Colorado River. Some adjustment to structure, such as the southeastward swing that now carries the creek into massive sandstones, seems to have been accomplished during the present cycle.

The headwaters of Warm Creek reach back only to the margin of the higher Cretaceous sandstones. Structurally its course roughly coincides with the axis of a shallow syncline that plunges upstream. The prominent sandstone escarpments and intervening benches in this area are crossed by the creek nearly at right angles.

Last Chance Creek extends to the eastern summit of the higher Cretaceous upland. Its valley follows a well-defined though shallow syncline that is separated from that of Warm Creek by an anticline that coincides with the interstream divide. Croton Creek, the largest tributary of Last Chance Creek, has also a synclinal position. Rees Canyon, which enters Last Chance Creek farther upstream, has a course oblique to the dip of the rocks, as does Dry Canyon, another tributary. The position of these streams seems to have been determined by their relations to the Wahweap sandstone cliffs, which doubtless formerly bordered Rees Canyon on the west, as they do now the upper part of Dry Canyon. These branches have thus a presumably subsequent origin in the zone of weak rocks at the base of the Wahweap formation. There are numerous consequent minor tributaries of these canyons on the northeast but almost none on the west.

Warm and Last Chance Creeks are not ancient streams consequent on a Tertiary surface or an old peneplain and superposed at random on the beds which they now cross; they are drainage lines that are disposed with clear relation to rock structure. There is ample evidence, however, that they antedate the present erosion cycle. As obsequent tributaries to the Colorado, lengthening headward by erosion, their observed relations to structure can be explained. The placement of Last Chance and Warm Creeks and some of the other tributaries of the Colorado River was possibly fixed by conditions in the very early history of the drainage system, perhaps by adjustment to the inclined surface of the hard Wahweap sandstone that formerly covered all the region. An interesting characteristic of these streams is the strong, even, intricate meandering that occurs in each of the hard-rock stretches. (See p. 136.) The intervening open, relatively straight portions of the valleys, which are carved in soft rocks, are in striking contrast.

The lower part of Rock Creek Canyon is narrow, and the sandstone walls are high. About 6 miles from its mouth, where it crosses the Rock Creek anticline, the canyon is considerably wider. The central part of the valley is floored by Navajo sandstone, and travel is feasible only along the bench above. The head of the canyon rises where extreme steepness, and a precipitous trail leads to the rim of the Kaiparowits Plateau (see pl. 2), where tributary valleys with sloping sides virtually hang above the lower canyon The rapid canyon cutting of the present cycle has produced an encroachment on the upland that makes the line between the topography of the plateau and the lower country a very striking boundary.

PARIA VALLEY

In the vicinity of Tropic the valley of the Paria River is flat-floored and broadly bowl-shaped. Wide exposures of soft Cretaceous shale have permitted rapid excavation by the stream and its tributaries, which has caused considerable recession of the overlying sandstone cliffs. Portions of the broad interstream areas that have smoothly eroded tops of accordant altitude and stand 300 to 500 feet above adjoining lower lands constitute the Cannonville erosion surface (p. 133). The total erosion at the head of the Paria Valley is enormous. The streams have not only obliterated the topographic effects produced by the Paunsaugunt fault but have cut down the uplifted block, so that the present surface of the downthrown block stands more than 2,000 feet above that of the upthrown block. (See fig. 7.) Most of the present tributary streams are actively deepening their valleys and cutting into the graded bottom lands. Along Sheep Creek dissection by deep, narrow ravines has advanced so far that travel across the alluvial plain is almost impossible.

The regional dip of the rocks in the northern part of the Paria Valley is northward, and the Paria River accordingly passes from the soft Cretaceous shale through a southward-facing escarpment made by the basal Cretaceous sandstone and underlying Upper Jurassic rocks into an open valley carved in weak rocks of the San Rafael group, which forms the flat lands around Cannonville.

A few miles south of Cannonville the Paria reaches the top of the Navajo sandstone and makes its way through massive rock walls, which opposite White Cliffs have a height of more than a thousand feet. South of White Cliffs the canyon continues with lower walls and a more meandering course. At one place—a cut-off meander bend—a tall rock island, which formerly was part of a projecting spur, is surrounded by stream channels, of which the one on the outer side is unused except in floods.

A short distance north of Paria soft rocks appear in the bottom of the valley, which consequently increases appreciably in width. (See pl. 26, *A*.) At the site of this old settlement the valley is bordered by a broad slope of Chinle shale beneath the Wingate sandstone cliffs, and the stream flows in a broad, flat gravel-floored wash that is sunk into an alluvial bench, now eroded to remnants. (See p. 143.) Opposite old Paria the sandstone swings westward in a high southward-facing escarpment, and a broad opening in the weaker rocks affords access over a low divide to the head of the House Rock Valley and at another place to the road along the Vermilion Cliffs to Kanab. But instead of following the belt of weak rocks that leads into the House Rock Valley, the river swings southeastward from Paria and flows in a short, narrow, vertical-sided canyon through the upturned Jurassic sandstone in the East Kaibab monocline, which at this point trends north. (See pl. 26, *B*.) Below this canyon the river maintains its course obliquely across a belt of weak rocks and passes into a valley that is inclosed in places by flat-lying Cretaceous sandstone and open where Cretaceous shale and soft Upper Jurassic strata crop out. (See pl. 27, *A*.) Here the river is joined by Cottonwood Creek, which heads in the broad-floored Butler Valley but in the lower 15 miles of its course flows as a subsequent stream along the East Kaibab monocline. A short tributary that is developed in this same weak zone joins the Paria from the south.

A short distance below the abandoned settlement of Adairville the river again enters the Navajo sandstone and in a narrow, winding, gradually deepening canyon cuts through the Paria Plateau. The last few miles of its valley in Arizona are carved in the underlying weak Chinle and Moenkopi beds.

The topographic features of the Paria Valley indicate that its course was established originally on a land surface unlike that of to-day. The region now occupied by the headwaters of the Paria was once part of the High Plateaus and was drained by northward-flowing streams that were unrelated to the Colorado system. The walls of the Paunsaugunt and Table Cliff Plateaus mark the present limit of a northward-sloping highland that once extended farther south. If any part of the surface now represented by the maturely developed top of the Paunsaugunt Plateau formerly sloped southward, the consequent drainage could have been related to the Paria. Likewise, if the surface of the upraised block east of the Paunsaugunt fault had originally a southward inclination the conditions would favor southward-flowing consequent streams in the general position of the Paria. But both regional structure and drainage patterns suggest that the inclination of the plateau blocks has remained essentially the same during the life of the present drainage.

In their courses through the East Kaibab monocline the Paria and its main tributaries—Hackberry, Sand Wash, and Kaibab Gulch Creeks—are superposed on the structure. Sand Wash and Kaibab Gulch in particular seem strangely out of accord with the attitude and hardness of the rocks. The topography suggests that the waters of these streams, as they come down the slopes of the Kaibab Plateau, should be gathered in the House Rock Valley and conducted along this almost continuous depression to the Colorado River. Instead these streams cross the longitudinal valley and head straight for massive sandstone walls, which they penetrate in narrow, deep canyons.

The drainage pattern of the Paria Valley seems impossible of explanation on the assumption that the Paria is an obsequent stream, the headward elongation of a one-time unimportant tributary of the Colorado. This interpretation becomes reasonable, however, when the Paria drainage is assumed to have originated on some higher surface from which monoclinal flexures were absent. This surface probably was not that represented by the fragmentary Cannonville erosion surface, for at that stage considerable topographic inequalities were present along the Paria, and the course of the stream with respect to major structural features had already been established. The evidence suggests that the Paria and its main tributaries were established as consequent streams on Tertiary deposits that were formerly more extensive and that as erosion of the Tertiary revealed the structure in the Cretaceous beds, the streams became superimposed on it.

ESCALANTE VALLEY

In the upper part of its course the Escalante River transects minor structural features, including a westward-dipping monocline in the Cretaceous sandstone just east of the Table Cliff Plateau. Eastward the stream flows for a few miles in a narrow canyon carved in horizontal Cretaceous sandstone and then emerges into a broad, open valley carved in the Cretaceous shale and weak Upper Jurassic rocks that extend continuously along the front of the Kaiparowits Plateau. Near the town of Escalante the river crosses this depression, which seems to offer an easy passage to the southeast, and farther eastward it plunges into the steep-sided Escalante monocline. Beyond the monocline a narrow, winding canyon, cut mostly in Navajo sandstone, leads to the Colorado.

As in the Paria Valley, the upper tributaries of the Escalante have established their position by headward erosion, reducing the area of the Table Cliff, Paunsaugunt, and Aquarius Plateaus and diverting the westward-flowing tributaries of the Sevier River. In the "Upper Valley" and at Escalante the stream is obviously superposed on monoclines. The lower 50 miles of the river has a relation to regional structure that suggests a subsequent origin, but its course is not that of a subsequent stream of the present cycle. At one time in its history the Escalante must have flowed in the belt of weak Upper Jurassic rocks between the Waterpocket Fold and the Kaiparowits Plateau. In deepening its bed it cut through these shaly gypsiferous rocks, transferring its pattern to the underlying Navajo sandstone.

Though the steps in the physiographic history of the Escalante Valley are not clearly defined, it seems probable that the consequent drainage system established on the surface of Tertiary rocks became subsequent as erosion revealed weak beds in suitable relations to resistant beds and that continued erosion revealed structure to which adjustment was made by superimposition. The Escalante might thus be termed a superposed subsequent stream.

The lower part of the Escalante Canyon has a remarkably intricate meandering course. From its mouth a traverse of 35 miles along the river bed measures 14 miles in a straight line. The inclosing sandstone walls exhibit typical features of "ingrown" meanders, with prominent slip-off slopes on the spurs and steeply undercut cliffs on the outer and downstream sides of the meander bends. Part of the meandering may have been inherited from an earlier cycle of erosion, but most of it has been developed during the present cycle.

MINOR PHYSIOGRAPHIC FEATURES

ALLUVIAL TERRACES

With unimportant exceptions all streams in the Kaiparowits region are vigorously eroding their beds. Those flowing on rock are scouring their floors, and those flowing on sand and gravel are rapidly cutting downward and sideward. Not only has aggradation ceased, but enormous quantities of valley fill are torn up and carried each season to the Colorado. In some valleys no alluvium is left; a rock-walled, rock-bottomed canyon has replaced a canyon that was deeply floored with alluvial sand and clay. The typical stream is one that flows between alluvial terraces included in a canyon whose walls are of rock. That this deep trenching of valley fill is characteristic of streams throughout Arizona, New Mexico, southern Utah, and southern Colorado is shown by the records compiled by Bryan.[24] The streams of southern Nevada and southern California likewise are developing arroyos. Field evidence supplemented by detailed historical accounts proves that the present habit of streams in southern Utah has been established within the last 50 years. The conditions that existed in 1878–1880 are described by Dutton[25] as follows:

> Most of those 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 breasts of perpendicular scarps. In some cases a smooth floor of alluvium extends from side to side of what was originally a canyon valley. The recurrence of a climate sufficiently moist to sustain a vigorous perennial stream would probably sweep out all this unconsolidated alluvium and return the valley to its former condition of an ordinary canyon.

[24] Bryan, Kirk, Date of channel trenching (arroyo cutting) in the arid Southwest: Science, new ser., vol. 62, pp. 338–344, 1925.

[25] Dutton, C. E., Tertiary history of the Grand Canyon district U. S. Geol. Survey Mon. 2, pp. 228–229, 1882.

The present conditions are in strong contrast to those pictured by Dutton. The meadows along streams have been destroyed, valley flats are deeply trenched, and the sod-bound soil, which once extended widely, even over such regions as the Waterpocket Fold, parts of the Escalante Basin, and valleys tributary to the Paria, is now represented by inconspicuous patches. On the streams in the Kaiparowits region excessive degradation began during the decade 1880–1890. (See p. 30.)

As elsewhere suggested[26] the great change in the valley topography of the plateau province may reasonably be ascribed to climate assisted by human agencies. Unfortunately the rainfall, snowfall, and temperature of southeastern Utah were not measured prior to 1890, but the meager rainfall records from outlying stations show that the years 1884–1889 were relatively wet. During this period the precipitation at Los Angeles and San Bernardino, Calif., and Fort Mojave, Ariz., was, respectively, 49, 42, and 100 per cent above normal. For these stations the heaviest rainfall ever recorded fell in 1884. Fort Wingate, N. Mex., received only a little more than its average rain during the period 1884–1889, but during the seven years 1867–1873 this station recorded 40 per cent more than the usual rain—a fact that may be causally related to the earlier beginning of terracing in the Puerco and Chaco Valleys.[27] The evidence from rainfall measurements is suggestive rather than conclusive. Some dry years are included in the records for 1884–1889, but the years preceding and following that period are neither consistently dry nor consistently wet. In the plateau province, however, variations in mean annual rainfall have relatively little significance. As bearing on erosion, the seasonal and daily distribution of rainfall, the nature of the showers and the area they cover, and the relation of rainfall to snowfall and to temperature are features of much more importance.

Erosion results from sudden violent showers, and if suitably distributed in time an annual rainfall of half the normal amount may be more effective in denudation than twice the normal. The spectacular erosion which in 1884–85 sunk the alluvial floor of Kanab Creek 60 feet and widened it 70 feet for a distance of 15 miles began in response to the melting of exceptionally deep accumulations of snow.

On the plateau tops and steep slopes and on canyon floors alike the balance between aggradation and degradation is in remarkably close adjustment. Only slight changes in amount and kind of rain, in stream gradient, and in cover of vegetation are sufficient to

[26] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 131–132, 1917.

[27] Bryan, Kirk, op. cit., pp. 339–340.

change stream habit. The construction of a dam or an irrigation ditch, the killing off of beavers, the building of roads, and the plowing of fields may begin far-reaching changes. The effect of grazing, especially overgrazing, on run-off and stream trenching is obvious. The net result of the interference by man with the delicately adjusted streams is an increase in amount of surface water and the number of intermittent springs accompanied by a destruction of forage and of arable land. (See p. 31.)

The smaller canyons of the Kaiparowits region were sunk deep into their rock floors and then filled with sediment 40 to 150 feet deep. Recently removal of the sediments began. The canyon cutting probably dates from the uplift that placed the Colorado in position to excavate Glen Canyon. The aggradation may have been contemporaneous with the formation of local peneplains in the Little Colorado Valley and elsewhere whose position and altitude are difficult to explain. Canyon cutting, canyon filling, and removal of fill constitute a series of stages that may have been duplicated several times; the bases of some canyon walls show the effects of erosion at different rates, and within the alluvial deposits are many erosional unconformities. The evidence shows several changes in the conditions of erosion and sedimentation, but neither the number nor the duration of the epicycles involved has been determined.

CANYON WALLS

In the Kaiparowits region, as elsewhere in the plateau province, canyons cut in massive thick sandstone are box headed. In most such canyons the walls are as steep and as high at their heads as along their sides; some of them overhang. The canyon walls are fluted by rincons and by less symmetrical recesses, many of which extend from the floor of the canyon to its rim. Perched high on the walls are caves and rock shelters. Some of them are mere toe holds; others are flat-floored caverns that extend tens of feet into the vertical sandstone walls and are protected by arched roofs—sites chosen by the cliff dweller. (See pl. 27, *C*.) As interpreted by Gregory,[28] stream erosion has played little part in the production of these features; they are the result of disintegration that was aided by ground water and guided by texture and structure of rocks. In some places two niches that were developed opposite each other in narrow rock walls have become united, producing a "hole in the rock" that resembles the windows made in the formation of natural bridges. Niches and wall pockets of different sizes are characteristic of the Navajo and Entrada sandstones and appear also in walls of Morrison and Upper Cretaceous sandstones.

[28] Gregory, H. E., op. cit., pp. 132–134.

BUTTES AND TOWERS

Under the attack of stream erosion, aided by weathering and guided by planes of structural weakness, the great plateaus are cut into mesas, and portions of the mesa walls become detached. Further weathering and disintegration reduces the size and modifies the form of these remnants, producing monuments, towers, chimneys, and spires that add much to scenic interest. Lone Rock, in Wahweap Valley, "The Chimneys," in Dry Valley, and the square fluted columns cut from San Rafael and Morrison beds along the face of the Straight Cliffs are picturesque erosion features, but most of the tallest monuments in the Kaiparowits region stand close to lofty cliffs and are therefore much less conspicuous than similar erosion features in the Navajo country. Tall rough-sided earth columns cut from materials of landslides are common. (See pl. 28, *A–D*.)

ARCHES AND BRIDGES

On the walls of many canyons cross-bedding outlines arches. Some of these arches appear as if drawn with crayon on the smooth rock face; others unite the tops of pilasters and form the borders of blind windows; still others form the roofs of niches and rock shelters. In fact, curved surfaces, in both horizontal and vertical positions, are characteristic of detailed sculpture on walls of Navajo and Entrada sandstones. As alcoves are recessed deeper and deeper into canyon walls there is a tendency for surface water to make its way through the arched roof along vertical joint planes, a process which if continued under favorable conditions results in a crack open to the sky. Enlargement of this long, narrow skylight permits the outer part of the alcove roof to stand alone as an arch separated from the canyon wall by the width of the opening. Further erosion gives the arch the form of a hoop rising above the general rock surface or detaches it completely from the wall, making a bridge which spans the original alcove. Arches having this history were noted near the head of Cottonwood Creek, at the "narrows" on Halls Creek, and on tributaries to the Paria. The largest one observed is in Escalante Canyon above the mouth of Sand Creek. This Escalante arch, which stands about 30 feet out from the wall of Navajo sandstone, has a span of about 130 feet, a height of 70 feet above the floor of an ancient alcove, and a thickness of 13 feet. The roadway on top is 12 feet wide. (See pl. 27, *D*.)

On Fortymile Creek a beautiful natural bridge has resulted from the undercutting of a meander spur and has reproduced the history of the well-known Rainbow Bridge in the Navajo country. As estimated by W. R. Chenoweth, of the United States Geological Survey, the Fortymile Bridge has a span of 200 feet and a height from stream bed to roadway of 75 feet. Above the mouth of Willow Creek on the Escalante River another bridge is in process of formation. A narrow wall that separates the compressed limits of a stream curve 2 miles long is already perforated by a window.

WATER POCKETS

Many bare rock surfaces in the Kaiparowits region are dotted with pits and saucerlike depressions that fill with water after rains. These features are common on the broad sandstone platforms that border Glen Canyon and on the floor of the Escalante Basin. Their abundance on the crests and flanks of the Waterpocket monocline account for the name of this flexure. They appear here and there on rocks of all kinds but are characteristic of the Navajo sandstone, which possesses to an unusual degree the texture and structure favorable for their development. In ground plan they range from irregular rings or curved-sided depressions a few inches across to irregularly bordered lake basins more than 100 feet across; in depth they range from a fraction of an inch to as much as 6 feet. The commonest ones are 1 to 3 inches deep and 2 to 5 feet in longest diameter. Some of them hold mere films of water, too thin to permit a horse to drink and disappearing within a few hours after a rain; others are deep, permanent wells that hold several barrels of water and constitute the chief supply for pack trains when the near-by gravel-floored washes are dry. These water pockets seem at first sight to be distributed in a haphazard fashion without reference to slopes or joints or differences in rock texture, but examination of the rock surface shows them to be located on inclined surfaces at places where joints or cross-bedding laminae intersect, where the rock cement is weak, or where lenses of coarse-grained rock join finer-grained rock. The position of some rock basins on the crest of the Waterpocket Fold is determined by sand dikes—the hardened filling of cracks.

The deepest pockets form rows at the bottom of poorly defined valleys. Many pockets have lips over which water escapes. During light rains the pockets are filled or partly filled by run-off in their immediate vicinity. During heavy thundershowers the water from surrounding slopes passes through these pockets as a stream or as a sheet flood that covers the entire surface. The running water merely makes little ripples when crossing the shallowest pockets, but it swirls in and out of the deep ones. When examined after the water has ceased to run, the pockets are seen to have lost the sand, hardened silt, and vegetable débris that previously had coated their bottoms; their floors are bare rock or clean sand. The basins have been scoured out and doubtless somewhat enlarged, although some have been made more shallow by the grinding down of their rims. During long periods between rains many shallow pockets are filled or partly filled by wind-blown dust, which forms mud in basins containing water and a fluffy coating on the floor of dry basins. One windstorm was observed to fill several basins to their rims with sand and to deposit some sand in others. Doubtless in favorable places wind removes dry materials from shallow basins and scours their floors with sand, but it seems not to be a very effective excavating agent. It is significant that leaves and twigs remain in dry water pockets during heavy windstorms and that many depressions exposed to the wind but beyond the reach of running water contain shrubs and grass growing in patches of soil.

WORK OF THE WIND

In the Kaiparowits region the winds are neither strong nor persistent; the topography is unfavorable for large-scale wind erosion or deposition. (See p. 12.) Low dune ridges appear here and there and on the Glen Canyon platform, and in the Escalante Valley are dune areas of a few acres, but most of the dust carried by the wind is piled at the corners of rock buttresses, dumped over canyon walls, or moved back and forth along dry washes awaiting its time of transport to the Colorado River.

Although bare flat rock forms much of the surface, and innumerable buttes and mesa walls lie across the path of prevailing winds, no abraded surfaces or wind etched rocks were observed. The shallow water pockets described by Bryan [29] as features of wind erosion are believed in the main to be the work of weather and running water.

LANDSLIDES

The efficiency of ground water as a factor in erosion is shown by the landslides in the Tropic shale and to a less extent in the Chinle. When the Chinle " marls " and shales on steep slopes are saturated they seem to move by their own weight, carrying their broken strata and talus blocks to lower levels. At the south base of the Paria Plateau slides in the Chinle have spilled over the Shinarump conglomerate and down the Moenkopi cliffs to the Kaibab below, and at a place about 14 miles south of the Burr trail the Chinle beds have lost their hold and have slid, accompanied by huge fragments, over the upturned beds of Navajo sandstone, down the west side of the Halls Creek Valley in a jumbled mass that is roughly three-fourths of a mile wide, 1½ miles long, and 80 feet deep. The slopes of Tropic shale along the southwest

[29] Bryan, Kirk, Wind erosion near Lees Ferry, Ariz.: Am. Jour. Sci., 5th ser., vol. 6, pp. 298–303, 1923.

flank of the Kaiparowits Plateau are in many places streaked with landslides; in places they are completely masked. The high-lying Tropic on the northeast face of the Kaiparowits Plateau between Coyote Hole and Willow Tanks is the seat of landslides which one after another have flowed down the shale slopes and out over the Dakota (?)-capped benches, carrying with them great talus blocks and slabs of Straight Cliffs sandstone.

As viewed from the rim of the Kaiparowits Plateau at Fiftymile Point the landslides are impressive. The slopes below the capping Cretaceous sandstone constitute a field about 2 miles wide and 10 miles long, everywhere strewn with boulders, the largest of which are square blocks of sandstone 40 feet thick. Successive slides have banked the materials in huge ridges like a series of terminal and lateral moraines.

Except in areas of Chinle and Tropic shales landslides were not observed. The steep slopes of other formations are bare or coated with only ribbons and scattered patches of débris. Surface water, ground water, and rock structure do not occur in combinations favorable for the production of talus; disintegrated rock is removed about as fast as it is formed.

CHAPTER 5. ECONOMIC GEOLOGY

The rocks of the Kaiparowits region are mineralized only to a slight extent. There are no metamorphic rocks, no pegmatites, and no igneous intrusions. In fact, except for the Tertiary basalts that cap the Table Cliff and Aquarius Plateaus, igneous rocks are lacking. Some of the sandstones and shales contain bits of gold, small amounts of low-grade copper ore appear in a few places, and carnotite has been reported.

Sandstone for building is abundant, and at a few places adobe and clay are available for brickmaking. Gypsum is widely distributed, but limestone suitable for cement is rare. Some of the Triassic strata are oil bearing, and oil seeps from sandstone at the southeast end of the Waterpocket Fold, but a well sunk at the Circle Cliffs gave unsatisfactory results.

In addition to water the one deposit of economic value is coal, which occurs at several horizons on the flanks of the Kaiparowits Plateau.

GOLD

Within the Kaiparowits region, as elsewhere in the plateau province, the Triassic and Jurassic rocks include widely distributed minute flakes of gold, and accumulations in gravel bars along the principal streams are sufficient to attract attention.

There are reports of prospectors along the Waterpocket Fold, in the Henry Mountains, and east of the Colorado River about Elk Ridge and the Abajo Mountains as early as 1870, and the finding of gold in sandstone and gravel of the San Juan River in the fall of 1892 led to the "Bluff excitement" of 1892–93.[1] Little prospecting seems to have been done along the Colorado River until the practicability of its traverse had been demonstrated by Powell. The wide desert stretches along the river, the difficulty of finding or making a feasible trail from the canyon rim to the stream below, and the ignorance of probable cataracts and whirlpools stood as discouragements. But the discovery in 1880 of the Dandy crossing (Hite) and of feasible routes leading to it resulted in the location of a working camp, to which supplies could be brought from settlements in both Utah and Colorado. The establishment of a miners' trading station at Hanksville in 1884 made conditions still more favorable. By using the Dandy crossing as a base the bars and alluvial gravel along the Colorado River between the mouth of the Fremont and Lees Ferry have been intermittently worked since 1883.

The following notes regarding placer mining in Glen Canyon were compiled from conversation and personal letters of Mr. Bert Loper, whose knowledge of the Colorado River between Hite and Lees Ferry is based on many years of experience.

Gold was discovered near the mouth of Trachyte Canyon by Cass Hite in 1883. Most of the mining in Glen Canyon was done during the years 1886–1889. A few men were at work during the following decade, and at least one man continued to pan gold until 1908. Doubtless in later years prospectors have worked here and there for short periods.

Beginning at the mouth of Crescent Wash, the larger bars explored for gold are North Wash, Hite, Grub Stake, Cape Horn, Monte Cristo, Red Canyon, Tickaboo, Good Hope, Sevenmile, Olympia, California, Moki, New Year, Burro, Boston, Anderson, Shock, Butler, Klondyke, Meskin, and Wright, the last of which is near the mouth of Navajo Creek. From all these bars enough gold to meet day wages was obtained. A good amount of gold was recovered at Boston, Red Canyon, Klondyke, Moki, Olympia, and Good Hope bars, and the California bar yielded more than $10,000. All the bars were located as prospects, except Good Hope, which is the only patented land within Glen Canyon.

Nearly all pay dirt is "wash gravel" that was deposited at high-water stages of the river, but tests showed gold in the Chinle shales and even in dune sands blown into the canyon from surfaces above the walls. The richest material mined is composed of streaks of adobe within the gravel—"powdery, sticky, mud, which quickly dissolves in water."

All the metal recovered was flour gold; there were no flakes or nuggets. Most of the gold came from the layers near the surface of the bars, "at grass roots" within the gravel, and at the contact of the gravel and bedrock. From bedrock itself the yields were insignificant. Assays made for A. P. Adams of "red marl," "blue marl," "blow sand," and river silt showed from 20 cents to $1.20 a ton.

Frank Bennett, who has long been familiar with the placer deposits of Glen Canyon, says that selected

[1] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 139–140, 1917.

gravel from the Gold Coin claim yielded about 72 cents a cubic yard and that a bar near the mouth of Red Creek yielded from 70 cents to more than $1 a yard.[2]

Nearly all the mining was done with rockers, but where conditions were favorable home-made sluice boxes and quicksilver riffles were installed. Some shafts were sunk, and the tunnels in gravel banks a hundred feet or more above high-water level on the Loper claim near Tickaboo represent much hard work with pick and shovel. Lack of water from sources above the gold-bearing gravel and the expense of pumping from the river below have prevented large hydraulic operations. A water wheel was tried at Good Hope Bar, and in 1900 a power dredge was installed and operated for a few weeks near the mouth of Bullfrog (Hanson; Pine Alcove) Creek, but the flour gold recovered was insufficient to pay the cost of installation. (See pl. 29, *A*.)

During the years 1910–1913 an ambitious scheme was developed for recovering gold from sandstone, shale, and silt on the Paria River at Lees Ferry and Paria. After preliminary study, including many assays, several hundred claims were located, assessment work was begun, and steam dredges and power shovels that were freighted from Marysvale were installed at the mouth of the Paria. To obtain fuel for operating the dredges a coal mine was opened in Warm Creek about 10 miles from its mouth, and a wagon road was constructed. From the end of the road a pack-horse trail was built through the narrow canyon portion of the Warm Creek Valley to the Colorado River, and a barge was constructed for carrying the coal to its destination. (See pl. 29, *B*.) The plan was to recover the gold known to exist in nearly all the beds of the Chinle formation, which is well exposed at the mouth of Glen Canyon and underlies thousands of square miles in Arizona and Utah with a thickness exceeding 500 feet.

Assays of 14 samples from Lees Ferry, received through the courtesy of Mr. C. H. Spencer, show an average of about 25 cents a ton for the "silts" derived from the Chinle beds. Analyses of three series of samples taken by Lawson[3] from equivalent beds at Paria showed an average of less than 5 cents of gold in a ton of shale and sandstone. The largest amount, 10 cents a ton, came from a bed of sandstone. Similar figures were obtained for the gold content of the Moenkopi formation immediately below the Shinarump conglomerate. Gold appears to be fairly evenly disseminated in the Chinle shales, and their composition and texture make them favorable for hydraulic mining. The metal occurs, however, as excessively fine flakes and dust and requires much skill for its recovery. Because of this difficulty and the isolation of the mining field, with the consequent enormous cost of operation, work at Lees Ferry was discontinued in 1913. A few years later an unsuccessful attempt was made to revive gold mining at Paria village in connection with an ill-starred irrigation project. (See p. 31.)

The gold of Glen Canyon is accompanied by black sands, consisting of magnetite, hematite, ilmenite, garnet, and small amounts of chromite, zircon, and rutile. One analysis showed 0.15 ounce of platinum to the ton.[4] Obviously these minerals have originally come from mineralized rocks that were different from those now exposed in the Kaiparowits region. Some of the placer gold probably has been carried to Glen Canyon by streams from the Henry, La Sal, and Abajo Mountains, where gold-bearing veins are known, but it seems reasonable to assume that most of it has come from the disintegration of near-by Triassic sediments.

COPPER

Prospecting for copper in the Moenkopi, Chinle, and Navajo formations has been carried on at a number of places in the Paria Valley, and some low-grade copper ore is said to have been shipped from the Hattie Green mine, 2 miles west of Adairville. Small lenses of impure green and blue mineralized material, including azurite and malachite, have been noted at several places in red beds assigned to the Glen Canyon and San Rafael groups. Copper appears also at prospect holes in the Tertiary beds of the Aquarius Plateau. No deposits of commercial value have been found.

COAL

DISTRIBUTION

A study of the Cretaceous rocks in the Kaiparowits Plateau and the upper Paria Valley indicates that beds of coal are restricted to the Dakota(?) sandstone, Tropic shale, and Straight Cliffs sandstone. Most of the coal deposits in the Dakota(?) and Tropic formations are so thin and so poor in quality that they have little commercial value, but some of the coal beds in the Straight Cliffs sandstone are thick and of good grade. (See pl. 30.) In the Dakota(?) sandstone coal appears in almost all places where this formation is exposed. In the Tropic shale coal is generally absent, but in the upper Paria Valley the lower 100 to 200 feet of this formation contains thin beds of coal.

[2] Butler, B. S., and others, The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, p. 638, 1920.

[3] Lawson, A. C., The gold in the Shinarump at Paria: Econ. Geology, vol. 8, pp. 446–448, 1913.

[4] Butler, B. S., and others, op. cit., p. 639.

In the Straight Cliffs sandstone the main exposures of coal are in two districts—one on Warm and Last Chance Creeks in east central Kane County and the other in canyons southwest of Escalante in Garfield County. Thinner and less extensive coal beds in the upper Paria Valley furnish coal for local use at Tropic, Cannonville, and Henrieville. In some places the Straight Cliffs sandstone appears to lack coal beds. Indeed, the known coal deposits of commercial value are distributed over an area of only four or five townships in the south-central and northern parts of the Kaiparowits Plateau. It is probable, however, that the coal-bearing beds of Warm Creek and Last Chance Creek are connected under a cover of younger beds with those at Escalante, so as to form a coal-bearing area 10 to 15 miles in width and 35 to 40 miles in length. Evidently coal was formerly much more abundant, for in most of the south-central part of the Kaiparowits Plateau, particularly between Warm and Last Chance Creeks, the coal-bearing beds in the Straight Cliffs sandstone have been much affected by burning; the shale which commonly underlies and overlies the coal is baked hard, altered in color, and much of it burned to clinker.

COAL IN THE DAKOTA(?) SANDSTONE AND TROPIC SHALE

Eastward from the point southwest of Cannonville in T. 38 S., R. 4 W., where the Dakota(?) is cut off by the Paunsaugunt fault, beds of coal and carbonaceous shale appear in the sandstone and sandy shale that cap the escarpments overlooking exposures of variegated Jurassic rocks to the south. As shown by marine fossils, most of these coal beds belong in the basal portion of the Tropic shale, and the Dakota(?) is very thin and consists in places entirely of conglomeratic sandstone. A measured section of the lower part of the Tropic shale in sec. 12, T. 38 S., R. 4 W., includes three beds of coal—a bed 7 feet thick, including several thin partings of bone and sand, another 1 foot 4 inches thick 5 inches below this thick bed, and a third 2 feet thick about 88 feet above it. On Sheep Creek in sec. 35, T. 37 S., R. 4 W., corresponding beds consist mostly of bone and very thin coal beds but include one bed of coal 2 feet thick.

This coal zone is continuously and rather prominently exposed in an extremely irregular line that follows the indentations of canyon valleys and the projections of intervening divides. In the vicinity of Cannonville and Henrieville the Dakota(?) and coal-bearing Tropic cap the bluffs that nearly surround each village. There is considerable variation in the coal beds, but sections show several beds 2 feet or less in thickness. On the south side of Little Creek in sec. 25, T. 37 S., R. 2 W., coal has been mined from a bed 2 feet 10 inches thick in the Dakota(?) sandstone. The coal is fair in quality, but it pinches out in a few hundred feet.

Southeast of Henrieville the coal zone swings around the north side of Butler Valley to the East Kaibab monocline, where the sandstone forms a low but persistent hogback for many miles southward in the Cottonwood Valley. Coal is well exposed on the Paria River southeast of the point where it crosses the monocline, and locally it is of workable thickness. A section measured in sec. 20, T. 42 S., R. 1 W., shows 36 inches of good coal and 8 inches of very impure, pyritiferous coal at the top. A short distance away this coal is thinner and much poorer; in sec. 21 of this township there is 5 feet of bone and coal, but no good bed more than a foot in thickness.

In the Dakota(?) outcrop, which may be followed from the Paria River eastward in an irregular line to the extremity of the Kaiparowits Plateau opposite Navajo Mountain, most measured sections show several coal beds. Few of them are more than 1 foot thick, but one bed in sec. 4, T. 41 S., R. 6 E., is 2 feet 3 inches thick. At the head of Rock Creek a very prominent dark band more than 6 feet thick at the Dakota(?) horizon consists entirely of bone and very black carbonaceous shale. The Dakota(?) is less persistently coal bearing on the northeast side of the Kaiparowits Plateau than in the territory farther south and west. Several sections measured southeast of Escalante show no Dakota(?) coal.

According to analyses of a sample of typical Dakota(?) coal of apparently good grade collected in sec. 4, T. 41 S., R. 6 E., the ash is 19.6 per cent and sulphur 2.1 per cent, which is relatively high, and the fixed carbon is 37 per cent, which is low. The heating value of this coal is only 7,280 British thermal units, which is very much less than that of good-grade coals from the Straight Cliffs sandstone.

COAL IN THE STRAIGHT CLIFFS SANDSTONE

Although the coal beds of the Straight Cliffs sandstone are much greater in prospective commercial value, they are in general much less prominent than those of the Dakota(?), because of the small area of the thick coal deposits and partly because of extensive burning and poor exposures. Determination of the number and extent of the different beds is seriously hampered by the impossibility in most places of tracing the coals along the outcrop. Because the coal has been destroyed by burning to within a few feet of the bottoms of the canyons, it is impossible to trace the coal beds found on the North Branch of Warm Creek to the Middle Branch, even where these streams are less than a mile apart. The same is true of other parts of the Warm Creek drainage basin and the country along Last Chance Creek and its tributaries.

As the bottoms of the canyons in the Straight Cliffs formation are in most places covered by stream deposits and talus, the unburned portion of a coal bed may be buried under rock waste. In several places the only observed exposure of coal was in the very bed of a creek. The fact that somewhat fortuitous shifting of stream cutting and deposition may reveal or identified, and its lithologic character changes rapidly in a horizontal plane. In addition, the burning has made unrecognizable beds or zones that might otherwise be traceable and has caused slumping, which disturbs the beds and more or less conceals them. In order to determine as precisely as possible the stratigraphic position of the coal beds geologic sections

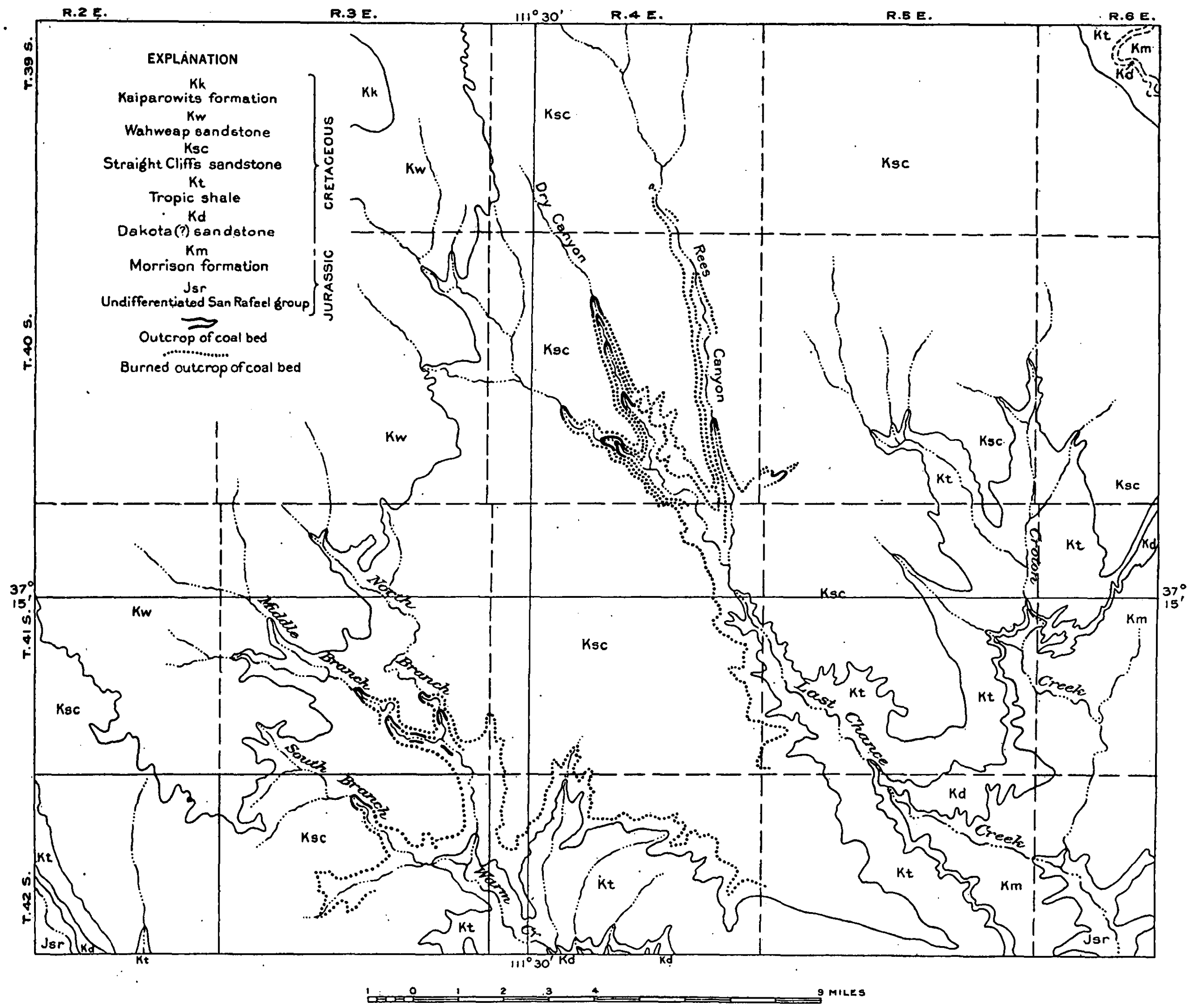


FIGURE 8.—Map of a part of Kane County, Utah, showing distribution of coal exposures in the Straight Cliffs sandstone along the tributaries of Warm and Last Chance Creeks. Base and geology by Raymond C. Moore

completely conceal a coal bed, in conjunction with the difficulty of procuring detailed stratigraphic information, makes it probable that the observed coal deposits in the Straight Cliffs formation are less than the actual coal resources present. (See fig. 8.)

In correlating the coal beds in the Kaiparowits region it has seemed necessary to rely mainly on the stratigraphic position in the formation and the relation of the coal to adjacent beds. In most places the Straight Cliffs sandstone lacks key beds that can be were prepared along each of the canyons where coal was found, and the vertical and horizontal positions of the coal exposures were plotted on the sections. In this way the stratigraphic position of each bed was determined with an approximate minimum of error. It was found that the thicker workable coal beds occupy a position that ranges from about 300 to 600 feet above the base of the Straight Cliffs formation and that several of the geographically more or less widely separated exposures fall at closely corresponding stratigraphic positions. The letters A, B, C, and D were assigned to the main coals thus correlated. (See pl. 30.)

In the south-central part of the Kaiparowits Plateau no workable coal beds were found below the horizon of bed A, a little more than 300 feet above the base of the Straight Cliffs formation. On Last Chance and Warm Creeks and locally at other places a number of coal beds that average 6 to 8 inches in thickness were found in this lower division of the formation.

Bed A is a workable bed of good coal. On the North Branch of Warm Creek in sec. 25, T. 41 S., R. 3 E., it has a maximum thickness of 3 feet 3 inches and stands 310 feet above the base of the Straight Cliffs. The coal is overlain by carbonaceous shale and yellow sandstone and underlain by dark carbonaceous shale. On the South Branch of Warm Creek in the northern part of T. 42 S., R. 3 E., this bed is seemingly represented by two coals 3 and 6 inches thick, separated by a few inches of carbonaceous shale. On Last Chance Creek in sec. 35, T. 40 S., R. 4 E., coal beds exposed at the horizon of bed A show 5 feet 6 inches of coal and bone in which the thickest bed of good coal is 1 foot 11 inches thick; in sec. 34 of the same township bed A is probably represented by four coal beds of which the thickest is 17 inches thick. In Rees Canyon, farther north, bed A has a thickness of 25 inches, but the upper 7½ inches is of poor quality.

Bed B is about 460 to 480 feet above the base of the Straight Cliffs sandstone. On the Middle Branch of Warm Creek in sec. 35, T. 41 S., R. 3 E., it consists of 5 feet 11 inches of coal and 1 foot 6 inches of bone. A bed of good coal 2 feet 6 inches thick on the North Branch of Warm Creek and about 20 feet lower stratigraphically seems to correspond to this bed. On the Middle Branch of Warm Creek in sec. 26, T. 41 S., R. 3 E., 6 feet 6 inches of coal in two beds is separated by 5½ inches of carbonaceous shale, and the top of the coal is 458 feet above the base of the formation. On the South Branch of Warm Creek in sec. 10, T. 42 S., R. 3 E., bed B consists of 3 feet of coal 480 feet from the bottom of the Straight Cliffs sandstone. The coal is of good quality and has been mined on a small scale at the only coal mine in the southern part of the Kaiparowits Plateau. On Last Chance Creek bed B is represented by 7 feet of very good coal that is exposed in the bottom of the canyon in the southwestern part of sec. 27, T. 40 S., R. 4 E. This coal bed and others have been destroyed by burning to within 15 or 20 feet from the bottom of the canyon. A coal bed that is exposed on lower Dry Canyon a little less than a mile north of this 7-foot outcrop has a thickness of 3 feet 8½ inches. Its correspondence to bed B is indicated by its stratigraphic position.

Bed C is best exposed and is thickest on Last Chance Creek in secs. 27 and 28, T. 40 S., R. 4 E., where the thickness ranges from 9 feet 7 inches to 15 feet 3 inches and the top is about 495 to 500 feet above the base of the Straight Cliffs sandstone. Near the mouth of Dry Canyon by digging in the stream bed 10 feet 6 inches of coal of fine quality was measured without reaching the base of the bed. On the Middle Branch of Warm Creek in sec. 26, T. 41 S., R. 3 E., 12 feet of coal of good quality, separated into two beds near the top by a layer of bone 1 foot thick, is exposed at the stratigraphic position of bed C. Exposures upstream from this locality indicate a thickening of the upper bed, though accompanied by intercalations of bone and carbonaceous shale. On the South Branch of Warm Creek in sec. 10, T. 42 S., R. 3 E., a 3-foot coal of good quality occurs at the approximate position of bed C and is tentatively correlated with it.

Bed D lies about 600 feet above the base of the Straight Cliffs sandstone. Where first examined on Last Chance Creek, in sec. 20, T. 40 S., R. 4 E., it has a thickness of 3 feet 9 inches and is overlain by several feet of carbonaceous shale that contains coal beds 15 inches or less in thickness. On Dry Canyon the highest coal discovered is about 605 feet above the base of the formation; it is a hard, lustrous bituminous coal of excellent grade more than 11 feet thick without a parting. After digging several feet in the bottom of the creek the base of the bed was not reached. As this coal is burned almost down to the canyon bottom no other measurement was made. On Warm Creek several coal beds 3 to 13 inches in thickness, separated by black carbonaceous shale, lie about 600 feet above the base of the Straight Cliffs sandstone, but no workable bed was found at this horizon.

In Dry Canyon good coal beds were found at horizons intermediate between beds C and D. In sec. 16, T. 40 S., R. 4 E., about 560 feet above the base of the Straight Cliffs, occurs a coal of very good quality, 3 feet 5 inches thick, which is overlain and underlain by brown carbonaceous shale. This coal was not identified at other localities. In the same section and approximately 20 feet higher occurs a bed of good grade coal 3 feet 4 inches thick at one exposure and 4 feet 5 inches thick at another a few hundred feet distant. A third coal bed 2 feet thick lies higher stratigraphically.

Two coal beds 16 and 19 inches thick were found on Last Chance Creek a short distance downstream from the place where bed D is exposed. The stratigraphic horizons of the beds are, respectively, about 510 and 525 feet above the base of the Straight Cliffs sandstone.

In the upper Escalante Valley and the upper Paria Valley the stratigraphic relations of the coal beds in the Straight Cliffs sandstone are less well known than those along the south flank of the Kaiparowits Plateau, but in general the beds are better exposed for study.

Within 5 miles of Escalante there are about eight coal mines and prospect excavations. From four of these mines the village is adequately supplied. No systematic development has been undertaken. The sites have been selected with reference to the thickness of beds, stability of roof, and access to feasible wagon routes. Pick, shovel, and hand drill are the tools used by the miners, who work when coal is needed.

The Christensen mine, in Coal Canyon, Willow Springs Wash, has been operated each year since about 1893. During 1917–18 350 tons of coal was taken to Escalante, the price being $1.50 at the mine or $3.75 delivered in the village. At this mine the strata are arranged as follows:

Section in Christensen mine, Willow Springs Wash, Utah

[Measured by Herbert E. Gregory]

	Ft.	in.
Sandstone, massive; cross-bedded at the top	6	
Shale, drab, carbonaceous		14
Coal, good quality		7
Shale, drab; resembles fire clay		8
Coal, with some "bone"	3	
Shale, drab, gypsiferous; many impressions of plants	3	
Coal, good quality; the present mine (see analyses of samples)	7	10
Shale, sandy		6
Coal, revealed by drill	12	
Shale and sandstone.		

The Richards mine, also in Coal Canyon, has produced about 100 tons each year since it was opened in 1913. The coal is obtained from a bed 11 feet 7 inches thick that lies between beds of drab shale. The bottom 4 feet is discarded because of "bone" and pyrite "nigger heads." The remainder is of good quality.

The Schow mine, in Coal Canyon, at a higher altitude than the Christensen and Richards mines, is developed in a coal bed 13 feet thick, the top 7 feet of which is discarded because it is "too bony for use." Massive sandstone beds lie above and below the coal with no intervening shale.

The Winkler mine, in Alvey Wash, contains a bed of good coal 9 feet thick and a second bed 2 feet thick below 3 feet of intervening shale.

A prospect hole in Willow Springs Wash reveals 3 feet 2 inches of good coal underlain in turn by 5 inches of shale that contains abundant fragments of plants and 7 feet 2 inches of coal of good quality. Another undeveloped mine shows four coal beds respectively 1 foot 3 inches, 8 inches, 6 feet, and 4 inches thick. All the cliffs southeast of Escalante that were examined show several coal beds, one of which at each locality exceeds 6 feet in thickness.

In a section measured on Cherry Creek about 12 miles west-southwest of Escalante the coal beds are distributed as follows:

Section on Cherry Creek near Escalante, Utah

[Measured by Herbert E. Gregory]

	Ft.	in.
Sandstone, massive, cross-bedded	64	
Shale, arenaceous	15	
Coal, upper part of good quality	1	6
Shale	2	3
Coal, of good quality; breaks into square blocks; contains resin	9	8
Covered, probably shale	16	
Coal, of good quality		6
Shale and thin sandstone	21	
Coal, with shale partings	7	
Shale, drab, with plant remains	4	
Coal, earthy, fibrous	5	
Shale, argillaceous		6
Coal, of good quality, with one thin shale bed	9	
Shale	1	2
Coal, earthy	2	
Covered; probably shale and thin sandstone	74	
Coal, with much "bone"	2	
Shale	1	6
Coal, of good quality	1	3
Partly covered shale and thin sandstone	80	
Coal, of good quality	2	2
Shale	3	
Coal, with many shale partings	5	10
Shale	8	
Coal, earthy	1	6
Shale, arenaceous, and thin sandstones, ripple marked	30	
Coal, of good quality		7
Shale, arenaceous	20	
Coal, upper two-thirds of good quality	12	
Shale and thin sandstone	160	
Coal of good quality	8	2

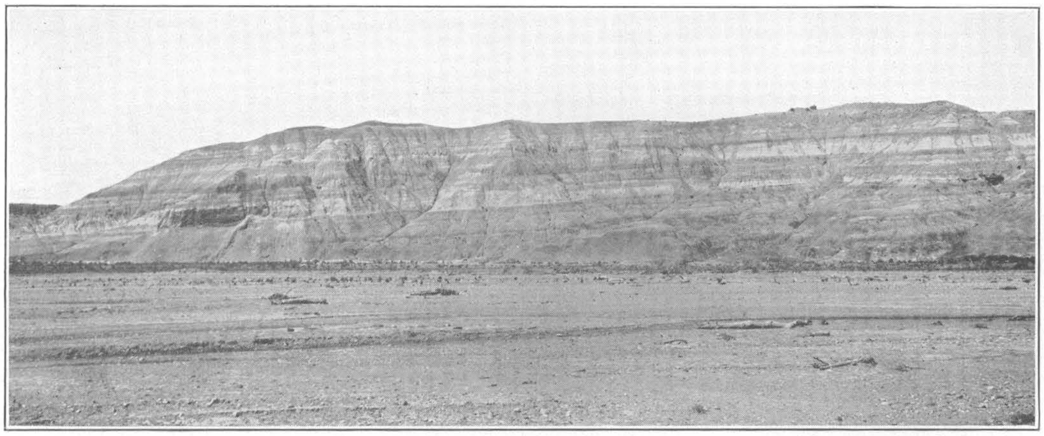
The 14 beds of coal shown in this section aggregate 68 feet 10 inches, more than half of which is probably suitable for commercial use.

Henrieville and some families in Cannonville and surrounding ranches receive coal chiefly from the Pollock mine, on a branch of Henrieville Creek about 5 miles north of Henrieville, in the east face of a mesa composed of Cretaceous sandstone. The beds at the mine are arranged as follows:

Section at the Pollock mine, near Henrieville, Utah

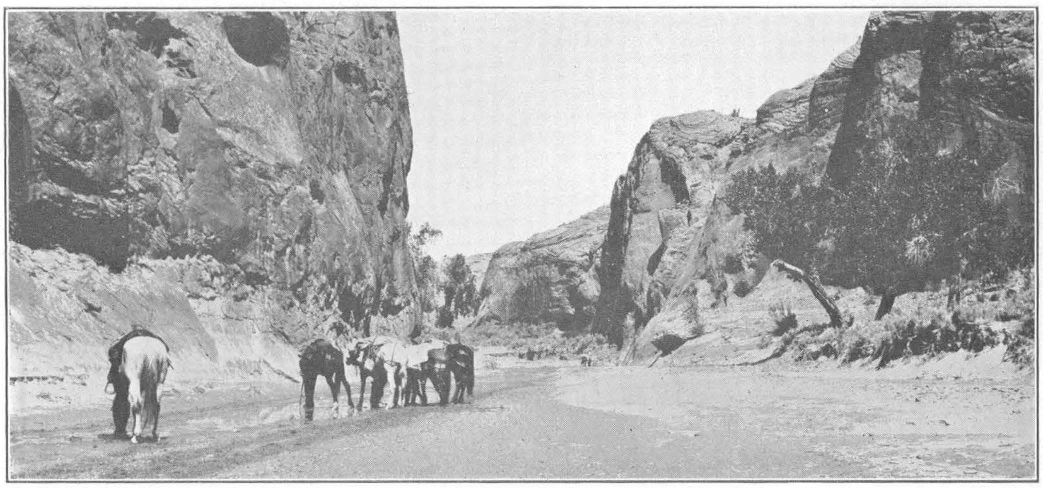
[Measured by Herbert E. Gregory]

	Ft.	in.
Coal, of good quality; the lowermost foot is used locally by blacksmiths; analyses show little resin and no sulphur	4	
Shale, carbonaceous		8
Coal, of good quality; has thin, irregular shale partings	6	10
Shale, purple and gray; contains impressions of plants and carbonized wood	2	3



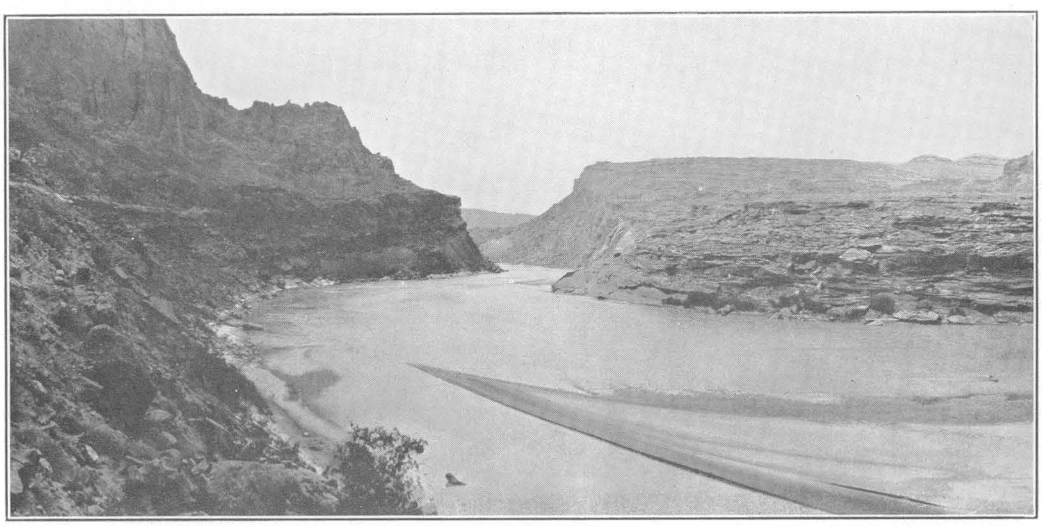
A. PARIA VALLEY NEAR PARIA

Remnant of local erosion surface 1 mile below mouth of Cottonwood Creek



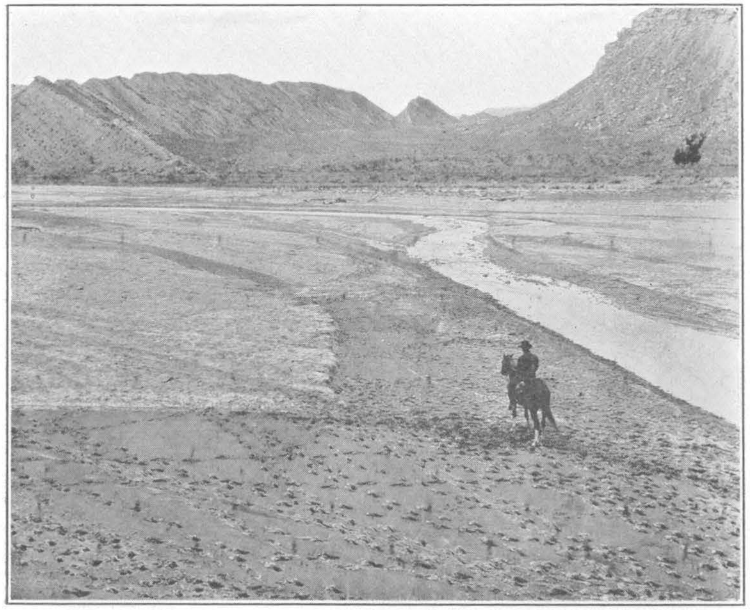
B. PARIA RIVER BELOW PARIA

Narrow canyon just above mouth of Cottonwood Creek. This constricted portion of the valley occurs where the river crosses obliquely the upturned Glen Canyon sandstones in the East Kaibab monocline.



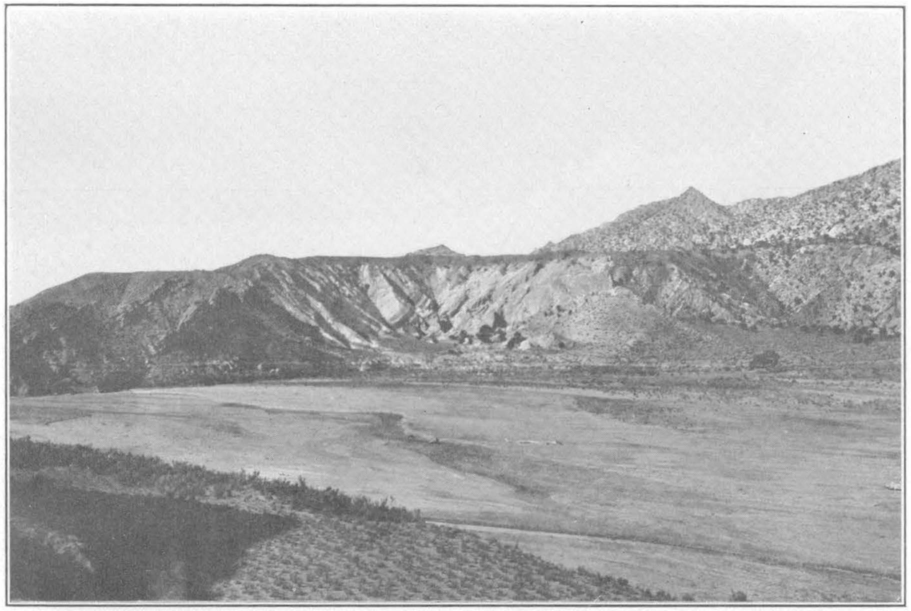
C. GLEN CANYON AT WATERPOCKET FOLD

The slabby sandstone at right is Todilto (?) formation. The Wingate and Chinle may be seen downstream. Photograph by E. C. La Rue.



A. PARIA VALLEY NEAR MOUTH OF COTTONWOOD CREEK

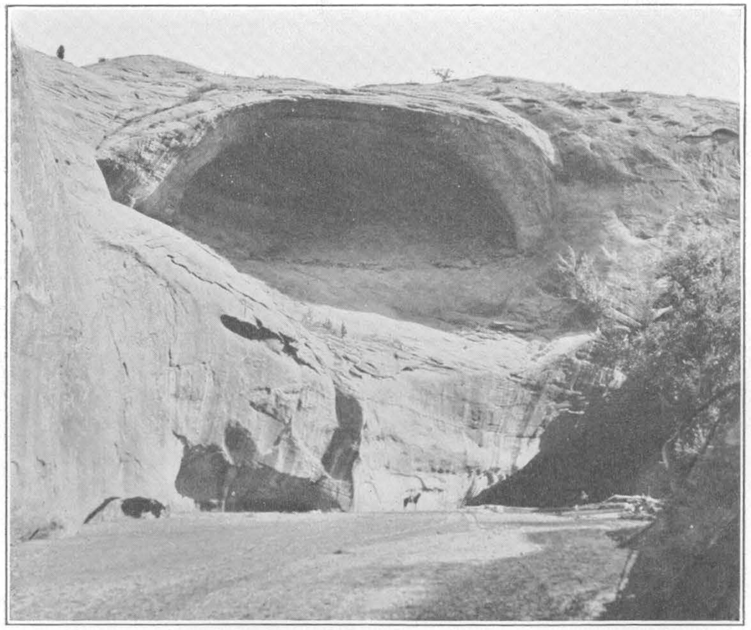
View looking north along the trend of the East Kaibab monocline. The hogback is formed by the Dakota (?) sandstone, the valley to the right by the Tropic shale. Photograph by G. C. Fraser.



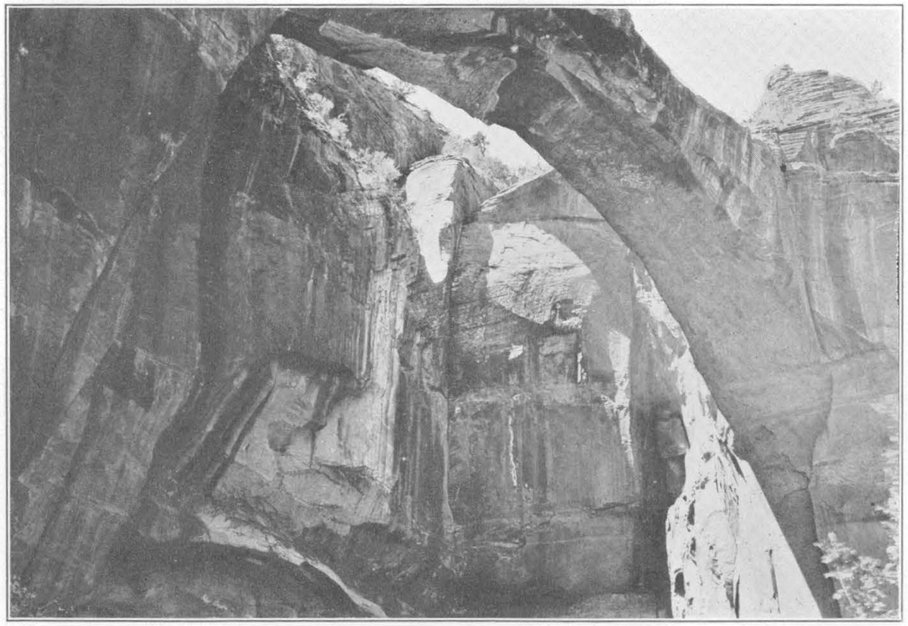
B. PARIA VALLEY 1 MILE BELOW MOUTH OF COTTONWOOD CREEK

View near the former settlement of Paria. The stratified rocks are Chinle shale.

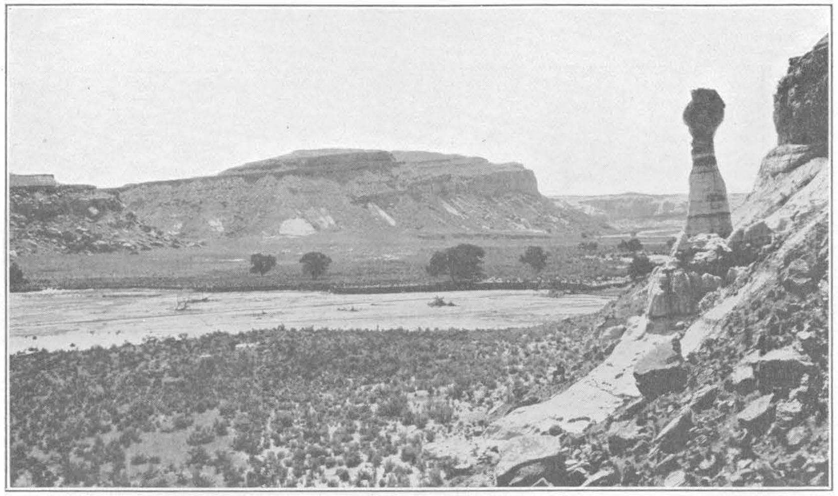
A and *B* show erosion and deposition along the channel of the Paria River. The river has carved a wide valley where the rocks are relatively weak. Flood erosion has stripped away most of the former grass-covered tillable alluvial bottom land, leaving a wide sand and gravel covered channel, which in many places is dry, except during floods.



C. CAVE IN NAVAJO SANDSTONE, HARRIS WASH SOUTHEAST OF ESCALANTE

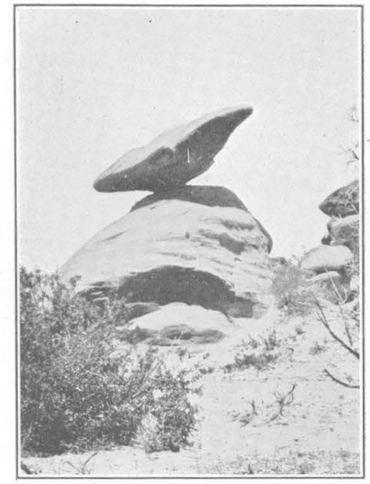


D. ARCH FORMED BY EROSION OF NAVAJO SANDSTONE IN WALL OF ESCALANTE CANYON ABOVE MOUTH OF SAND WASH

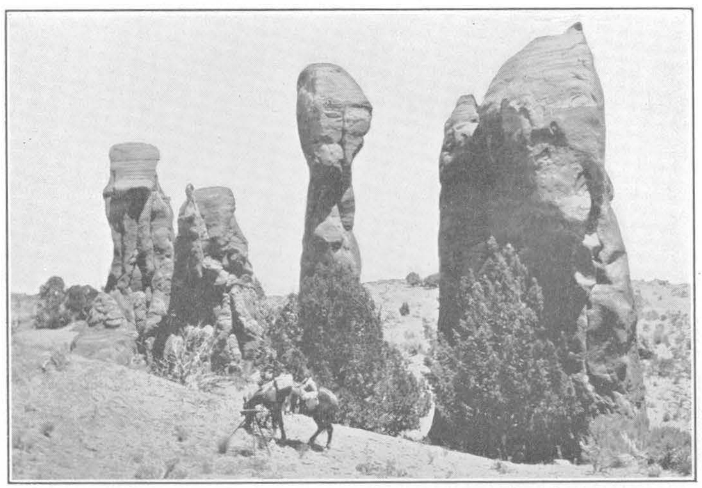


A. CHIMNEY ROCK AND OBELISK CARVED IN SANDSTONE OF SAN RAFAEL GROUP ON PARIA RIVER NEAR OLD ADAIRVILLE

Photograph by G. C. Fraser.



C. BALANCED ROCK, ENTRADA SANDSTONE, HARRIS WASH, SOUTHEAST OF ESCALANTE



B. ROCK MONUMENTS WEATHERED FROM ENTRADA SANDSTONE, COLLETT CREEK, SOUTHEAST OF ESCALANTE

D. DEMOISELLES ON CHINLE SLOPE, NORTH FORK OF SILVER FALLS CANYON, CIRCLE CLIFFS

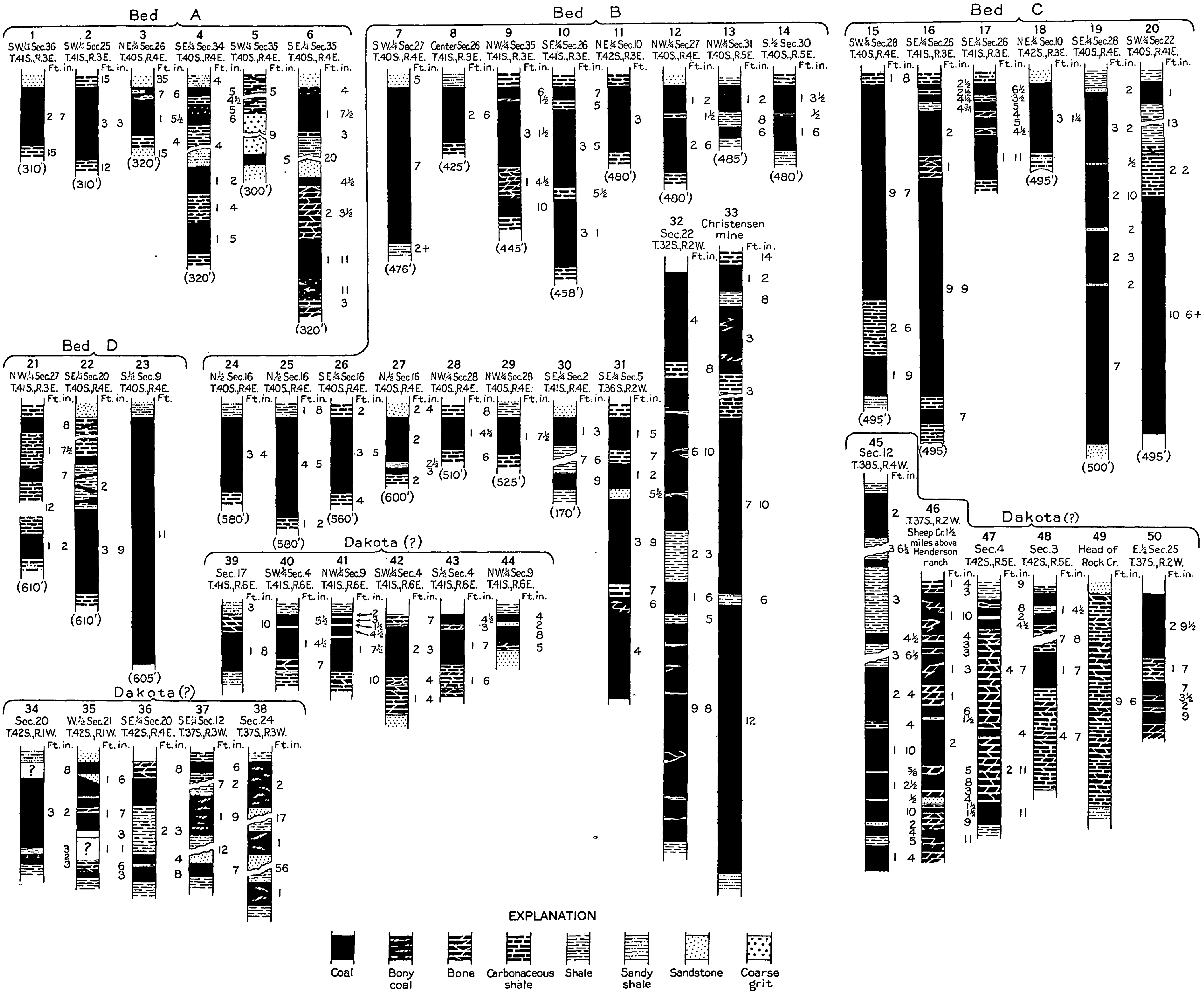
EROSION REMNANTS

A. GOLD DREDGE ON COLORADO RIVER NEAR MOUTH OF HANSON (PINE ALCOVE) CREEK

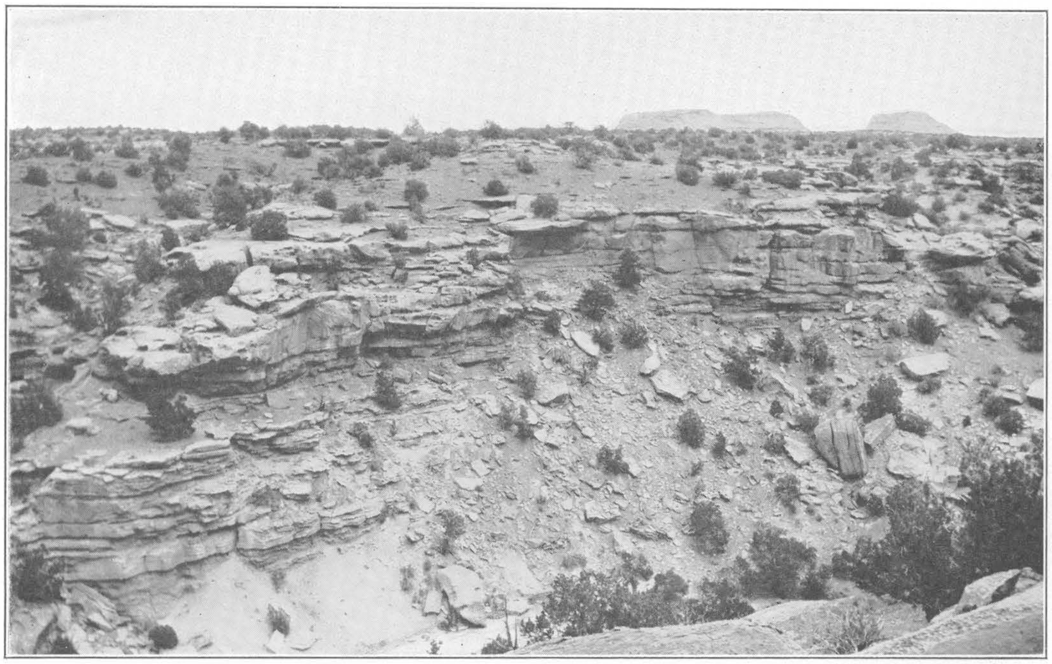
Installed in 1900 by R. L. Stanton. Photograph by E. C. La Rue, August, 1915.

B. STEAMBOAT "CHARLES H. SPENCER," CONSTRUCTED TO TRANSPORT COAL FROM WARM CREEK TO LEES FERRY FOR PLACER MINING

Photograph by E. C. La Rue, August, 1915.



COAL SECTIONS MEASURED IN KANE AND GARFIELD COUNTIES, UTAH



A. PETROLIFEROUS MOENKOPI STRATA IN EASTERN PART OF CIRCLE CLIFFS

B. OIL SEEP ON BANK OF COLORADO RIVER AT "BENNETT'S OIL FIELDS"

	Ft.	in.
Coal, of good quality, uniform bed; breaks with glistening surfaces	1	6
Dense clay shale, "fire clay"		5
Coal, of good quality, with shale partings and "some bone," "excellent for stoves; in forge burns to white ash but makes clinker"	9	8
Shale, dense, drab, part massive; fire clay, used locally to make brick for stove linings	20	

Below the coal is 130 feet of bedded sandstone that overlies the Tropic shale, and above the coal lies 160 feet of gray-buff sandstone with subordinate shale and included thin lenses of coal 24 feet above the top of the section, and a bed of coal 2 feet thick 140 feet higher, on the face of the mesa.

In a mine on the north branch of Henderson Canyon in sec. 5, T. 36 S., R. 2 W., the lower part of the Straight Cliffs sandstone includes 13 feet 4 inches of fairly good coal in four beds.

Section of coal at mine in Henderson Canyon, Utah

[Measured by Raymond C. Moore]

	Ft.	in.
Shale, carbonaceous, sandy; forms roof of mine.		
Coal, of fair quality	1	5
Shale, carbonaceous		7
Coal, of good quality	1	2
Sandstone, light yellowish brown		5½
Coal, of good quality	3	9
Shale, carbonaceous		7
Bone and thin streaks of coal		6
Coal, of good quality	4	

In the southwestern and southeastern parts of the Kaiparowits Plateau, where no workable coal beds were observed, there are indications that the conditions at the time of deposition of the Straight Cliffs formation were unfavorable for the making of coal. On the upper part of Croton Branch of Last Chance Creek and farther east, where the Straight Cliffs sandstone is excellently exposed, marine fossils were found at several horizons, indicating that this region was more or less constantly under water. Along Wahweap Creek and the Paria River, where the entire thickness of the Straight Cliffs sandstone is exposed in bare rock cliffs and where coal is almost absent and no fossils were seen, the sandstone possibly represents a fresh-water landward facies that is separated from the marine deposits farther east by the coal-bearing intermediate belt. In a similar relation to the coal area of the upper Paria Valley northeast of Tropic and east of the Table Cliff Plateau is the non coal-bearing Straight Cliffs sandstone west and southwest of Tropic. Well-exposed sections of the sandstone on the Paria River in T. 36 S., R. 3 W., in Bryce Canyon, and in other valleys farther south show no coal beds, but several beds contain fresh-water mollusks such as unios.

In physical features the coal of the Straight Cliffs formation differs more or less in different beds and in different parts of the region. In general it is distinctly bedded and has a fairly bright luster. Some of it is very hard and has a subconchoidal fracture and a brilliant luster. Some beds show a fine banding of alternate bright and dull layers, but other beds are massive and either bright or dull. The jointing and cleavage are commonly more or less unevenly columnar, but in places there is a prominent blocky, subcubical jointing. That the coal is in general resistant to weathering and has excellent stocking qualities is shown by the condition of the coal where it is exposed in natural outcrops and by the comparatively fresh, unslacked condition of coal about the workings and dumps. Some of these exposed piles of coal have been subject to weathering for as much as a dozen years.

A number of samples of the Straight Cliffs coal were collected for analysis. A partial statement of the analyses is given in the following table. The coal samples were carefully dried slightly above room temperature until the weight became constant.

Analyses of coal samples from the Kaiparowits region[a]

Locality	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	British thermal units
Mine on Warm Creek, bed B (?), NE. ¼ sec. 10, T. 42 S., R. 3 E., Kane County	4.7	40.7	48.6	6.0	0.7	12,190
Outcrop on Last Chance Creek, bed B, sec. 27, T. 40 S., R. 4 E., Kane County	6.7	38.5	50.2	4.6	.6	10,460
Prospect near Escalante, Garfield County	11.55	37.23	47.64	3.58	.59	11,107
Don Shurtz mine, near Escalante, Garfield County	12.20	39.35	44.20	4.25	.82	11,108
Outcrop on Cherry Creek, near Escalante, Garfield County	15.30	37.13	37.07	10.50	.47	8,366
Do	7.70	39.58	41.54	11.18	.76	9,995
Do	10.30	41.23	40.69	7.78	.55	9,093

The coal from the Straight Cliffs formation is materially better in average heating value and has a lower content of ash and sulphur than the coal from the Dakota (?). Comparison of the analyses given above with analyses of typical coals from Colorado, Wyoming, and elsewhere in Utah shows that some of the Straight Cliffs coal of the Kaiparowits region is quite as good as most of that in neighboring regions. In the best of the Kaiparowits coals the moisture, sulphur, and ash are relatively low, and the fixed carbon is high. The heating value of the coal from the sample collected in the mine on Warm Creek, 12,190 British thermal units, indicates a satisfactory bituminous coal.

The distance from markets and the extremely rugged character of most of the country will certainly retard development of the coal deposits in Kane and Garfield Counties. The small settlements in the region can be supplied readily, but there are neither roads nor habitations in the vicinity of the best coal deposits.

OIL AND GAS

STRATIGRAPHIC CONSIDERATIONS

The occurrence of oil seeps and oil-impregnated sandstone in parts of the Kaiparowits region, the presence in the San Juan field, not far distant, of producing wells that obtain oil from rocks that probably underlie most of southern Utah, and the existence of large anticlinal folds have suggested the possibility of obtaining oil and gas in commercial quantities in Kane and Garfield Counties. These apparently favorable indications may be considered briefly and the results of exploration up to the present time recorded.

Cambrian rocks probably underlie most of southern Utah, but though they consist in part of shallow-water marine deposits with somewhat abundant evidences of life and have a lithologic character suitable for the accumulation of oil, no oil seeps or other definite indications of oil have been found in these rocks anywhere in western America.

The Cambrian beds are deeply buried. In most parts of the Kaiparowits region they lie several thousand feet below the surface, and they need not be considered as prospective oil producers.

The thin deposits of Devonian age and the dense, massive limestone of Mississippian age, ranging in thickness from 100 to at least 700 feet, probably underlie all of southern Utah. However, on account of the very dense, massive character of these formations, which indicates an absence both of suitable mother rocks and of reservoir beds, it is not likely that commercial quantities of oil or gas will be found in them.

The Pennsylvanian rocks yield heavy oil in the San Juan oil field, and they are distinctly bituminous at many places in southwestern Colorado. As deposits of this age crop out on nearly all sides of the Kaiparowits region, they doubtless continue beneath it. But their suitability as oil carriers can be only surmised, for exposures of Pennsylvanian rocks in different parts of the plateau province show widely different physical features. In southwestern Colorado the Pennsylvanian comprises about 2,000 feet of alternating beds of coarse arkosic sandstone, conglomerate, dense limestone, and a little shale—deposits that were formed in rather shallow water on the west side of a crystalline land mass, where mechanical weathering was comparatively active. The conditions are not very favorable for accumulations of oil or gas in commercial quantities. In southeastern Utah about 1,350 feet of Pennsylvanian rocks are exposed in San Juan Canyon. They are dominantly fine-grained limestones but include some fine-grained, essentially nonfeldspathic sandstones and thin layers of bituminous shale. The stratigraphic relations, especially as regards the relative scarcity of the shale, do not favor production of oil, in spite of the fact that oil seeps are found and that high-grade oil is obtained in a number of wells. In east-central Utah the Pennsylvanian rocks are more sandy than those in San Juan Canyon and include large quantities of salt and gypsum, which point to conditions of sedimentation unlike those in any other part of the plateau country. In association with the salt deposits a little oil has been discovered. In the Grand Canyon region the Pennsylvanian is represented by thin-bedded limestone, part of the Supai formation, and perhaps by some higher beds, all unlike those on the San Juan River or in Cataract Canyon. In Nevada thick marine deposits, chiefly limestone, show the presence of the sea in Pennsylvanian time. In the Muddy Mountains Longwell[5] measured more than 1,100 feet of massive Pennsylvanian limestones, and at Eureka Hague[6] reported 3,800 feet of beds, chiefly limestone.

There is a singular lack of rocks that were originally muds in the known Pennsylvanian sections of Colorado, Utah, northern Arizona, and Nevada. Either conditions were unsuitable for making the usual proportion of fine clastic deposits, which are commonly accompanied by abundant organic remains and the conditions favorable for the accumulation of oil, or these clastic materials are largely localized in parts of the region where the Pennsylvanian is concealed. At all events, the physical character of the Pennsylvanian deposits, as indicated by widely scattered outcrops and borings, is rather discouraging to exploration for oil and gas. However, some oil has been found in these rocks, and conditions suited to commercial production may possibly exist at places not yet explored.

The Permian rocks in southern Utah consist mainly of thick sandstone without associated beds that could serve as mother rocks for oil. No surface indications of oil have been observed in them, and they are not considered promising.

The Triassic rocks of the Kaiparowits region include the Moenkopi formation, one of the most persistently oil-containing series in the plateau province. (See pl. 31, *A*.) In places oil occurs in the Shinarump conglomerate, also of Triassic age. The sandstones of these formations are suitable reservoir rocks, and where oil-containing beds are covered by younger beds in favorable attitudes it would seem possible to find oil in commercial quantity. The Moenkopi is a shallow-water deposit that contains marine fossils, but it is mostly a "red beds" formation, which is commonly regarded as an unfavorable source rock for oil. The oil in the Shinarump is probably derived from the Moenkopi.

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[5] Longwell, C. R., The Muddy Mountain overthrust in southeastern Nevada: Jour. Geology, vol. 30, p. 66, 1922.

[6] Hague, Arnold, Geology of the Eureka district, Nev.: U. S. Geol. Survey Mon. 20, pp. 85–86, 1892.

The thick Jurassic sandstones afford little encouragement to the oil prospector, for the conditions under which most of these rocks were deposited were extremely unfavorable for the preservation and burial of any oil-yielding organic materials.

The Cretaceous formations of the Kaiparowits region comprise alternating porous sandstone and carbonaceous shale that contain in part abundant remains of organisms. With favorable geologic structure the commercial production of oil from these rocks should be possible, and the results of drilling in adjacent areas of Cretaceous beds show that gas may be expected.[7] No surface indications of oil or gas in the Cretaceous rocks of the Kaiparowits region have been observed.

The Tertiary beds, because of unfavorable lithologic character, topographic position, and the absence of suitable structure, need not be considered as a possible source of oil, notwithstanding the fact that oil might conceivably be derived from one of the upturned older beds which the Tertiary unconformably overlies.

STRUCTURAL RELATIONS

Structural conditions apparently favorable for accumulation of oil and gas are known in the Kaiparowits region.

In the Circle Cliffs upwarp (see p. 119) the Kaibab limestone, of Permian age, is exposed near the apex of a very large asymmetric dome, and the underlying Paleozoic rocks, including probable equivalents of the oil-bearing Goodridge formation, are under cover at moderately shallow drilling depth. (See fig. 9.) There is approximately 1,000 feet of closure, although on the east, south, and southwest the beds descend uninterruptedly thousands of feet below the lowest closed contour. The average dips on the gentler sides of the fold range from about 100 to 250 feet to the mile, and there is a possible collecting area of several hundred square miles. A detailed reconnaissance of the upper part of the Circle Cliffs upwarp shows the presence of minor undulations of the beds with axes subparallel to the direction of dip but no subordinate folds that might serve to trap oil or gas on the flanks of the major anticline.

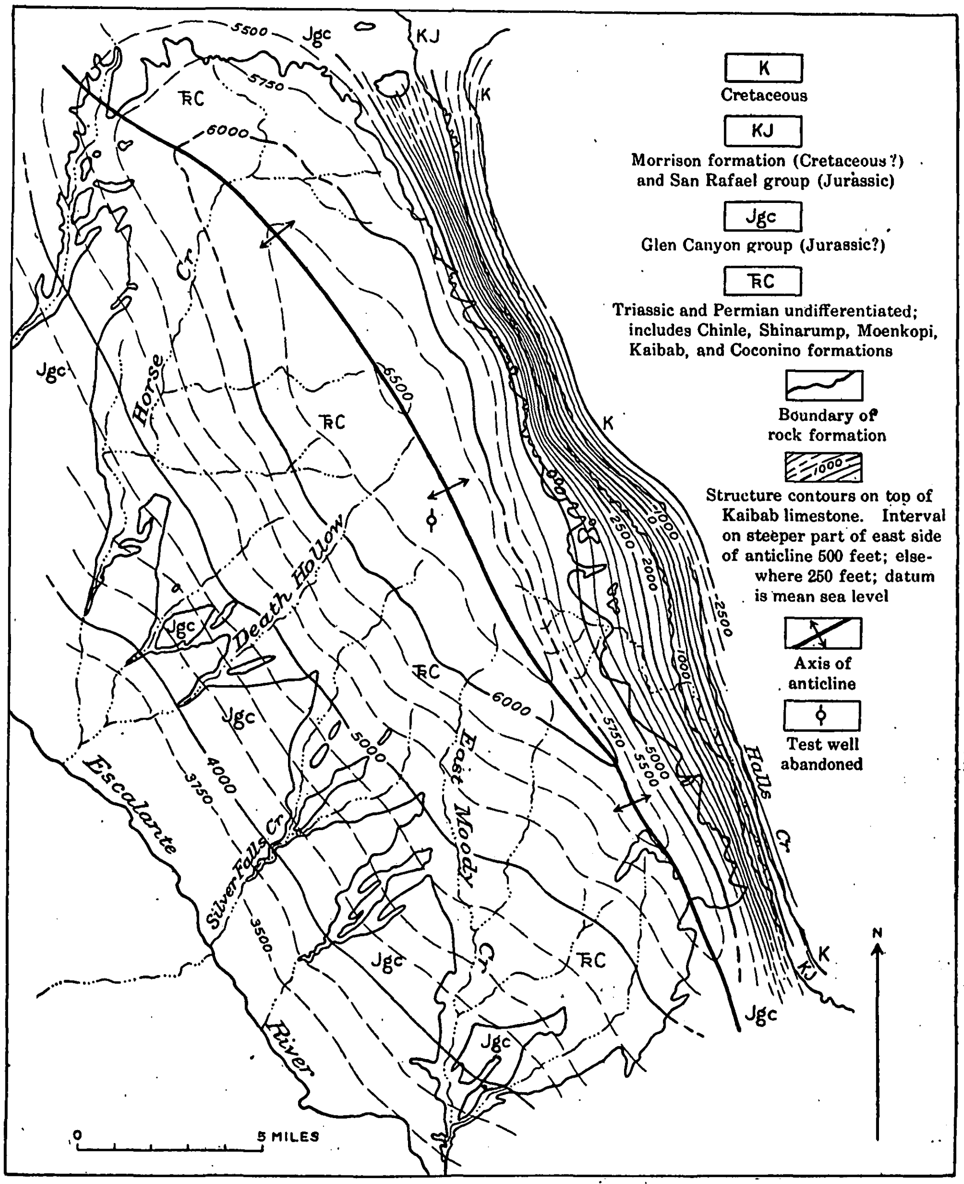

FIGURE 9.—Outline stratigraphic and structural map of the Circle Cliffs area, Garfield County, Utah. Based on plane-table surveys by Raymond C. Moore

The Escalante monocline is essentially a structural irregularity on the southwest slope of the Circle Cliffs upwarp. (See p. 120.) Its major axis is parallel to that of the main upwarp, but the steep dip is on the west side. The anticline plunges sharply southward; whether or not it is closed on the north is undetermined. The Navajo sandstone forms the crest of the fold; the Shinarump is probably about 2,300 feet below the surface, and the petroliferous beds in the

[7] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, pp. 115–134, 1914.

Moenkopi about 2,500 feet. The Goodridge formation or its equivalent is almost certainly not less than 1,000 feet deeper.

The Collett anticline is a southward-plunging fold or rather a " nose " superposed on the southwest flank of the Circle Cliffs upwarp. Although in some places a concentration of fluid hydrocarbons might be effected by such structure, this fold is regarded as unpromising.

The Rock Creek anticline is a well-defined, rather symmetrical elongated dome, very low on the Circle Cliffs upwarp and practically at its southwest margin. (See p. 121.) The amount of closure was not determined definitely but appears to be at least 400 feet. On account of the very low position of this anticline with reference to the regional structure as a whole, it might be assumed that the possible collecting area of the fold would be small, but the probability that the rocks of this region are only partly water filled may greatly modify the distribution of oil, as may also the movement of ground water. The Navajo sandstone is exposed along the crest of the anticline near the head of Rock Creek. The Shinarump conglomerate, which yields oil on the Colorado River about 25 miles to the northeast, is probably not less than 2,000 feet below the surface in places where erosion has removed most of the overlying rocks, and the possibly petroliferous Moenkopi sandstone is a few hundred feet deeper. Because of the great thickness of the Triassic and perhaps also of the Permian rocks in this part of the Kaiparowits region, the top of the Pennsylvanian is probably about 3,500 to 4,000 feet below the surface. Extreme topographic difficulties and the isolated location almost preclude drilling.

The Smoky Mountain anticline, on the southeast flank of the Kaiparowits downwarp, is a clearly defined fold that trends almost at right angles to the regional strike. There is no observed closure, and no oil seeps or indications of gas have been observed in the Cretaceous rocks that are involved in the anticline.

In the Paria platform and the Kaibab upwarp there seems to be small reason to expect accumulations of oil or gas.

The Paunsaugunt fault involves the sandy beds and richly organic shale at the bottom of the Cretaceous section. The sandy beds are well fitted to serve as reservoirs and the shale to serve as a source rock of oil or gas, and on the west side of the fault there would be a possibility of finding commercial quantities of oil or gas if the strata were adequately sealed. As these Cretaceous beds are dropped to a position opposite porous and very thick Jurassic sandstone and as, so far as known, the beds west of the fault dip somewhat uniformly northward so that the beds are open to the south, an accumulation which under other conditions would be likely is made very unlikely. No seeps or other indications have been observed along the line of the Paunsaugunt fault.

EXPLORATION

The only oil well in the Kaiparowits region is that drilled by the Ohio Oil Co. near the topmost part of the Circle Cliffs upwarp, just west of Wagonbox Mesa, in sec. 25, T. 34 S., R. 7 E. (unsurveyed). Drilling was begun January 24, 1921, with a standard rig. Work was retarded by difficulties of various sorts, and finally, after penetrating 122 feet of water-bearing sandstone, the well was abandoned November 9, 1921, at a depth of 3,212 feet.

This well is believed to have reached the top of the Goodridge formation (Permian and Pennsylvanian) at a depth of 1,630 feet. (See p. 157.) As there is no satisfactory basis for correlating the bottom rocks in the well it is very uncertain whether all the 1,582 feet of beds that are tentatively assigned to the Goodridge really belong to that formation. It is reasonably sure that beds corresponding in position to those from which the oil is obtained in the San Juan field were penetrated in the Circle Cliffs test.

At the point where the Waterpocket Fold is crossed by the Colorado River and where an oil seep is found in the Shinarump sandstone, a number of oil claims have been filed and some preliminary development work done. (See pl. 31, *B*.) In the summer of 1921, when this place, locally known as "Bennett's oil field," was visited, the rig was on the ground, but only a few feet of hole had been drilled. The position of the site a little above the petroliferous beds in the Moenkopi on the axis of the Waterpocket monocline, far below the crest of the dome in the Circle Cliffs, makes a test well especially interesting. If the oil-bearing zone is only partly filled by oil and water commercial production might be obtained from a well drilled a considerable distance below the crest of an anticlinal fold, or even in an adjacent syncline, as has been done in the San Juan field. The position of the zone of such an accumulation of oil would depend on the extent to which the porous reservoir was filled with liquid. Possibly, therefore, oil may be found here, even though the well in the Circle Cliffs did not produce oil.

About 3 miles west of Caineville, in Wayne County, the Ohio Oil Co. drilled another test well to a depth of 3,650 feet, on the top of a small dome. In this locality Upper Jurassic sandstones occur at the surface. No oil or gas was reported. As this well was started nearly 3,000 feet stratigraphically above the top of the Circle Cliffs well, it did not reach the Pennsylvanian, but it did reach the Shinarump and Moenkopi formations. As oil-impregnated sand is known at several places where these formations crop out, the failure of the Caineville well is possibly due to incomplete filling of the rock with oil and water.

An unsuccessful well was drilled in 1921 and 1922 by the Carter Oil Co. on the San Rafael Swell in Emery County, where the general geologic conditions are similar to those in the Circle Cliffs. The well was abandoned at a depth of 3,035 feet, water having been encountered at 2,900 feet.

CONCLUSIONS

The Kaiparowits region contains oil-bearing formations as well as anticlinal structure, and in spite of adverse findings in the wells in the Circle Cliffs and near Caineville oil may possibly be found in commercial quantities. However, the difficulties and the expense of exploration are relatively great.

A factor that should not be overlooked in forming conclusions concerning the possibilities of obtaining oil in this region and the significance of the test wells is the possible or even probable absence of abundant water in the oil-containing beds. In partly water-filled rock the oil will not be lifted by difference in specific gravity to the uppermost part of the anticlines but may be found on the flanks or even in the synclines, as in the San Juan field. It is perhaps significant that the marked surface indications of oil in beds that are exposed occur on the east side of the Circle Cliffs dome, where the dip is steep, and at the axis of the anticline in the Colorado River Canyon, where it is far below the summit of the dome in the Circle Cliffs. If oil is present in the Pennsylvanian or other beds beneath the surface at Circle Cliffs, and if it only partly fills the reservoir space and is gathered on the flanks rather than at the apex of the dome, the test of the Ohio Oil Co. would be inconclusive. Except at such a point as "Bennett's oil field," on the Colorado River, where the potentially oil-bearing formations lie within practicable drilling depth and in a favorable position on the anticline, it would be difficult or impossible to test the flanks and the adjacent synclines to the stratigraphic depths reached by the Circle Cliffs well. Similar structural situations may readily be selected on the Kaibab upwarp—for example, in T. 41 S., R. 2 W.

Record of the Ohio Oil Co. well No. 1, Circle Cliffs, Garfield County, Utah

[Geologic correlation by R. C. Moore]

	Thickness (feet)	Depth (feet)
Kaibab limestone, Coconino(?) sandstone, and Supai(?) formation:		
Yellow soil and sandy clay	36	36
Brown sandy soil	15	51
Hard white sand	99	150
Yellow sand	10	160
Hard white sand	5	165
Sandy white shell	10	175
Hard white sand	135	310
Loose brown sand	60	370
Hard white sand	5	375
Fine yellow sand	135	510
Gray shell	25	535
Hard red sand	65	600
Red clay	20	620
Red rock	40	660
Lime shell	20	680
Gray slate	65	745
White sand	885	1, 630
Goodridge(?) formation:		
Limestone	70	1, 700
Hard white sand	550	2, 250
Gray sand	40	2, 290
White lime	35	2, 325
Gray sand	15	2, 340
Reddish sand	20	2, 360
Hard white sand	35	2, 395
Gray sand	55	2, 450
White lime	85	2, 535
White sand	25	2, 560
White lime	260	2, 820
Red sand and shale	20	2, 840
Red rock and shale	20	2, 860
Red sand and shale	20	2, 880
Red rock	30	2, 910
Red sand	10	2, 920
Red sand and shale	20	2, 940
Red shale	25	2, 965
Sand	20	2, 985
White lime	105	3, 090
White water sand	122	3, 212

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