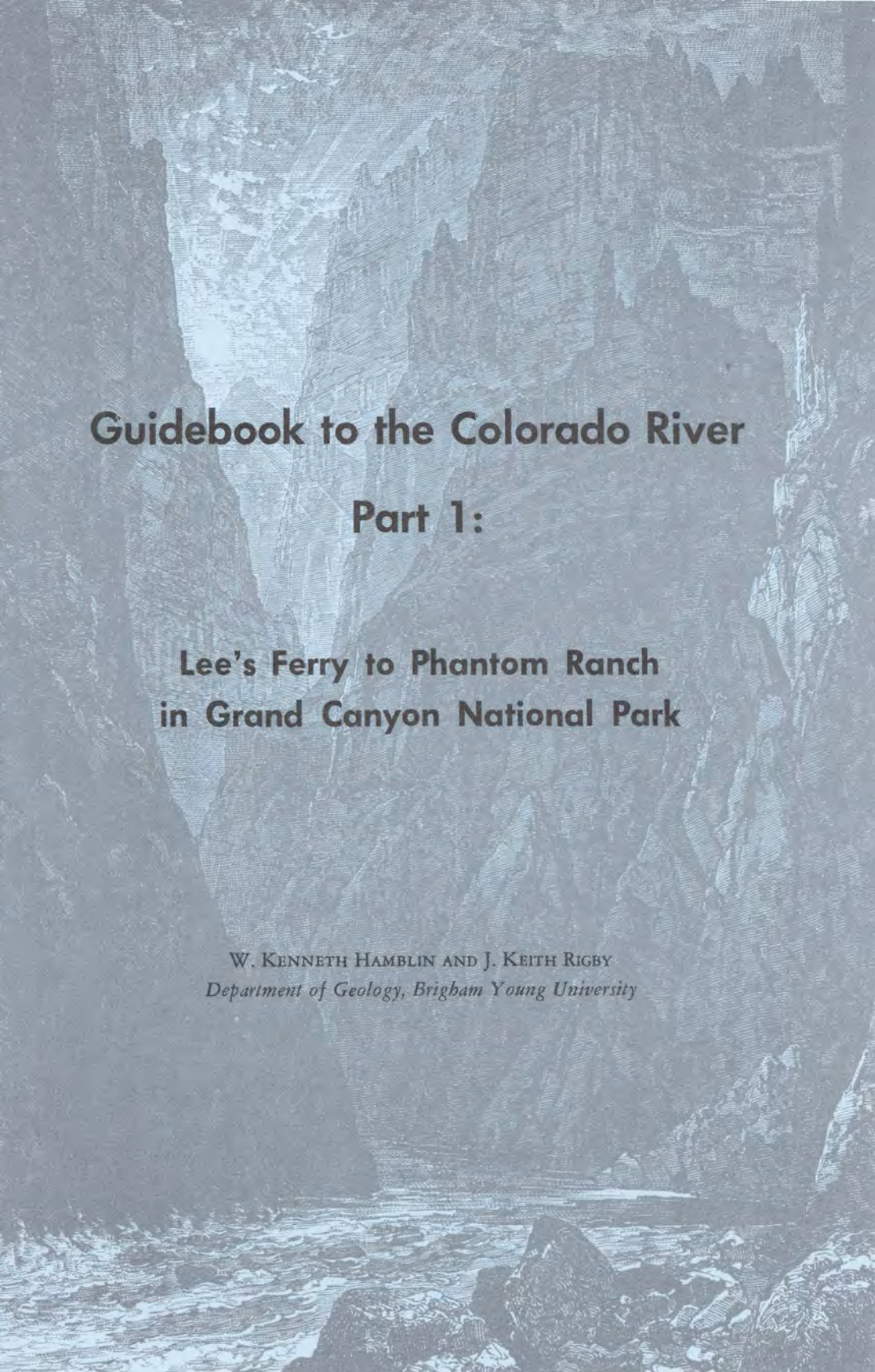




Guidebook to the Colorado River

Part 1:

Lee's Ferry to Phantom Ranch in Grand Canyon National Park

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**Guidebook to the Colorado River, Part 1: Lee's
Ferry to Phantom Ranch in Grand Canyon
National Park**

with Notes on Aboriginal Cultures by Ray T. Matheny and on Biological
Features by Joseph R. Murphy

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PREFACE

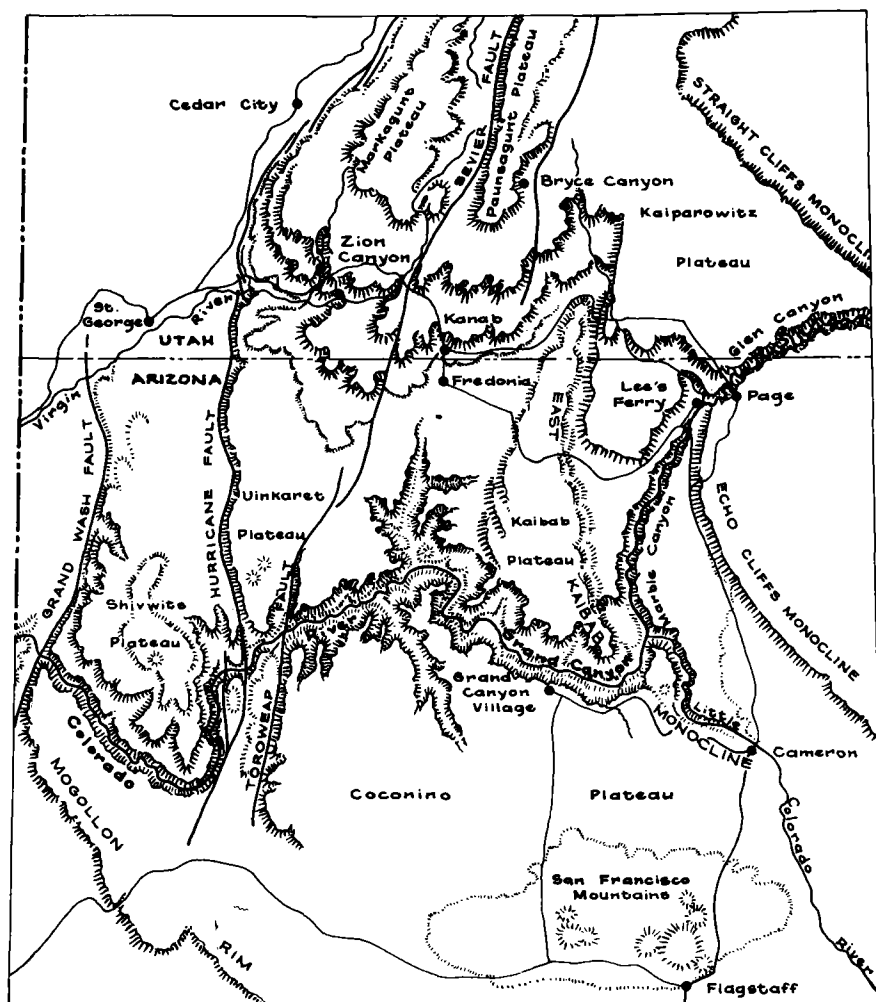
A trip down the Colorado River through the Grand Canyon offers the unique opportunity to study close-hand a classic cross section into the earth's crust. Such a trip would not have been practical for students of geology some years ago, but with the innovation of pontoon boats and the establishment of regular float trips through the canyon by experienced boatmen, this trip is now feasible. Experience in taking students down the Colorado River over the past several years as part of their educational program has prompted us to write this guidebook, not only for the geology student but for all interested persons who desire to understand the scenery of the Canyon. We have written the guide so that the trip can be self-conducted. All points are made with reference to mileage downstream from Lee's Ferry. A number of vertical aerial photographs are included in the illustrations to give complete coverage of the river so that locations can be made without difficulty.

Inasmuch as the Grand Canyon is largely a response of geologic phenomena, we have included within the river log a brief description of the major features of each formation as well as discussions of how the rocks respond to erosion. Interpretation of the environment in which the rocks are accumulated is also presented. This is the first of a series of guidebooks being prepared for rivers of the Colorado Plateau where boat trips are feasible.

We appreciate the assistance of Mr. William L. Chesser who drafted the illustrations. We are also indebted to Mr. John Cross, of Cross Tours, who provided boats and equipment on our several trips through the canyon. Dr. Myron Best and Dr. Lehi Hintze reviewed the manuscript and together with Doctors Richard Poll, John Gardner, Morris Peterson, Ray Matheny, Joseph Murphy, Jesse Bushman, James McKee, and Thomas Laudon accompanied us on preliminary trips and offered many valuable suggestions. We are also indebted to personnel of the Grand Canyon National Park and Glen Canyon National Recreation Area for their cooperation in assisting us with our research programs along the Colorado River.

INTRODUCTION

The Grand Canyon of the Colorado River (Text-fig. 1) is located near the southwestern edge of the Colorado Plateau Province, a circular area of approximately 130,000 square miles centered around the Four Corners area of Utah, Arizona, Colorado, and New Mexico. It is a region of horizontal strata in contrast to the deformed rocks of the adjacent basin and range and southern Rocky Mountains. Many people have referred to the plateau as the "standing-up" country of the West for exceptional isolated buttes, mesas, rock pinnacles, and other erosional forms are here well expressed. It is also distinguished by great elevation. Except for the canyon bottoms the region rises to an elevation of from 5,000 to 11,000 feet above sea level. It is an arid area where weathered rock debris is moved swiftly to the sea during sudden storms. The broad Colo-



TEXT-FIGURE 1.—Index map of the southwestern part of the Colorado Plateau showing the major physiographic features associated with the Grand Canyon.

rado Plateau Province can be subdivided into several sections, each with its own geologic setting and scenic splendor.

The Grand Canyon section extends from the Utah-Arizona line southward to the Mogollon Rim, a prominent escarpment overlooking the low country of central Arizona. This region is characterized by exceptionally broad plateaus formed on top of the Kaibab Limestone. Except for the San Francisco Mountains

and other small patches of volcanics the plateau surface is nearly flat, broken only by a few north-south trending faults, most of which are located north of the canyon (Text-fig. 1). Practically all younger Mesozoic rocks have been stripped from the Kaibab surface and are eroded back northward to the Utah state line and eastward to the Echo Cliffs.

Geologically, Lee's Ferry is in a rather unique position along the Colorado River. Throughout most of its course the river flows through deep canyons, but at Lee's Ferry the flexure in the Echo Cliffs Monocline causes the horizontal strata to bend down to the east, bringing the soft, easily eroded Moenkopi and Chinle Shales to river level. As a result no canyon is formed where the river crosses these rocks. Because of this the Lee's Ferry area has been an extremely important transportation route or crossroad throughout the history of northern Arizona, for it was here and only here that feasible crossings of the Colorado River could be made within distances of more than 300 miles. Downstream the only realistic crossing used by the early pioneers was beyond the Grand Canyon at Pierce Ferry near the present Lake Mead. At least one crossing was made with wagons at "Hole in the Rock," where early Mormon pioneers lowered their wagons by rope over the steep vertical cliffs of the Navajo Sandstone. "Hole in the Rock," however, never did become a feasible crossing. It is perhaps by chance that the early Catholic fathers, led by Father Escalante in 1776, were unable to find the Lee's Ferry crossing of the Colorado River and crossed upstream north of Page. Lee's Ferry crossing was not known by the early pioneers until the 1850's when Jacob Hamblin discovered this important point. Later John D. Lee was sent here to maintain a ferry route for Mormon pioneers and colonizers going southward into Arizona from Utah. This particular point offered the only feasible crossing for automobiles until the Navajo Bridge was constructed. (The bridge was built in this area because any other point along the Colorado River would have required a fantastically great effort to construct a crossway to span the canyon.) Even today there are still only three places within several hundred miles from here where one can cross the Colorado River with an automobile. These are at Boulder Dam, Glen Canyon Bridge, and Hite, Utah.

The Grand Canyon cuts a gorge over a mile deep through the northern end of the flat-topped Kaibab Plateau (Text-fig. 1) and exposed a cross section of the earth's crust which, for completeness of exposures and spectacular geologic features, is probably unexcelled in the world. All of the Paleozoic strata beneath the Kaibab Plateau are well exposed in the canyon walls. In addition, large areas of the basement complex of Early and Late Precambrian rocks, upon which the younger strata lie, can be seen in the lower part of the gorge. Nearly 5,000 feet of sedimentary rocks overlie the Kaibab Limestone in southern Utah and are exposed in a sequence of terraces and platforms which ascend up to the high plateaus of Utah near Bryce Canyon (Text-fig. 1).

Paleozoic rocks form the upland of the Marble Platform, the Kaibab and Coconino Plateaus, the walls of Marble Gorge, and the upper two thirds of the walls of Grand Canyon and erode to form the colored cliffs and slopes that produce much of the scenic grandeur of the Grand Canyon. Excellent, though often inaccessible, exposures of the Paleozoic Formations can be seen in the canyon. Trails such as the Bright Angel or Kaibab trails offer limited access. These rocks may be best examined along the defile of the Colorado River through the Marble Gorge. On a float trip one descends through the entire sequence and can observe each formation in the walls of the canyon.

THE RIVER

From Lee's Ferry to Lake Mead the Colorado River flows through Marble Canyon and Grand Canyon, a distance of 285 miles. In traversing this distance it falls from an elevation of 3,090 feet at Echo Cliffs to 870 feet at Lake Mead. The average gradient is approximately 7.7 feet per mile, or more than 25 times that of the Mississippi River. The depth and width of the canyon through which the river flows are directly related to height of the Kaibab Plateau above the river. The Grand Canyon was cut by the Colorado River through the Kaibab Plateau during great earth movements which elevated this plateau as the stream sawed through the rising blocks to maintain its constant gradient.

From Lee's Ferry to Phantom Ranch the canyon cut by the Colorado River is separated into two natural divisions. For the first 52 miles the gorge of the Colorado is relatively narrow. This section, from Lee's Ferry to Nankoweap Canyon, was named "Marble Canyon" by Powell because of the thick limestone cliffs which form its vertical walls. The second division is that developed in Grand Canyon National Park and is named the "Grand Canyon Section." Here the gorge opens to over 12 miles wide and one mile deep and is floored by rounded, rolling hills with a steep inner gorge. This difference in the two divisions is related to uplift on the East Kaibab Monocline.

The natural flow of the Colorado River has been checked by construction of dams upstream so that now the discharge varies only slightly. Before construction of the dams, however, the stream ranged from 1,300 to 300,000 second feet of water with an average of approximately 23,000 second feet. Depth of the river averages 50 feet and widths of 300 to 400 feet are common. During floods, before construction of the Glen Canyon Dam, the river is reported to have risen 50 or 60 feet; in exceptionally narrow channels rises of 100 feet were noted.

RAPIDS

Rapids in the Colorado River between Lee's Ferry and Lake Mead have long been a favorite of "white water" enthusiasts. There are 161 rapids in the Colorado River in the Grand Canyon region; approximately one half of these are between Lee's Ferry and Phantom Ranch (see Tables 1, 2).

Rapids and falls in most rivers are produced by resistant rocks which project above the general gradient of the stream. A fall is produced, for example, as water cascades over the resistant dolomite lip of Niagara Gorge. With the vast differences in profiles formed on rocks within the Grand Canyon, one would expect rapids or waterfalls to develop over the alternating resistant and nonresistant units. One would expect that rapids might form over the Tapeats

Table 1

RATING OF RAPIDS IN THE GRAND CANYON (Modified from Jones 1962)

Numerical Designation	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(10) +
Description	Riffle	Light		Medium			Heavy			Maximum Recommended	Not Recommended
Number of Rapids	78	22	13	17	17	6	6	1	2	3	1

Table 2

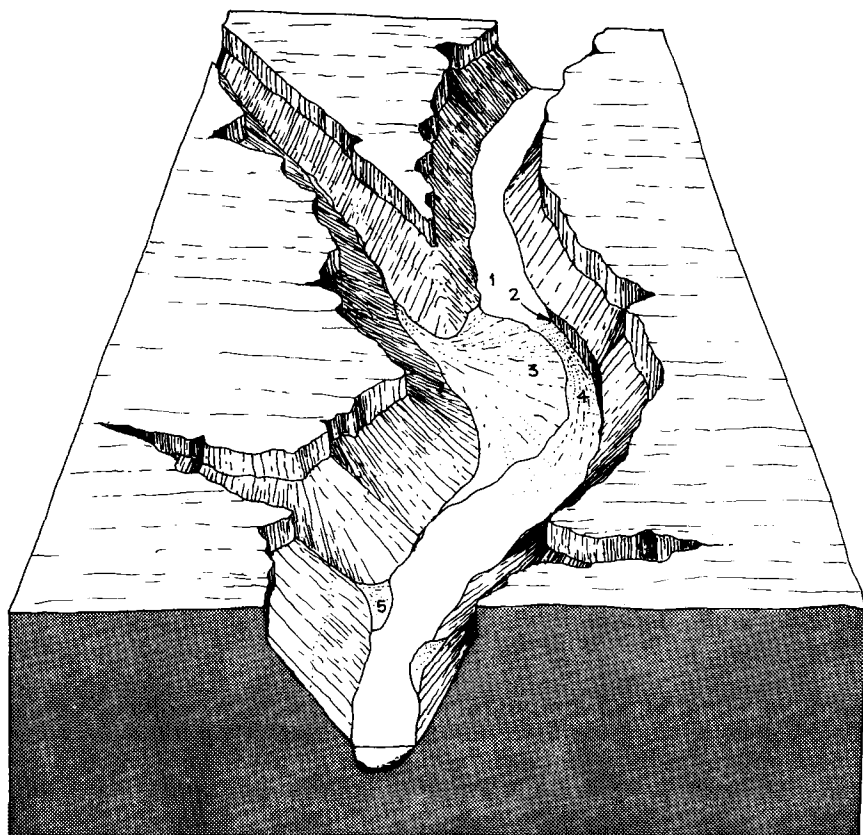
RAPIDS FROM LEE'S FERRY TO PHANTOM RANCH (Modified from Jones 1962)

MILE	NAME	RATING	DROP
7.8	Badger	(7)	15'
11.2	Soap Creek	(8)	17'
14.4	Sheer Wall	(7)	8'
17.0	House Rock	(7)	10'
18.5	Boulder Narrows	(1)	3'
20.5	North Canyon	(5)	12'
21.2	Twenty-one Mile	(5)	5'
24.5	Tanner Wash	(8)	9'
25.0	Twenty-five Mile	(6)	8'
25.5	Cave Springs	(5)	6'
26.0	Twenty-six Mile	(2)	4'
26.7	Twenty-seven Mile	(5)	7'
29.0	Twenty-nine Mile	(4)	7'
43.7	President Harding	(4)	4'
52.0	Nankoweap	(3)	25'
56.0	Kwagunt	(4)	7'
65.4	Lava Canyon	(3)	4'
68.5	Tanner Canyon	(6)	20'
72.4	Unkar	(10)	25'
75.2	Seventy-five Mile	(6)	15'
76.5	Hance	(11)	30'
78.6	Sockdolager	(8)	19'
81.5	Grapevine	(10)	18'
83.6	Eighty-three Mile	(6)	7'
84.6	Zoroaster Canyon	(5)	5'

Sandstone, the Redwall Limestone, and Coconino Sandstone with relatively smooth quiet water on the Hermit and Bright Angel Shales. This is not the case, however, for the gradient of the Colorado River is relatively smooth and consistent across all of the formations from Lee's Ferry to Grand Wash Cliffs at Lake Mead. There is no single place on the river where differential erosion of bedrock has produced a resistant ledge sticking above the gradient of the stream bed to produce falls or rapids.

Without exception rapids in the Grand Canyon are produced by debris from tributary streams which have partially choked the main channel of the Colorado River (Text-fig. 2). These fans of debris at the mouths of tributaries form virtual dams across the river while the rapids are produced at the overflow point in the main channel.

Abnormally steep tributaries are able to transport huge boulders and great quantities of erosional debris down into the Colorado River at a rate far greater than the river is able to move them on downstream. One can see on aerial photographs (Text-figs. 3, 14), as well as on the ground, the accumulation of this debris at the mouth of practically every tributary regardless of apparent size. Badger Creek Rapids, one of the first rapids to be encountered, is approximately eight miles downstream from Lee's Ferry and illustrates this point very well (Text-fig. 2). Large boulders and blocks up to 15 feet in diameter have accumulated at the mouth of Badger Creek and partially obstruct the channel of the river, causing a steep drop over the edge of the "dam." This pattern is typical of the entire length of this section of the Colorado River Gorge, where even minor tributaries have developed rapids. Partial blocking of the stream commonly ponds the river to develop areas of abnormally quiet water for a mile or two upstream above each major rapids—the "calm before the storm."



TEXT-FIGURE 2.—Block diagram showing the origin of rapids in the Colorado River. Broad fans of coarse debris accumulate at the mouth of steep tributaries and partially obstruct the flow of the main river. 1, quiet water; 2, cut face; 3, 5, debris fan; 4, rapids.

Size of the rapids varies somewhat from year to year with the amount of debris brought in by flash floods. In 1966 an abnormally intense cloudburst on the North Rim in the national park caused flash floods to occur along Bright Angel Creek and Crystal Creek, several miles on downstream. The debris brought into the gorge constructed new fans and greatly modified and intensified the rapids. Some rapids thus can be drastically altered after a single storm while others may be little affected over a number of years. Erosion by the Colorado River then wears down and removes debris with a tendency toward obliterating and smoothing out the irregularities in gradient which cause the rapids. This, however, is seldom if ever accomplished because new material usually is brought in before the older debris can be removed.

Before construction of Glen Canyon Dam near Page, Arizona, the flow of the river through the Grand Canyon was greater than at present. It will be interesting to note during the coming years the effect that this decreased flow will have upon the development of the rapids. One would expect that the small debris fans built up at the mouths of tributaries will grow very large in



TEXT-FIGURE 3.—Vertical aerial photograph of the Lee's Ferry area. The deep entrenched lower section of Glen Canyon is in the Navajo Sandstone and is shown in the upper half of the photograph. The Paria River flows along the strike of the Chinle Shale and has built a small debris fan in the vicinity of Lee's Ferry. Boats are launched at the upper end of the fan. A resistant ridge, dipping upstream, near the boat landing in the center of the photograph, is held up by the Shinarump Conglomerate which overlies the chocolate brown Moenkopi Formation that shows as dark gray in the central part of the photograph. The Kaibab Limestone is exposed near the river in the lower right corner of the photograph.

the future. This is because the small discharge of water down the Colorado River may be unable to accomplish the normal removal of sediments. The net effect will probably be that of making all of the rapids within the Grand Canyon and Marble Gorge more severe with time. It is not unlikely that some of the more active tributaries could bring down enough debris to completely dam most of the flow of the Colorado River for a short time, forming a temporary lake upstream.

Even within Granite Gorge, where extremely hard crystalline rocks are exposed, there is no evidence at present to suggest rapids forming by any process other than that described above. This process may seem rather unlikely since most of the tributaries of the Colorado River are dry most of the year. It should be remembered, however, that influx of sediments by tributary streams is a very intermittent process. It is usually accomplished only during major flash floods, at which time great quantities of debris are transported and dumped into the Colorado River in a matter of a few hours. When the boatmen stop to survey a course through the rapids, examine the size of boulders and blocks which have accumulated at the mouth of the tributaries, and imagine the force of the water necessary to bring this material down side canyons to the debris fans. Such periodic erosion and transportation is a fundamental process in arid regions and is most vividly displayed here in the Grand Canyon.

Aboriginal Cultures of the Grand Canyon

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Even though much of the Grand Canyon seems inhospitable for human habitation, several Indian groups of the past made use of the area. The earliest human occupation is evidenced by over 100 split-twigg figurines found in caves scattered throughout the canyon. Although the figurines have not yet been associated with other ancient cultures, radio-carbon age determinations of organic materials found with the figurines fix the date of the culture that made them between 1600 and 1200 B.C. Peculiarly, the caves in which the figurines occur are only found between 4,000 and 5,000 feet, the boundary between Lower and Upper Sonoran life zones. The reason figurines were left in caves of this zone and why the figurines were made in the first place remains a mystery.

Table 3
Cultural Periods of the Southwest
Anasazi Culture

Periods	
Pueblo IV	1300 A.D.
Pueblo III	1100 "
Pueblo II	900 "
Pueblo I	750 "
Basketmaker III	450 "
Basketmaker II	100 B.C.

The next human inhabitants, for whom we have evidence, are represented by Basketmaker II Period (Table 3) remains. They mark the beginning of Anasazi culture in the Grand Canyon. These Basketmakers were early horticulturalists who obtained knowledge of corn and squash planting from other Indians who were in contact with Mexican cultures. It is thought that the Basketmakers, previous to their acquisition of domestic plants, were southwestern foragers seeking small game and wild food plants. Acquisition of domestic plants permitted a more sedentary way of life with house and village building, and new tools were demanded because of horticultural activities, but the gathering of wild plants and the hunting of small game continued.

Basketmaker II Period sites excavated in the Grand Canyon show circular semisubterranean houses; cache pits in the floors, evidence of baskets, sandals, bone awls, and stone spear points.

The later Basketmaker III and following Pueblo I Periods (A.D. 450-850), which introduced pottery manufacture in this part of the Southwest and which developed a sound horticultural system, have not yet been found in the Grand Canyon.

The Pueblo II Period culture (A.D. 900-1100) expanded into all of the lands of the Grand Canyon where horticulture could be practiced. This culture also merged with that of the Cohonina, south of the confluence of the Little Colorado and Colorado Rivers. Sites representing the Pueblo II Period show rectangular, above-ground, coursed-stone houses; similarly constructed granaries tucked up in cliffs; and subterranean religious structures called kivas. Distinctive pottery black-on-white decorated, plain white, and corrugated types. Bows and arrows, small stone arrow points, irrigation works made of stone, and corn grinding stones are also characteristic, along with cranial deformation in humans.

Horticulture during this period was the mainstay of economy whereas hunting and gathering activities were supplementary. In addition to corn and squash, beans and cotton were grown. The domestic turkey was also raised.

The later Pueblo III Period (A.D. 1100-1300) is barely represented in the canyon and general abandonment of the canyon took place by 1150 A.D. It is thought that the expansive Pueblo II Period culture may have over-exploited the canyon's resources which could not support intensive horticultural practices.

Present-day Indians, such as the Yuman Havasupai, Ute, Paiute, and Hopi, exploit canyon bottom lands, utilize about 400 wild species of flora for food and medicine, and hunt wild game from the canyon.

Archaeological sites representing the Anasazi culture can be seen today in the following tributary canyons: Cataract Creek, Shinumo Creek, Bright Angel Creek, Clear Creek, Nankoweap Creek.

Biological Features of the Grand Canyon at River Level

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The Grand Canyon is, at first impression, so preeminently a geological phenomenon, that one tends to relegate living organisms and biological processes to a position of little importance in the overall scheme of things. Upon further observation, however, it can be seen that, as is true of any other habitat or environmental complex, the living organisms are responsible for considerable modification of the canyon ecosystem. Living things are not merely passive

acceptors of the environmental conditions in any given area; they actively participate in changing the physical circumstances under which they live and grow. Therefore the plants and animals of the Grand Canyon are not simply interesting additions or sidelights to the geological phenomena, but are in fact active molders, if only on a reduced scale, of the canyon scene.

The plants and animals of the canyon should be considered along with their physical environment as constituting a series of living communities in dynamic equilibrium with the environment and with each other. As environmental conditions change through time or space the plant and animal components of the region also change. This can be readily discerned in the Canyon area because of the vast difference in elevation between the river level and the canyon rims. A number of environmental gradients exist as a result of this altitudinal difference. These gradients include differences in precipitation, temperature, evaporation, light, air currents, soil types, and a number of other factors which we generally consider physical or chemical aspects of the environment. The result is that as we trace the living communities upward from river level to the top of the canyon, we find that entirely different assemblages of organisms are occupying these various altitudinal levels. This observation led C. Hart Merriam of the U. S. Biological Survey to develop an early (1894) theory of ecological zonation based on his studies in the Grand Canyon district. Merriam's "life zones" were based almost entirely on temperature criteria and tended to equate the altitudinal changes in community composition to the changes occurring on a latitudinal basis in the North American continent, beginning with the arid Sonoran deserts in the south and culminating with the arctic tundra. Although the "life zone" concept has become rather firmly entrenched in biological literature relating to the Grand Canyon, it would be more accurate to disregard Merriam's terminology and recognize that the changes in community composition along the altitudinal gradients are based upon a complex of environmental factors; local differences in microclimate and microhabitat promote a considerable degree of intermingling and interdigitation of community components.

A "river run" through the Grand Canyon provides an opportunity to observe at close hand the plants and animals characteristic of the deeper, more arid parts of the canyon. The presence of the river modifies the arid conditions along the banks of the stream and frequently promotes the development of a streamside community which is markedly different in species composition from the surrounding desert communities. At Lee's Ferry the streamside thickets consist primarily of willows, some poplars, and dense stands of *Tamarix*, a species introduced from the Old World within historic times, which has now become widespread in aquatic situations throughout western North America. A short walk through this streamside vegetation will usually provide ample evidence of the presence of beavers, mostly in the form of felled willows or cottonwoods. Beavers live in bank lodges along the river and are evidently maintaining healthy populations wherever there is adequate vegetation.

The Colorado River itself provides a habitat for a variety of aquatic organisms, although the high turbidity of the water precludes the growth of most aquatic plants. The invertebrates and fishes of the Colorado are therefore primarily dependent upon organic detritus as a basic food source, rather than the conventional food base of green plants. The generalized food chain relationship is therefore as follows: organic detritus is consumed by invertebrates and small detritus-feeding fishes; these in turn are consumed by the smaller

predatory fishes, which in turn are eaten by the larger species of predaceous fishes. There may be a further "link" in the food chain in that the larger fishes may in turn be preyed upon by fish-eating birds or mammals (including man!). The species composition of the fish populations in this section of the Colorado River has undergone drastic changes within the last few decades, owing primarily to the construction of dams and impoundments along the course of the river. Many species that were originally endemic or "native" to the Colorado River were adapted specifically to the swift, turbulent waters occurring here; this included such interesting forms as the Colorado River squawfish (largest member of the minnow family in the world) and the bonytail chub. The construction of dams and their resulting impoundments has resulted in the loss of appropriate habitat for these endemic species which are rapidly disappearing over most of their former range. Environmental conditions have now shifted in favor of such introduced "sluggish water" species as catfish, bass, and a number of small bait fishes.

The river traveler should bear in mind that between Lee's Ferry and the head of Lake Mead the Colorado will accomplish a descent of some 2,000 feet. The accompanying physical and climatic changes, with an overall trend towards greater aridity, produce marked differences in the communities of living things that may be observed in the canyon depths. The changes occur so very gradually that one is not aware of any abrupt transitions, however. In addition to the streamside thickets mentioned previously, the conspicuous woody plants growing in the river bottoms of Marble Canyon are wavy-leaf oak, Fremont Mahonia (a shrub with holly-shaped leaves which is closely related to the ornamental Oregon Grape), squaw bush, coyote bush, and a number of characteristic desert shrubs of the goosefoot and composite families. About midway through Marble Canyon mesquite becomes a common species and in places forms nearly closed stands.

Among minor communities of ecological interest are the "hanging gardens" which form in alcoves of the canyon walls, particularly in the Redwall Limestone. Excellent examples can be seen at the Royal Arches, Mile 41.5. The hanging gardens owe their presence to moisture seeping to the surface along permeable zones in the limestone. The additional moisture permits such plants as ferns, columbines, monkey flowers, and even orchids to grow in what would otherwise be for them an impossible environment. Wherever waterfalls or large springs emerge from the canyon walls, a similar increase in the luxuriance of the vegetation occurs. An outstanding example in the upper canyon is at Vasey's Paradise, Mile 32, where the large discharge of a series of springs provides moisture for a profusion of grasses and flowering plants.

Even the austere depths of the inner Granite Gorge are by no means devoid of life. Conspicuous among the plants growing on the substrate of weathered schist and granite are yuccas, agaves, *Ephedra* ("Mormon tea"), and a variety of cacti. Because of the steep cliffs in the inner gorge, there is little or no development of streamside vegetation. At elevations lying generally below the 2,000 foot contour, the plant communities become increasingly more typical of the low, arid deserts. The shrubby vegetation now consists mainly of such forms as creosote bush, burro bush, ocotillo, cholla, yucca, barrel cactus, fishhook cactus, beavertail cactus, and several other "hot desert" forms.

In reference to the vertebrate inhabitants of the inner canyon, the principal groups with good representation are the mammals, birds, and reptiles. The larger mammals include the mule deer (which is more frequent near tributary

canyons leading to higher elevations, desert bighorn sheep, and burro. The latter species is not, of course, native to the area; the burros living in the canyon today are descendents of animals which escaped from domestication. Just what effects these herds of feral burros are having upon the natural plant communities is not completely known at present. There is also an abundance of smaller herbivorous mammals, but because of their nocturnal habits their presence and importance is not generally appreciated by the casual visitor. The major carnivores or predatory mammals would include occasional cougars, coyotes, bobcats, foxes, and the ring-tailed "cats," which are not feline but are actually closely related to the raccoons.

The bird fauna of the canyon is characterized by a number of summer resident species which breed in the streamside vegetation and by a variety of migrant waterfowl and shorebirds present in the spring and fall. Perhaps no one species is more symbolic of this region than the Canyon Wren, whose characteristic descending trill can be heard echoing from the canyon walls nearly anywhere along the river. Some fish-eating birds are apt to be encountered, notably the Great Blue Heron and one or more species of mergansers ("fish ducks").

Reptiles are well represented, particularly the lizards which are generally more diurnal than the snakes and are represented by a greater number of species. Utas, whiptails, and collared lizards are the more prominent species. The most distinctive reptile of the canyon is undoubtedly the subspecies of rattlesnake known as the Grand Canyon rattler. The pinkish hue of the skin closely approximates the color of the pink granite or red sediment found in the inner gorges, but whether or not this is an authentic case of an adaptation representing concealing coloration is not certain.

River Log

W. KENNETH HAMBLIN AND J. KEITH RIGBY

Mile O. LEE'S FERRY.—From the vicinity of the boat landing of Lee's Ferry one can see several prominent geologic and scenic features of northern Arizona. To the east, upstream, the mouth of Glen Canyon opens upon the broad surface of the Marble Platform. To the south the Echo Cliffs form the bold escarpment. To the west the Vermillion Cliffs rise above the Chocolate Cliffs and form the skyline beyond the campground. To the northwest the Paria River Valley is entrenched in soft, colorful shales. The prominent cliffs behind the old buildings at the ferry site are at the junction of the Vermillion and Echo Cliffs.

The tortuous meandering Colorado River in Glen Canyon has cut a deep vertical-walled gorge in the Navajo Sandstone and clearly shows on the aerial photograph and topograph maps (Text-fig. 3). Exposures in the cliffs east of Lee's Ferry are the youngest rocks to be seen on the river trip. From here downstream the Colorado River encounters older and older rocks until it reaches the ancient metamorphic sequences of Granite Gorge.

Topographically Lee's Ferry is at the junction between the Vermillion Cliffs, which stretch from here westward almost to Nevada, and the Echo Cliffs, which trend southward to the vicinity of Cameron. Each of the cliffs have different structural settings, although they form on the same rock sequence. Strata in the Vermillion Cliffs to the north and west dip gently to the north, whereas

the Echo Cliffs are controlled by the north-south trending Echo Cliffs Monocline where the beds dip steeply eastward. U. S. Highway 89 to the south, as well as to the west, is located along the slopes formed on the Moenkopi and Chinle formations and all transportation routes, both ancient and modern, have been largely restricted in this part of the plateau.

Although the recent history of the Colorado River has been mainly that of erosion, evidence of stream deposition can be seen in the gravel-capped terraces just west of Lee's Ferry in the campground area. Most of these gravels represent erosional debris derived from the Colorado Rockies, hundreds of miles upstream.

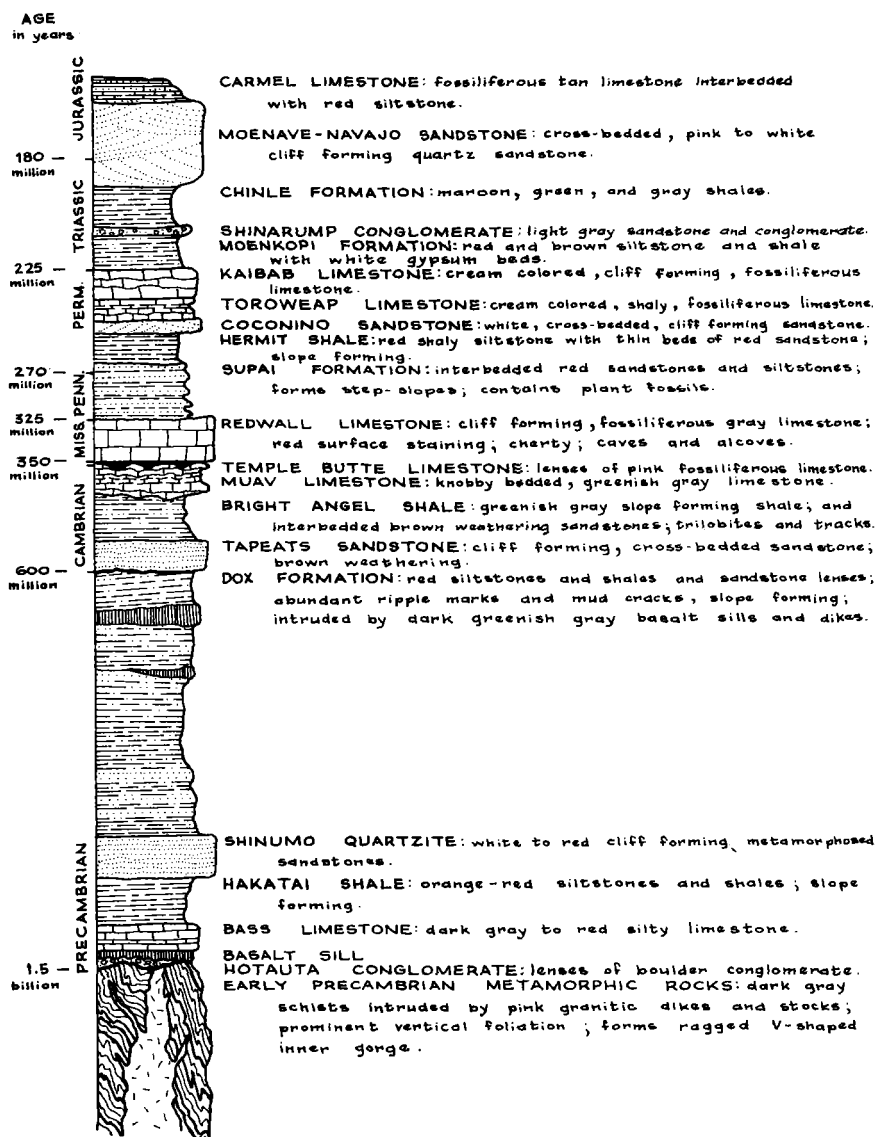
The flexure of the Echo Cliffs Monocline is well illustrated at Mile O, just downstream from Lee's Ferry, where the resistant Shinarump caprock above the Moenkopi Shale dips to the east at an angle of more than 15 degrees. Less than a quarter of a mile downstream from Lee's Ferry the grade of the old road used at the time of ferry operation can be seen ascending the red Moenkopi slope. The cut is a distinct dugway supported by fill in many places along the slopes.

From Lee's Ferry to the Grand Canyon the course of the Colorado River is typically that of a meandering stream in many places. This pattern is formed, only on streams of low gradient which flow over a relatively homogeneous, gently sloping surface. The pattern is typical of a sluggish stream in which little downcutting occurs. It is apparent that the meandering pattern in the Colorado River was formed at a time when conditions were much different from those that we see today. The original surface must have been one of little relief with no canyons. Gradual uplift permitted erosion of deep canyons and resulted in entrenchment and preservation of the ancient pattern of meanders (Text-fig. 3 and 32). This pattern is similar to that found in the Goosenecks of the San Juan River in Utah.

The Paria River to the northwest is cut along the easily eroded Moenkopi Shale that forms the chocolate, castellated surface below the first prominent ledge. Variegated pink, green, maroon, and gray bentonitic shales above the Shinarump Conglomerate north of the boat landing are in the Chinle Formation. These grade up to a series of thick-bedded, massive, windblown sands which form the overlying vertical cliffs. The Navajo Sandstone on top of the cliffs is the formation in which Zion National Park has been cut and the same rock units seen at Capitol Reef National Monument and throughout much of the canyonlands in Utah.

SEQUENCE OF ROCKS

Rocks of this part of the Colorado Plateau can be subdivided into four thick, distinctive groups or sequences. The upper, youngest sequence is of Mesozoic age and is exposed around the northern and eastern margin of the Grand Canyon district up to 75 miles back from the canyon rim. These rocks were deposited during the Age of Dinosaurs, during an interval of 60 to 230 million years ago. The second major sequence is of Paleozoic age. It is exposed as horizontal beds in the Marble Gorge region and on the walls of the Grand Canyon. These rocks were deposited in a variety of environments, ranging from shallow ancient seas to vast deserts, and cover a time span from 230 to 600 million years ago. The third major sequence occurs below Paleozoic rocks and is exposed only as isolated beds in the lower part of Grand Canyon. It is the thickest sequence and was deposited during Late Precambrian time, 600 to 1,500 million years ago. The fourth great group of rocks are of Early



TEXT-FIGURE 4.—Sequence of rock formations exposed in the vicinity of Lee's Ferry and Grand Canyon.

Precambrian age and are now exposed only in Granite Gorge of the Grand Canyon. They are over 1,500 million years old and have been intensely deformed and altered by heat and pressure. These are the oldest rocks known in the Grand Canyon and among the oldest known rocks of the earth's crust. Descriptions of each rock unit is included in the river log as the unit is encountered on the trip.



TEXT-FIGURE 5.—Remains of early buildings at Lee's Ferry site.

Excellent exposures of the Mesozoic sandstones and shales are seen in the Vermillion and White Cliffs which parallel U. S. Highway 89 below the Kaibab Plateau eastward from Jacob's Lake to Lee's Ferry and southward to near Cameron, Arizona. One therefore has a chance to examine this sequence of strata, as Lee's Ferry is approached from either direction, and to become familiar with a considerable thickness of rock which lies directly above the formations exposed in the canyon.

The Mesozoic rocks are divided into eight formations, most of which are readily distinguishable at Lee's Ferry by development of a prominent cliff or slope plus a distinctive color (Text-figs. 3, 6). It is the Mesozoic sequence which provides much striking scenery and color to the landscape of the region north and east of the Marble Platform.

NAVAJO SANDSTONE (JURASSIC)

One of the most prominent and distinctive formations in the Colorado Plateau is the massive Navajo Sandstone. It weathers into nearly vertical cliffs and dominates the landscape wherever it is exposed. In the vicinity of Lee's Ferry the Navajo Sandstone is approximately 1,400 feet thick and caps the high Vermillion and Echo cliffs behind the boat landing (Text-fig. 3). Exposures of the formation are abundant throughout much of the Navajo country to the northeast. In Utah the Navajo Sandstone forms the prominent White Cliffs north of Kanab and the walls of Zion Canyon. Precipitous canyons controlled by joints (fractures) (Text-fig. 3) are cut into most exposures of the formation and produce some of the most rugged and spectacular scenery of the West.

Large scale cross-bedding characterizes the Navajo Sandstone wherever it is exposed. Many outcrops contain some of the most spectacular development of this structure to be found anywhere in the world.



TEXT-FIGURE 6.—View of the Colorado River and Vermillion Cliffs downstream from the landing of Lee's Ferry. The low cliffs to the left are developed on the resistant Shinarump Conglomerate which also caps the Chocolate Cliffs beneath the major escarpment of the Vermillion Cliffs in the background and the right of the photograph. Rocks as young as Carmel Limestone are exposed on the Vermillion Cliffs near the skyline.

Navajo Sandstone consists of well-sorted, rounded grains of translucent quartz, many of which are etched and frosted. This, together with the large-scale cross-bedding, indicates that the Navajo sediments accumulated in a vast desert which covered much of Utah, Arizona, and New Mexico during early Jurassic time.

Glen Canyon Dam is built in the vertical gorge cut through the formation by the Colorado River.

KAYENTA FORMATION (JURASSIC-TRIASSIC)

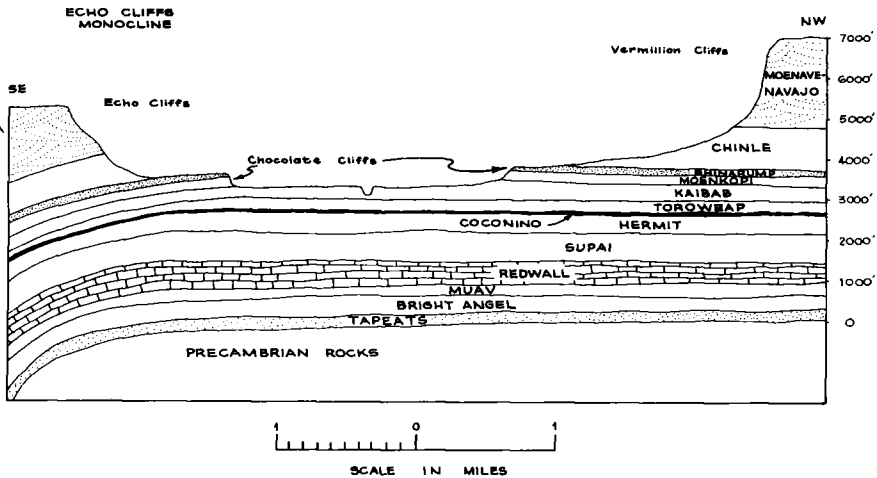
The Kayenta Formation is approximately 400 feet thick and consists of a fine-grained sandstone interbedded with layers of siltstone. The alternation of these units generally produces a series of ledges and slopes between the cliffs of the Navajo and Moenave formations. Dinosaur tracks are fairly common in the siltstone, and fresh-water mussels and snails occur but are rare. The Kayenta Formation is colored pale red and adds to the splendor of the Vermillion Cliffs. It accumulated as deposits of rivers.

MOENAVE FORMATION (TRIASSIC)

The Moenave Formation is a cliff-forming unit which forms part of the bold escarpment of the cliffs surrounding Lee's Ferry. It overlies the soft colorful Chinle Shale and is characterized by various shades of red, orange, and reddish brown. It consists of lenticular beds of sandstone and is the lowest of three formations in the surrounding prominent cliffs. The Moenave Formation is approximately 350 feet thick near Lee's Ferry and represents sediments deposited by stream systems over a low-lying land.

CHINLE FORMATION (TRIASSIC)

The Chinle Formation consists of a relatively thick sequence of shales which display a variety of brilliant colors ranging from blue, purple, green, pink, gray, maroon, to brown. It weathers into a slope which is carved into an intricate network of gullies and forms typical badlands. West of Lee's Ferry most of the Chinle Formation is covered with



TEXT-FIGURE 7.—Cross section showing the structural and stratigraphic relations near Lee's Ferry as viewed downstream. Echo Cliffs Monocline forms the flexure in the rocks to the left. The sequence of rocks below the river will be encountered through Marble Gorge and in Grand Canyon National Park.

erosional debris from the overlying cliffs, but southward toward Cameron, Arizona, large areas of the formation are exposed and the unit forms one of the most colorful and distinctive formations in the region. Low, dome-shaped hills commonly develop on the Chinle Formation and are almost devoid of vegetation, so that the multicolored nature of the rocks is exceptionally well displayed.

Southward, in Arizona, the formation forms the famous Painted Desert, and fossil wood and plant remains are abundant in Chinle beds in the Petrified Forest. The formation contains some of the best preserved and most colorful fossil wood in the world. The Chinle is also noted for its important uranium deposits.

SHINARUMP CONGLOMERATE (TRIASSIC)

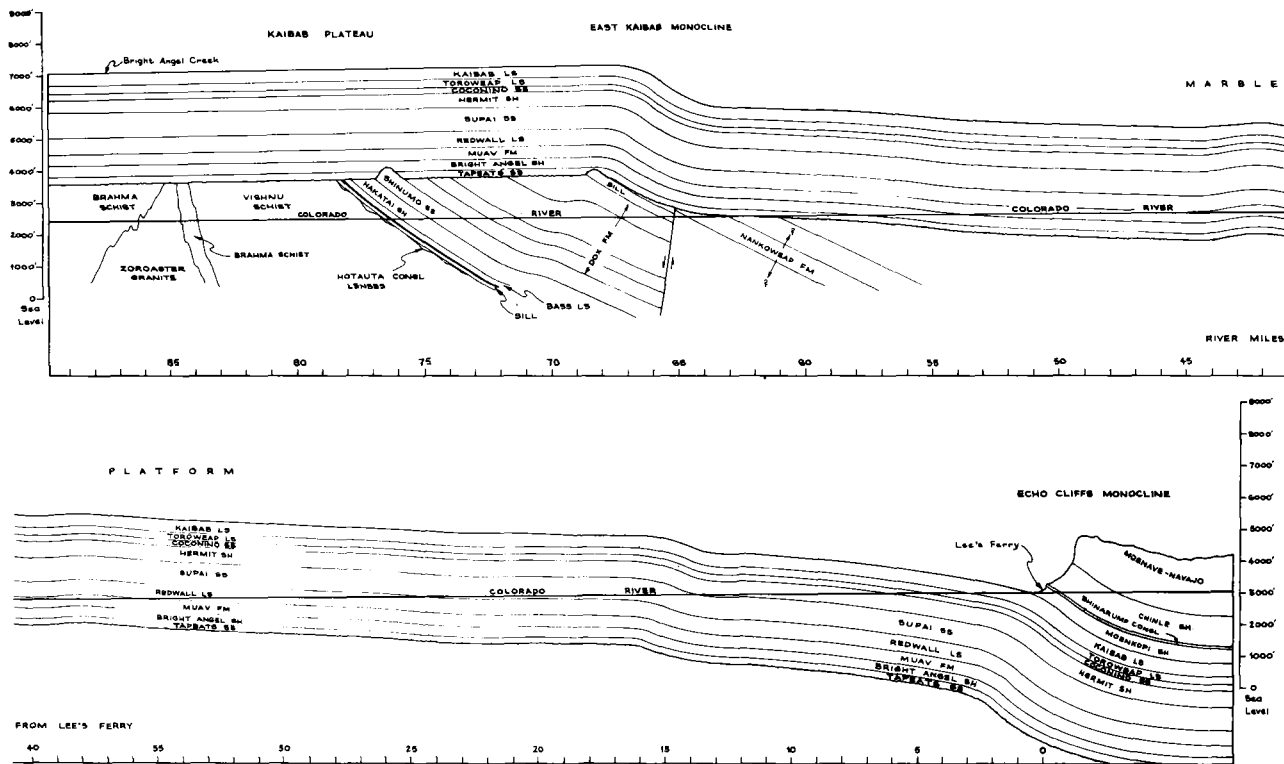
A relatively thin resistant formation of coarse sand and gravel known as the Shinarump Conglomerate overlies the soft, chocolate-colored Moenkapi Formation and forms a vertical cliff ranging from 50 to 100 feet high. The formation is well known in the Colorado Plateau area for its uranium and fossil wood. The Moenkapi and Shinarump exposures together are commonly referred to as the Chocolate Cliffs. Excellent exposures are seen near the Arizona-Utah state line south of Kanab, Utah. In the vicinity of Lee's Ferry the Shinarump Conglomerate is inclined 15 degrees to the east and dips below the level of the river a few hundred feet west of the boat landing.

Shinarump beds consist of well-rounded, well-sorted pebbles of quartz and chert averaging less than an inch in diameter. Medium-to coarse-grained sand is also a major constituent and in many places the entire formation is made of sand. Fossil wood is locally abundant and is commonly mineralized with yellow carnotite and other uranium minerals. Much of the Shinarump Conglomerate is thought to have been deposited in stream channels.

MOENKAPI FORMATION (TRIASSIC)

The Moenkapi Formation consists of many thousands of layers of dark, reddish brown shale and siltstone with a total thickness of 200 feet in the vicinity of Lee's Ferry. These rocks rest directly upon the hard, cliff-forming Kaibab Limestone, but because they are soft and easily eroded they have been stripped back away from the canyon rim several tens of miles, leaving a bare surface on the Marble Platform.

The Moenkapi Formation is easily recognized by its chocolate brown color, and in the vicinity of Lee's Ferry it forms the gentle slopes and low cliffs in the vicinity of the



TEXT-FIGURE 8.—Cross section of the rock sequence along the river from Lee's Ferry to Phantom Ranch.

campground. One of the most obvious characteristics of the formation is the thin horizontal stratification so prominently displayed wherever a fresh surface is exposed. Close examination of these strata will reveal numerous ripple marks and mud cracks indicating deposition in shallow water. Many tracks and trails of reptiles have also been found in Moenkopi beds. A prominent zone of white gypsum alternates with thin layers of typical reddish brown siltstone to form a very colorful unit in the upper part of the formation.

Geologists consider the Moenkopi to represent deposition in a large tidal flat environment, with the open sea located westward in Nevada. Gypsum in the upper part is the result of evaporation and indicates an arid climate in the region during Moenkopi time.

The lack of canyon development on the Colorado River here at Lee's Ferry is largely the result of the soft Moenkopi and Chinle beds brought down to river level on the Echo Cliffs Monocline.

One encounters the Kaibab, Toroweap, and Coconino formations (Text-fig. 4) in very rapid succession downstream from Lee's Ferry. These formations usually are distinct rock units expressed in the canyon by topographic differences. However, here in upper Marble Canyon, they have not been etched into differential relief and appear almost as a single massive wall. This is due, at least in part, to the shallow depth and narrowness of the canyon.

Mile 0.5.—The old dugway and the rip-rap bouldered support of old U. S. Highway 89 (until 1929) can be seen on the southeast side of the river (Text-fig. 9). At the first riffle white gypsum stringers show very well in the Moen-



TEXT-FIGURE 9.—Old dugway on the south side of the Colorado River leading from the Lee's Ferry landing up to the Marble Platform. This road was the main north-south route between Utah and northern Arizona for many years until Navajo Bridge was constructed in 1928.

kopi beds in the middle part of the unit. Gravels of the Paria River can be seen on the north side and are like the gravels of the terrace at the picnic grounds.

Mile 1.0.—THE KAIBAB FORMATION APPEARS AT RIVER LEVEL AT APPROXIMATELY MILE 1, just below the first minor rapids, opposite the picnic grounds, below the ferry landing. The Kaibab, Toroweap, and Coconino formations form the prominent, nearly-vertical walls of Marble Canyon from here downstream beyond Navajo Bridge. Distinction between these formations (which are so obvious in the walls of the Grand Canyon National Park area are not easily made in Marble Canyon. It is therefore difficult for the beginner, in some cases, to pick out contacts or boundaries between these three major rock units.

KAIBAB AND TOROWEAP FORMATIONS (PERMIAN)

The Kaibab and Toroweap Formations form the uppermost 500 to 700 feet of strata exposed in the canyon walls southwest from Lee's Ferry (Text-figs. 7, 10) and constitute the surface upon which the Kaibab Plateau on the north and the Coconino Plateau and Marble Platform on the south are carved. Thus, where they form the rim they are the most widely exposed formations in the Grand Canyon region. In the eastern part of the canyon the Kaibab and Toroweap limestones are separated by a thin, sandy zone which tends to form a slope, so that these two rock formations are generally expressed by two separate cliffs.

Both formations are characteristically well bedded, as seen in many of the outcrops in the Marble Gorge. When viewed from a distance, however, stratification is generally obscure. There are variable amounts of sandstone and chert in the Kaibab Formation, but the dominant rock type is limestone. The limestone is a creamy, yellow-gray although parts of it may be stained reddish gray from interbedded colored sandstone and siltstone units. Many marine fossils are found in both the formations. More than 80 genera of invertebrate fossils are represented plus a few fossil fish teeth. Where chert is abundant it generally occurs as nodules and may superficially appear as small boulders and gravel. Many of the spherical nodules are cored by fossil sponges.

The Kaibab and Toroweap Limestones form a near-vertical wall immediately below the Moenkopi Formation and are seen at river level the first few miles of the trip. Downstream they form the uppermost cliff which rims the entire canyon

Mile 1.5.—The top of the cream-colored Kaibab Limestone shows very well on the east side of the river beneath the red Moenkopi Shale. Ripple-marked sandstones characterize the upper beds of the unit. The massive upper limestones are very cherty. Solution features show fairly well as enlarged joints within the Kaibab Formation. Just around the bend, downstream from Mile 1.5, small flexures can be seen where minor reversals of dip occur at about the Kaibab-Toroweap boundary.

Mile 1.7.—THIN-BEDDED SANDY TOROWEAP FORMATION APPEARS AT RIVER LEVEL. Around the bend at Mile 1.8 the Kaibab forms an upper silty slope and a thick, well-bedded, lower ledge zone. Sandy gray, relatively thin beds of the Toroweap appear at river level.

Mile 1.9.—Silty banks from high water of the Colorado River can be seen at about river level. These terraces mark one of the maximum high points of river rise before construction of Glen Canyon Dam upstream.

Prominent fractures can be seen within the Kaibab. Black shiny coating, termed "desert varnish," shows in the upper part of the Kaibab. This results from capillary action which brings iron and manganese to the surface where they are oxidized to form a black, shiny film. Kaibab in here is stained pinkish by the overlying Moenkopi.

Mile 2.0.—The effects of the Echo Cliff Monocline (Text-figs. 7, 8) have diminished so that for the next several miles the river flows through almost horizontal strata.

Mile 2.7.—Small ripples at the mouth of one of the tributary canyons from the west. Here Toroweap beds comprise the lowermost 50 feet of the canyon wall.

Mile 3.0.—Small flexures show in the Kaibab and Toroweap, bringing the upper beds of the Toroweap close to river level. These are small folds parallel to the East Kaibab Monocline (Text-figs. 1, 7, and 8).

Mile 3.2.—Reverse drag on a small fault in the Kaibab and Toroweap Formations. This fault is parallel to the Echo Cliffs Monocline. The first view of the west abutment of Navajo Bridge can be seen on downstream.

Mile 3.9.—SMALL CLIFFS ON THE EAST SIDE ARE COMPOSED OF THE TOP BEDS IN THE COCONINO SANDSTONE.

COCONINO SANDSTONE (PERMIAN)

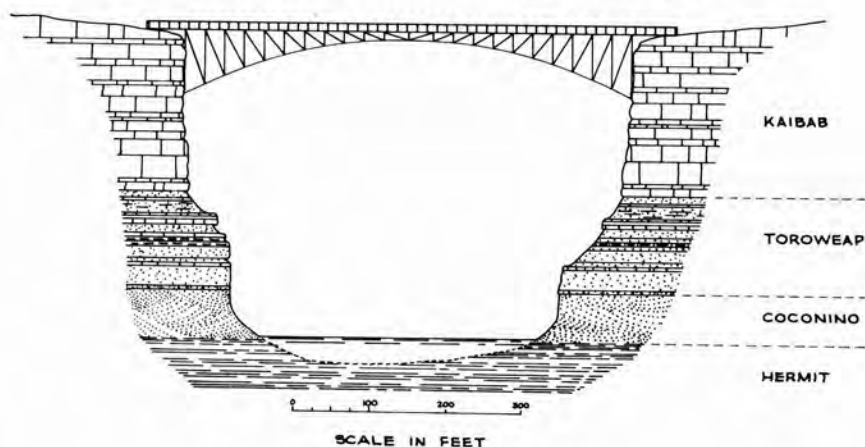
The Coconino Sandstone is the prominent, white-colored, homogeneous cliff-forming formation beneath the Kaibab and Toroweap Limestones. It is one of the most distinctive and homogeneous formations throughout the Grand Canyon. But in the eastern part, near Marble Gorge, it is very thin and is poorly expressed. It commonly almost blends with the Kaibab and Toroweap Limestones to form a single, unbroken cliff. It is characterized by fine-grained, almost pure quartz sand grains, which are well rounded, pitted or frosted, and show excellent sorting or sizing. The Coconino Sandstone is characterized by well-developed cross-stratification which is the most distinctive and conspicuous feature of the formation. The cross-strata are similar to that in the Navajo Sandstone and they develop low sweepingly inclined laminae, some of which are as much as 70 feet long. Such cross-laminated structure is typical of that found in modern sand dunes. Ripple marks are also preserved in many parts of the Coconino, as are a large number of fossil footprints. At least 22 varieties of fossil tracks have been found, all of which have been interpreted to have been made by reptiles. No other fossils or evidences of life have been found in the formation. The dune-like cross-stratification in the Coconino Sandstone, together with the reptile tracks and ripple marks, indicates that the sediments accumulated in a great desert. Its present distribution over 32,000 square miles has led many geologists to postulate a depositional environment similar to that of the present-day Sahara or Arabian Deserts.

Although the Coconino Sandstone is one of the most distinctive formations throughout much of the canyon where it forms a cream-colored white vertical wall, it is relatively inconspicuous in the Marble Gorge. It is not until some distance down the canyon that the Coconino Sandstone is expressed as a separate cliff, then it is the second cliff below the rim of the canyon.

Mile 4.0.—Excellent exposures of cross-bedded Coconino Sandstone can be seen near river level. The top of the Coconino forms the angular massive ledge with desert varnish four or five feet above the river.

Prominent landslide debris shows on the skyline to the south of a small creek that comes in from the west.

Mile 4.3.—PASS BENEATH NAVAJO BRIDGE (Text-figs. 10, 11, and 12). Coconino beds extend to about 20 feet above the river. The Toroweap forms the slope and lower ledge beneath the cliff of the Kaibab. The bridge made a roadway connection from northern Arizona to Utah and eliminated the necessity for the ferry. This was the main route of all north-south traffic through Arizona around the eastern edge of the Grand Canyon until the 1960's when the Glen Canyon Dam and the bridge near Page, Arizona, were completed. Most traffic now flows through Page.



TEXT-FIGURE 10.—Cross section showing the profile of the canyon and rock sequence exposed at Navajo Bridge. The Coconino Sandstone is exposed near water level and Kaibab and Toroweap formations form the nearly vertical cliffs.



TEXT-FIGURE 11.—View upstream along the Colorado River in the vicinity of Navajo Bridge. The Coconino Sandstone forms the lower cliffs and Kaibab Limestone caps the cliff at the abutments. Navajo Bridge was constructed in 1928 and constituted the major access way for traffic from northern Arizona into southern Utah until construction of the Glen Canyon Dam and the bridge at Page, Arizona.



TEXT-FIGURE 12.—Vertical aerial photograph showing the section of the Marble Gorge in the vicinity of the Navajo Bridge from Mile 2 to Mile 8. The tilted rocks of Mesozoic age along Echo Cliffs form the high ridge to the right. The red rocks of the Triassic, Moenkopi, and Chinle formations form the dark tones at the base of the cliff and in the upper left corner of the photograph. The light-toned rocks along the margin of the river are the Kaibab Limestone in the northeastern corner of Marble Platform. Note the increase in depth of the canyon from Mile 2 to Mile 8, as the river cuts down to lower and lower beds. U. S. Highway 89 trends north along the foot of Echo Cliffs and crosses the river at Navajo Bridge. Compare canyon depth in this figure with that of the long profile of Text-figure 8.

Old river travelers still tell of silver coins being thrown to them off the bridge as good-will gestures—gestures which punctured their boats below.

Notice here how the vertical walls of the Kaibab rise steeply from the rather quiet Colorado River. Even here occasional sandbars formed of material swept down stream from the Colorado Rockies accumulate in quiet waters along the shore.

Mile 5.2.—The lowermost cliff represents the total thickness of the Coconino Sandstone (Text-fig. 13) beneath which are exposed the upper beds of the HERMIT SHALE APPEARING AT RIVER LEVEL.

HERMIT SHALE (PERMIAN)

The Hermit Shale, a sequence of thin-bedded, red and maroon shales, siltstones, and fine-grained mudstones, occurs beneath the Coconino Sandstone (Text-fig. 4) and weathers to a continuous prominent slope. The entire formation is characteristically deep red and is responsible for much of the red staining of lower units in the Grand Canyon. Along the river the Hermit Shale is only 200 to 300 feet thick but in the western Grand Canyon it thickens to more than 900 feet.

Thirty-five species of fossil plants have been described from the Hermit Shale within the Grand Canyon region, many of which have not been found anywhere else in the world. These plants apparently represent a savannah-type environment with long, dry seasons.

Mile 5.8.—View downstream shows the upper Kaibab cliff, the Toroweap slope, the Coconino cliff, and the lower slope now carved on the Hermit Shale which is, in large part, veneered by boulders and debris from above. In this general vicinity Coconino Sandstone is only about 20 feet thick at the base of the lower cliff.



TEXT-FIGURE 13.—Rock sequence exposed in Marble Gorge one-fourth mile below Navajo Bridge. The upper cliff is largely Kaibab Formation with the slope and the upper half of the lower cliff in the Toroweap Formation. Coconino Sandstone forms approximately the lower half of the lower cliff near river level.



TEXT-FIGURE 14.—Vertical aerial photograph of Marble Gorge from Mile 7 to approximately Mile 14. Aerial photographs through the guide overlap slightly and give a complete coverage of the river from Lee's Ferry to Granite Gorge.

A debris fan built into the Colorado River by Soap Creek is expressed by the light tones in the center of the photograph. Smaller fans can be seen at Badger Creek, in the upper right-hand corner, as well as two minor tributaries approximately one mile below Soap Creek Rapids. The cliff on Kaibab, Toroweap, and Coconino formations can be seen at the canyon rim with slopes developed upon the Hermit Shale particularly well expressed in the vicinity of Soap Creek.

Mile 7.0.—Excellent exposures of the Hermit Shale can be seen beneath the fans of debris and on the east side of Badger Creek Rapids (Text-fig. 12 and 14). Here the opposing tributary valleys may be structurally controlled. Both valleys contribute erosional debris to produce the rapid down the center part of the gorge. Excellent exposures of Hermit Shale continue downstream with slopes partly veneered by debris from above.

Mile 7.8.—**BADGER CREEK RAPIDS (7) 15' DROP.** Badger Creek forms the first major rapid down river below Lee's Ferry and shows the characteristic relationship of the rapids to the coarse erosional debris brought in by tributary streams. The quiet water upstream from the rapids is typical. The banks are overgrown by sandbar willows and *Tamarix* in the quiet water areas. *Tamarix*, the feathery-appearing plant, was introduced into the area only a short time ago and now covers many of the softer sandy shores and marginal marshes of the Colorado River drainage.

Near Badger Creek Rapids, the profile of rocks consists of the Hermit Shale, which forms the slope at river level, overlain by the Coconino-Toroweap formations which form the first cliff followed by the Kaibab Limestone which forms the cliff that rims the canyon.

Exposures of the Hermit Shale are visible on the northeast side of Badger Creek Rapids. In this section of the canyon these more easily eroded siltstones and shales are characteristically blanketed by slope wash, which is an expression of the manner in which the canyon is being widened and deepened. Erosion by the river is mainly along its bed, but it is the slumping and down-slope creep of weathered boulders and blocks that fall from the canyon walls which widen the canyon by transporting debris to the river and thence to the sea.

Badger Creek at Mile 7.8 and Soap Creek at Mile 11.2 are two of the most vigorous rapids in the Marble Canyon area and it is commonly necessary to stop and check the best route for the boats to pass through the rapids. By chance there are important geologic contacts at both places. At Badger Creek Rapids contact of the top of the Hermit Shale and the base of the Coconino Sandstone can be observed, while at Soap Creek Rapids one can see the contact between the Hermit Shale and the underlying Supai Formation. The rocks are accessible for those interested in examining these contacts at the rapids stop.

Mile 9.6.—Large block of the Kaibab material in the channel. Excellent views of the Hermit Shale can be seen where the alluvial covers have been stripped away beneath the vertical cliff of Coconino, Toroweap, and Kaibab formations.

Mile 11.2.—**SOAP CREEK RAPIDS (8) 17' DROP.** Soap Creek Rapids, one of the most rigorous in the Marble Gorge, is a result of influx of sediments from Soap Creek (Text-figs. 15 and 16).

At Soap Creek the entire section of Hermit Shale is clearly exposed as a gentle slope midway up to the top of the canyon. The overlying Coconino, Kaibab, and Toroweap are welded together into one cliff-forming unit so that boundaries between these rock formations are not expressed physiographically (Text-figs. 16 and 17). The Hermit is characterized by alternating layers of shale and siltstone with horizontal stratification. The lower part of the Hermit contains more silt and therefore forms a series of ledges 10 to 20 feet thick. Most of the Hermit, however, contains little silt and so a gentle slope has developed throughout the upper three quarters of the formation.

One of the best views of the Hermit Shale is at Soap Creek Rapids where the entire formation is exposed. This is the last place where the Hermit beds



TEXT-FIGURE 15.—Running Soap Creek Rapids.

will be seen at river level and where it is readily accessible for hunting for fossil plants. Contacts between the formations are essentially planar. The Coconino is remarkably thin in this part of the canyon. It is estimated to be no more than 20 to 40 feet thick, but the Hermit is much thicker in the Soap Creek area than in the national park. At Soap Creek the elevation of the rim of the canyon is 4,100 feet and the river level is 3,025 feet to produce slightly more than 1,000 feet of relief to the canyon in this particular area. A few hundred yards downstream from Soap Creek Rapids is the TOP OF THE SUPAI FORMATION which appears as massive, light-colored, ledge-forming sandstones.

SUPAI SANDSTONE (PENNSYLVANIAN AND PERMIAN)

A sequence of thick-bedded sandstones, shale, and siltstone occurs beneath the Hermit Shale and has been named the Supai Sandstone. This formation characteristically erodes into step-like slopes with individual sandstone beds forming small, nearly vertical ledges and the interbedded shale eroding back to form small slopes. Throughout much of the park the Hermit Shale is considered only as the upper unit of the Supai Formation. In many places, especially where the Hermit Shale is thin, the contact between the Supai and the Hermit formations is difficult to identify, especially from a distance.

Supai rocks are red-colored in the main, and together with the Hermit Shale contain a number of fossil plants. Some fossil ferns and other primitive plants, together with numerous tracks of four-footed animals, constitute the only fossil remains found in the middle and upper part of the formation.

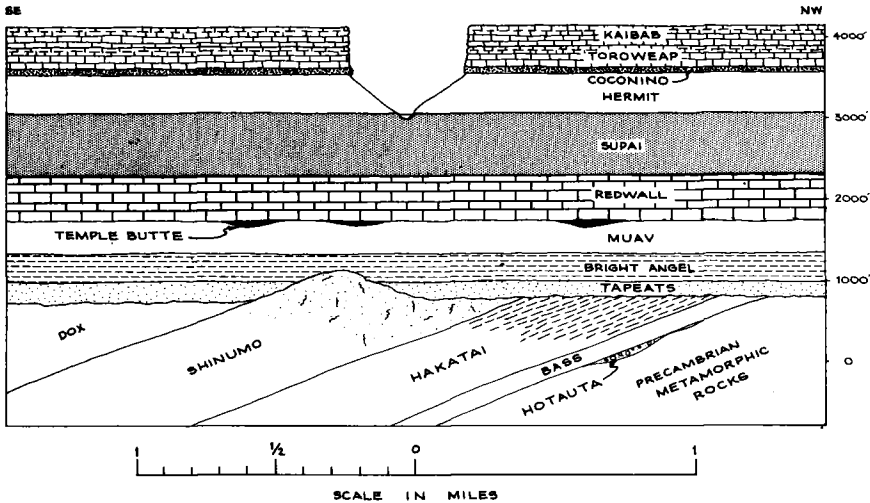
Lowermost Supai rocks in the western part of the Grand Canyon are composed of thin-bedded limestones which erode to form a rather prominent slope beneath the more



TEXT-FIGURE 16.—View across Soap Creek Rapids of the east canyon wall. Basal ledges at river level are on upper beds of the Supai Formation. The minor ledges and the slope of red or dark-toned Hermit Shale form the prominent break below the vertical cliff of Coconino, Toroweap and Kaibab formations. A segment of the broad debris fan of Soap Creek is in the lower left.

massive sandstone units of the main part of the formation. Marine fossils have been found only within the lenses of these lower limestone units. The Supai characteristically erodes to a nearly vertical wall in the Marble Canyon area where it forms an inner gorge to the canyon below Soap Creek Rapids (Text-figs. 18, 19, 20, and 21).

The character of the canyon changes markedly immediately below Soap Creek because resistant Supai Sandstone forms vertical walls through which the Colorado River has cut an impressive channel (Text-figs. 18, 19, and 20). Erosion in the Supai Formation produces a rugged, rather jagged, irregular wall here in contrast to the smooth walls of the Redwall Limestone downstream and the Kaibab Limestone upstream. Good views of upper Paleozoic strata, including the Kaibab-Toroweap cliff and a very well-expressed slope on the Hermit Shale, can be seen within this stretch of the canyon.



TEXT-FIGURE 17.—Cross section showing the canyon profile and rock sequence exposed at Soap Creek Rapids. Compare this cross section with Text-figure 16.

Mile 12.0.—Two ledges of cross-bedded white sandstone can be seen in the upper part of the Supai Formation beneath the overlying red Hermit Shale. Basal beds of the Hermit are channeled and form a semi-ledge zone above the cross-bedded Supai sandstone.

Mile 13.0.—The river begins to cut through the Supai Formation just below Soap Creek Rapids, and in several places it has begun to undercut, forming overhanging cliffs on the formation. Well-expressed cross-stratification is shown throughout the Supai Sandstone, particularly where it is cleanly exposed at river level.

One can observe numerous circular potholes cut in canyon walls of resistant sandstone. Potholes are formed where gravels accumulate in a natural depression in the river bed. The gravel fragments are swirled around by current action. The gravel fragments wear a hole down into the rock, holes in which larger boulders in turn act as a major cutting tool of the river. Boulders trapped in the potholes do not escape but are finally ground down to small particles.

Mile 13.8.—Excellent potholes can be seen in the massive cross-bedded sandstone of the upper part of the Supai Formation in the sheer canyon walls just upstream from Shear Wall Rapids. Excellent festoon cross-bedding can be seen in the massive angular ledges of sandstones which form the steep, inner gorge. Much desert varnish is developed on some of the massive sands particularly at river level.

Mile 14.0.—The whitecaps of Shear Wall Rapids can be seen jumping above the generally smooth, serene surface of the river.

Mile 14.4.—SHEAR WALL RAPIDS (7) 8' DROP. Boulders are strewn through the somewhat irregular channel. The river continues on below Shear Wall Rapids through the Supai Formation.



TEXT-FIGURE 18.—View down the canyon at Mile 14.3. Ragged ledges of the upper Supai Formation form the steep-walled inner gorge with the overlying slope in the thick Hermit Shale. The Coconino, Toroweap, and Kaibab formations form the vertical cliff on the skyline. Small, well-defined potholes are visible in the Supai Formation along both sides of the canyon wall.

Mile 16.3.—Cross-bedded lower part of the Supai Formation first appears above river level beneath the light-colored cliffs of the upper part of the formation. The lower Supai is largely fine-grained sand but still forms the characteristic step-slope topography. The steep-walled inner-gorge and overlying slope developed on the Supai and Hermit Formations show well in the canyon profile (Text-fig. 21). Compare this profile with that at Navajo Bridge where only the upper cliff-forming formations are exposed.

Mile 17.0.—HOUSE ROCK RAPIDS (7) 10' DROP. Here the river is pushed by a debris fan in close against the ledges of Supai Formation where the sandstone and the red silty character can be seen, hopefully not too close at hand.

House Rock Creek has brought in exceedingly coarse boulders of Supai and overlying formations. Should the boatman stop to survey the course to be taken through the rapids, examine rocks on the shore, because here Coconino, Kaibab,

and Supai fragments can be identified. Examination of boulders brought down Rider Canyon will reveal fossils from the Kaibab Formation.

Mile 18.0.—The lower Supai is expressed as alternating light-colored cross-bedded sandstones separated by softer, brick-red units in a rather characteristic cyclic sequence consisting of (1) light-colored, cross-bedded sand, (2) even, horizontally bedded sand, (3) a weakly cross-bedded sand with silt, and (4) an uppermost slope-forming red silty unit. This is repeated several times in the lower Supai.

Mile 18.5.—An exceptionally large block from the Supai has rolled into the middle of the river and caused the channel to bifurcate (Text-fig. 19). This block was originally part of the large landslide mass which only recently broke away from the canyon wall. This is one of the larger blocks observed in the Colorado River along its entire course.

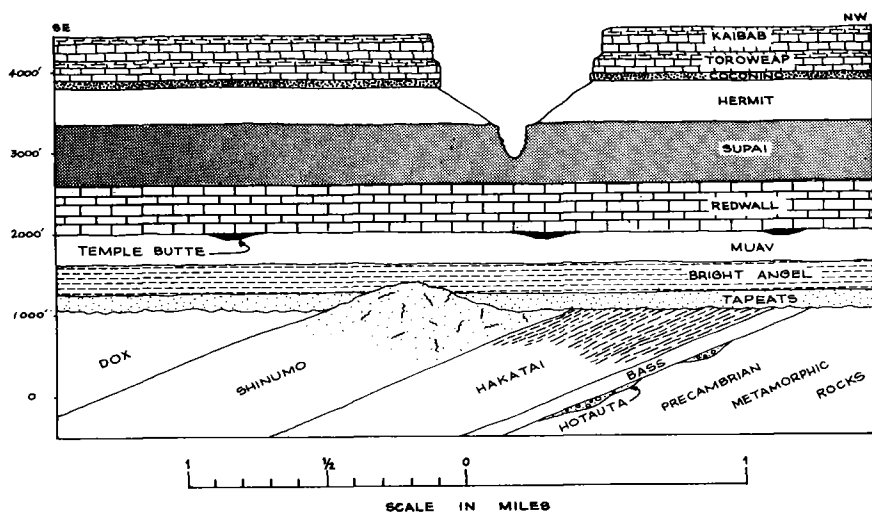
Mile 19.0.—One can see the beginning of distinct differentiation between the Kaibab and Toroweap sequence, which upstream has been generally expressed as a single cliff. Here a very definite slope forms in the middle of the uppermost cliff reflecting the upper member of the Toroweap.



TEXT-FIGURE 19.—View downstream at approximately Mile 18.5. Large tumbled block of Supai Sandstone partially obstructs the Colorado River. Ragged ledges of the upper Supai beds form the inner gorge with a slope formed on the overlying Hermit Shale. The Coconino Sandstone is differentiated as the lower half of the lower ledge; the Toroweap Formation is divisible into a lower cliff and an upper slope zone. The Kaibab Limestone forms the cliff on the skyline.



TEXT-FIGURE 20.—Vertical aerial photograph from Mile 13 to approximately Mile 20. House Rock Creek is the major tributary from the left and has developed a small debris fan into the Colorado River which produces House Rock Rapids. The surface on Marble Platform is on the top of the Kaibab which has been stripped of all overlying formations. The large block of Supai Sandstone shown in Text-fig. 19 can be seen as a black dot near Mile 18.5. An inner gorge is developed in the Supai Formation, with an overlying slope on the Hermit Shale and the cliff rim formed on the Kaibab, Toroweap, Coconino sequence. A profile through this area is shown in Text-fig. 21.



TEXT-FIGURE 21.—Cross section showing the rock sequence and canyon profile in the vicinity of House Rock Rapids. The inner gorge forms on the resistant Supai Sandstone. The overlying slope is on the Hermit Shale and the vertical cliff in the upper one third of the profile is developed on the resistant Kaibab, Toroweap, and Coconino formations. Text-figs. 7, 10, 17, and 21 show a very close relationship between the resistant nature of the rocks and development of the canyon profile. Where only the Kaibab and Toroweap Formations are exposed, Marble Canyon consists of a steep, nearly vertical walled gorge. Where a significant section of the weak Hermit Shale is exposed the canyon is much wider, with well-developed slopes beneath the upper cliffs. A lower, steep inner gorge is formed where the Supai is encountered.

A number of important variations occur within the stratigraphic sequence not heretofore seen along the river. The basal Supai is well expressed and forms a very definite step-slope characterized by thin bedding in contrast to thicker beds of sand which form the upper part of the formation.

The Coconino Sandstone is 4 to 5 times thicker here than at Soap Creek. It is a sheer wall generally covered with a dark desert varnish. Between Mile 19.9 and Mile 22.2 several faults cross the river.

Mile 20.5.—NORTH CANYON RAPIDS (5) 12' DROP. Thin beds of white limestone appear in the lower part of the Supai Formation at river level. Inner gorge developed in the Supai Formation is well expressed (Text-fig. 22).

Mile 21.2.—TWENTY-ONE MILE RAPIDS (5) 5' DROP.

Mile 21.5.—Numerous small ripples across debris fans. The fractured nature of the canyon wall is related to a strong joint system developed parallel to minor faults.

Mile 22.2.—Reverse drag shows on the downthrown western block in the Supai Formation. Some trails in and out of the river are along fault zones which have broken cliff-forming units. This gives relatively easy access to the canyon rim. One could climb out of the river here with some difficulty along the faults. The fault produces some of the rough topography at the bend in the river. Mile 22.2 is the last place where the Supai Formation is seen at river level.



TEXT-FIGURE 22.—Vertical aerial photograph showing the segment of Marble Gorge from Mile 20 to Mile 26. The large tributary in the upper part of the photograph is North Canyon. Tiger Wash is a smaller tributary near the lower left corner of the photograph. Debris fans are built up by even the very small tributaries. This perspective shows the vertical cliff which forms the rim of Marble Gorge carved on the Kaibab, Toroweap, and Coconino formations approximately 1 mile below North Canyon. The slope developed on the Hermit Shale is expressed on the aerial photograph by a delicate network of drainage lines. The underlying ledge-slope which forms the inner gorge is developed on the Supai Formation.

Mile 22.5.—The step-slope on the Hermit Shale shows above the massive Supai cliff. The basal sandy beds of the Hermit Shale can be seen grading into the underlying Supai beds.

Mile 22.6.—FIRST GRAY BEDS OF THE REDWALL LIMESTONE APPEAR AT RIVER LEVEL as medium and thin-bedded units which form the walls of the river gorge below the red Supai rocks. Base of the Supai Formation is very shaly and forms a slope zone on top of the more resistant, greenish and grayish pink ledges of the Redwall Limestone.

REDWALL LIMESTONE (MISSISSIPPIAN)

The Redwall Limestone is one of the most distinctive and prominent formations within the Grand Canyon. It characteristically weathers into an unbroken vertical cliff more than 500 feet high, stained red from the overlying Hermit and Supai formations. The Redwall cliff is located almost midway between the river and the canyon rim in the national park area and is responsible for many of the majestic alcoves, mesas and buttes within the canyon proper. It weathers and erodes into a vertical cliff in Marble Gorge and has been polished by water action of the river. Powell was impressed at this sight and called this a marble, naming this section of the canyon Marble Canyon.

The Redwall Limestone is medium gray on fresh exposures but is colored by a superficial red stain derived from the overlying formations. It is characteristically well bedded; but, when viewed from a distance it appears almost as a single massive unit, because the subtle divisions between strata are not etched out in sufficient relief to be seen from the canyon rim. In many places, especially in the lower part of the Redwall Cliff, beds of bright red jasper are found, some of which are semiprecious gem quality. The Redwall Limestone is a very pure calcium carbonate rock containing less than one percent sand and shale particles. Its origin is as interesting as its topographic expression. The pure limestone indicates that it was formed in a relatively wide, shallow, quiet sea, far from shale and clay deposition near the shore. Fossil sea shells and a wide variety of other marine life including common corals are found within the Redwall Limestone. Most of the fossils are preserved in remarkable detail.

The Redwall Limestone is susceptible to much solution activity by groundwater and has produced numerous caves, solution caverns, arches, and springs within the canyon. In several places these solution features give rise to a number of important springs like those of Vasey's Paradise, where large quantities of water can be seen issuing forth from springs high on the cliff face midway in the formation.

Mile 23.0.—Recent river silts can be seen on both sides of the canyon. These are 20 to 25 feet above the river level and represent pre-Glen Canyon Dam high-water stands.

Mile 23.4.—Polished Redwall Limestone exposed along both sides of the gorge 20 to 30 feet above the river level. Swell and swale, or broad, small anticlinal and synclinal structures, appear near river level. These outcrops show the thin-bedded nature of the limestone which is not expressed well in the park on down river.

Mile 24.5.—TANNER WASH RAPIDS (9) 9' DROP. Upper contact of the Redwall Limestone with the overlying Supai Formation is exposed in the vicinity of the Tanner Wash Rapids. Since it may be necessary to beach the boat to plan a course through the rapid, one again has the opportunity to examine rock types at a contact zone.

The river erodes deeper and deeper into the Redwall Formation along the stretch of the river below Tanner Wash Rapids. The Redwall Limestone seen here consists of remarkably well-bedded, gray-brown limestone. The red stain of the surface is derived entirely from iron oxide washed down from the overlying red Supai and Hermit Formations.

Tanner Wash Rapids has been one of the very rough rapids of the Marble Gorge section of the river. Powell posted and lined these rapids in 1869. Two men from the Stanton party were lost here in 1889. Bert Loper upset here in 1949 and was never seen again.

Mile 25.0.—TWENTY-FIVE MILE RAPID (6) 8' DROP. An excellent cavern, developed along a joint system, with a trend approximately 90 degrees to the river, can be seen on the south side of the river in the Redwall Limestone.

Mile 25.5.—CAVE SPRING RAPID (5) 6' DROP.

August 9, 1869—And now, the scenery is on a grand scale. The walls of the canyon, 2,500 feet high, are of marble, of many beautiful colors, and often polished below by the waves, or far up the sides, where showers have washed the sands over the cliffs.

At one place I have walked, for more than a mile, on a marble pavement all polished and fretted with strange devices, and embossed in a thousand fantastic patterns. Through a cleft in the wall the sun shines on this pavement, which gleams in iridescent beauty. (Powell, 1875, p. 75.)

Mile 26.0.—TWENTY-SIX MILE RAPID (2) 4' DROP. Approximately 200 yards downstream from Mile 26 a number of other small solution cavities can be seen in the upper Redwall rocks. This zone in the formation appears to be particularly susceptible to solution activity, for small caves occur on both walls of the gorge.

Mile 26.6.—Solution features are well developed on the basal part of the exposed Redwall Limestone. Note the thin bedding with alternating light gray and dark gray limestone. The lower half of the Redwall cliff is scrubbed clean and the surficial red stain is removed so that one can see excellent stratification consisting of alternating light and dark gray limestone units two feet thick. The upper part of the cliff is still red, however, stained from the overlying Supai and Hermit formations. Some of the bedding planes appear stylolitic, even from a distance. Solution not only has followed the vertical joints but has also developed along stratification.

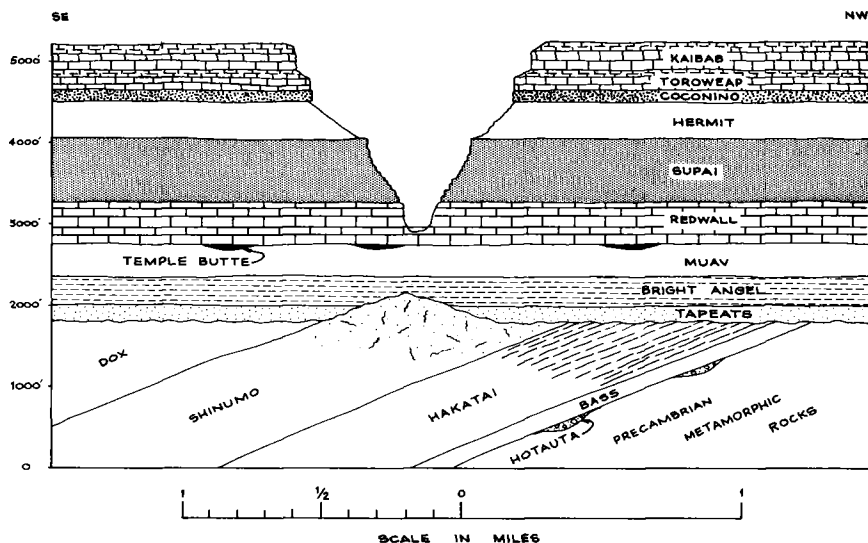
Mile 26.7.—TWENTY-SEVEN MILE RAPIDS (5) 7' DROP. Nature of the Redwall Limestone is well exposed especially on the left side of the canyon where the red stain colors the massive wall brilliantly. In many places stream action has produced a polished surface on the Redwall in this area.

Mile 27.7.—Small rapids. Notice the very narrow tributary canyon through the Redwall cliff through which most of the debris has been transported. Locally, heaps of debris have been thrown over the sheer wall from hanging-type valleys. Notice how the floors of tributary streams are polished and how joints are expressed in some units in the Redwall but not in others.

Mile 28.0.—From Mile 28 downstream to the base of the Redwall Limestone, the profile of the canyon near the river is dominated entirely by the steep, sheer cliffs of the massive limestone. One has the impression of being in an inner gorge within the canyon (Text-fig. 23).

Tops of the canyon walls, approximately 2,000 feet above the river, can be seen around river bends in this vicinity. Thus one is here over 2,000 feet stratigraphically beneath rocks exposed at Lee's Ferry.

The boundary between rocks of Pennsylvanian and Mississippian ages (Text-fig. 4) is here drawn at the top of the Redwall Limestone, where the



TEXT-FIGURE 23.—Cross section showing the profile and sequence of rocks exposed at Mile 28. The canyon here is 2,300 feet deep. The river has cut through the entire Supai Formation and well into the underlying Redwall Limestone to form a lower, vertical-walled inner gorge. The canyon profile has thus evolved from a gorge with vertical wall at Navajo Bridge to one consisting of a series of cliffs and slopes. Compare Text-fig. 23 with Text-figs. 7, 10, 17, and 21.

vertical wall breaks into the step-slope topography of the overlying Supai Formation.

Mile 29.0.—TWENTY-NINE MILE RAPIDS (4) 7' DROP.

Mile 30.2.—Small rapids. One could possibly climb over the Redwall cliffs because the sheer wall is broken by several faults. There are graveled access roads to the rim on the east side of the gorge between Mile 31 and 35 (Text-fig. 24).

Mile 31.4.—Breccia-filling and some cavern collapse rubble are evident within the Redwall Limestone. Solution features are controlled in large part by the prominent joint pattern.

Mile 31.7.—VASEY'S PARADISE.

Riding down a short distance, a beautiful view is presented. The river turns sharply to the east, and seems inclosed by a wall, set with a million brilliant gems. What can it mean? Every eye is engaged, every one wonders. On coming nearer, we find fountains bursting from the rock, high overhead, and the spray in the sunshine forms the gems which bedeck the wall. The rocks below the fountain are covered with mosses, and ferns, and many beautiful flowering plants. We name it Vasey's Paradise, in honor of the botanist who traveled with us last year. (Powell 1875, p. 76.)

The Redwall Limestone like many other limestone bodies is susceptible to solution by groundwater. Here at Vasey's Paradise is a spectacular display of groundwater activity. It is shown as the springs gush from cave systems within



TEXT-FIGURE 24.—Vertical aerial photograph showing a segment of Marble Gorge from Mile 27 to Mile 34. South Canyon is the major tributary from the west. The large tributary from the east is Shinumo Wash. Unpaved roads show well in the southeast and lead to Cedar Ridge at the base of Echo Cliffs Monocline. The canyon at Vasey's Paradise has an elevation of 2,785 feet. Elevation of the rim is 5,200 feet. The profile of the northwest wall of the canyon is exceptionally well expressed from this perspective and shows the alternating cliffs and slopes developed upon the rock sequence by differential erosion. Near the lower part of the photograph at the meander bend the inner gorge is cut through the resistant Redwall Limestone which is expressed as a vertical cliff. (See text-fig. 26.)



TEXT-FIGURE 25.—Vasey's Paradise—The springs issue from solution caverns within the Redwall Limestone and provide water for the luxurious vegetation below.

the Redwall cliff. The water permits a lush growth of vegetation clinging high upon the cliffs and the gentle slopes below. The amount of water fluctuates greatly depending upon the season and the amount of rainfall. Upwards of several thousands of gallons per minute have been seen issuing from these solution caverns. Very seldom are they dry (Text-fig. 25).

Upstream approximately one third of a mile from Vasey's Paradise is a tributary canyon from the north called Paradise Canyon or South Canyon. This is the place where Stanton and his party made an exit after a rather catastrophic attempt on the canyon from Lee's Ferry. Their objective was to survey a water-level railroad route down through the Colorado River Canyon to California. They abandoned the idea only after two attempts on the river failed.

Indian ruins, plus some skeletal remains and pottery sherds, can be seen by a short hike up Paradise Canyon. Indians apparently had access to the river through Paradise Canyon at this locality and did considerable farming on the beaches and sandbars in this area.

The Colorado River gorge at the base of Paradise Canyon is 2,500 feet deep.

Mile 32.0.—In the canyon walls much chert can be seen in the lower part of the Redwall Limestone beneath the alternating tan and light gray unit. This ribboned part is exposed well in the vicinity of Vasey's Paradise (Text-fig. 26).

Mile 33.1.—REDWALL CAVERN. Redwall Cavern is a large solution cavern exposed near river level and was named by Powell on his expedition down the Colorado. Stanton cached his supplies and equipment in the cavern just before leaving the Colorado Gorge via Paradise Canyon, upstream a mile. The cavern was thought to have been excavated by the Colorado River undercutting the relatively easily eroded Redwall Limestone; but it is only one of a number of large solution caverns developed at this horizon, many of which are high above the river. Numerous marine fossils can be seen in walls of the cavern and in blocks



TEXT-FIGURE 26.—Redwall cliff near Mile 32 showing the nature of the Redwall Limestone where it is exposed near river level. Although the Redwall Formation appears as a single massive unit throughout much of the park area, intricate details of stratification are seen where polished by river action. Red staining of the upper part of the formation is derived from the Hermit Shale and obliterates much of the structural detail visible at river level.

that have fallen from the roof. The floor of the cavern is now blanketed with soft sand, although in the past the cavern must have been swept clean since it was subjected to flooding during periods of maximum water. This stretch of the canyon, where the Redwall Limestone is at river level, is particularly serene and very impressive, in part due to the sheer, unbroken vertical cliffs which form the gorge (Text-figs. 26 and 27). Redwall Cavern is one of the unique landing spots along the route of the Colorado River.

It is much larger than one would expect from viewing it upstream. It is largely filled with sand at the present time and is above the levels of fluctuation of water coming from Lake Powell. Major Powell camped here at Redwall Cavern and had considerable apprehension about the safety of his men and boats because it was clear that this cavern had been flooded by high water from the river.

From a geologic standpoint it is very interesting to note the intricate internal structure of the Redwall Limestone consisting of relatively thin beds and lenses of light colored chert which are highly irregular. Downstream from Redwall



TEXT-FIGURE 27.—Entrance to Redwall Cavern seen downstream from near Mile 33.



TEXT-FIGURE 28.—View upstream from inside Redwall Cavern. Roof of the cavern is essentially flat and has developed largely from collapse. Numerous fossils can be found in the limestone material.

Cavern the lower part of the Redwall Formation exhibits an undulatory structure similar to minor anticlines and synclines. These could very well be primary features such as giant ripples. One of these large ripple-like structures can be seen at the western margins of the cavern itself.

Upstream from Redwall Cavern the upper member of the Toroweap forms a very prominent slope. The Coconino is at least as thick as the Toroweap, and, although it cannot be distinguished easily by its physiographic expression, desert varnish and broken joints are largely restricted to the Coconino Formation in this area.

Although details of the configuration of the channel below river level are not definitely known, at Redwall Cavern, in all probability, the channel has a relatively flat bed and vertical walls so the depth of water would increase very rapidly from shore.

The entire sequence of Paleozoic strata above the Redwall beds can be seen clearly expressed in alternating cliffs and slopes. The uppermost cliff consists of the Kaibab Formation, the unit which was bedrock at the surface at Lee's Ferry. The second cliff is formed on the Toroweap and Coconino formations;

the underlying Hermit Formation is expressed in a slope, covered partially with talus debris; the third cliff is formed in the Supai Sandstone; and the lower Supai beds form a step-slope unit. The Mississippian Redwall Limestone forms the high vertical wall of the inner gorge.

The area from Redwall Cavern downstream to Mile 36 presents one of the finest displays of solution activity to be seen on the trip. Literally hundreds of large caverns are exposed in the canyon wall. Many of these have been filled with collapse debris, whereas others are only partially filled or empty. Control of the solution caverns is exerted by both vertical joints and selected bedding planes.

Mile 34.0.—The lower unit in the Redwall is exposed at river level. It has thicker beds and occurs below the giant ripples. Several members of the Redwall can be recognized: (1) the lower 40 feet, (2) a middle unit of 40 feet with ribboned bedding (light to dark gray), (3) the candy-striped (red, brown, and gray) beds of about 80 to 100 feet thick, and (4) the massive upper part of the limestone near the top of the Redwall cliffs.

The most spectacular development of Marble Gorge is from Redwall Cavern downstream. Almost the entire thickness of the Redwall is exposed and forms vertical cliffs which plunge straight down into the river so that there is no shore developed whatsoever.

Redwall beds are particularly interesting because of the interbedded chert or jasper in the lower part of the cliff. Chert is a prominent part of the rock and can be noted in many areas along the river banks. In places it is expressed by dark, thin-bedded lenses, but one can observe masses which are a brilliant red.

Powell referred to the rocks exposed in the canyon as marble. The limestone is far from being a marble but where the river and water have polished the Redwall beds they have a smooth surface and high luster.

Mile 34.8.—Opposite a minor tributary from the south there is a truly exceptional exposure of an ancient solution cavern filled with collapse material. This cavern would be 50 to 60 feet wide and possibly 30 feet deep.

Up the small canyon of Nautiloid Creek on the east side, in the lower part of the Redwall Formation, several large fossil nautiloids can be seen on a polished bottom of the gorge floor (Text-fig. 29 and 30). The largest one is about two feet long and about six inches across.

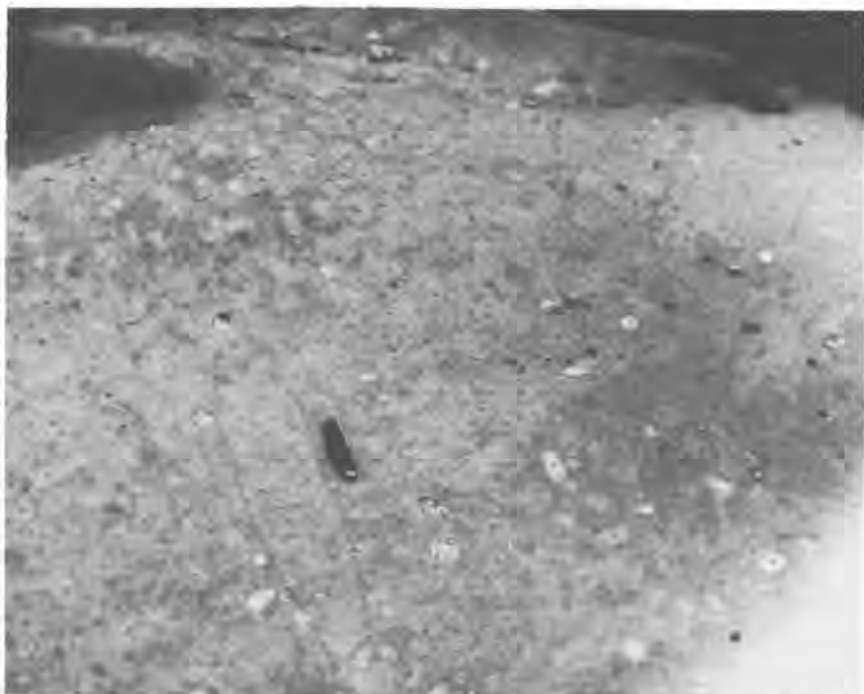
Cavern development on both sides of the canyon is particularly well expressed here.

Mile 35.0.—Solution activity along vertical joints is well developed.

Mile 35.9.—THE CONTACT OF THE REDWALL LIMESTONE AND THE UNDERLYING MUAV LIMESTONE IS AT RIVER LEVEL. The Muav is typically thin bedded, almost laminated, and produces sort of a speckled- or popcorn-type texture on the surface. The base of the Redwall is largely a disconformity with very little relief but locally rubble can be seen along this zone where it is exposed.

MUAV LIMESTONE (CAMBRIAN)

The Muav Limestone occurs beneath the Redwall Limestone as a sequence of alternating gray limestone and greenish gray calcareous siltstone. This formation characteristically erodes into three units within the national park area. The basal cliff is followed by



TEXT-FIGURE 29.—Nautiloids exposed in the bottom of Nautiloid Canyon near Mile 34.8. These are large fossils related to the present-day octopus. The segmented-appearing, cigar-shaped shell approximately two feet long (near the knife in the lower left of the photograph) is a cross section of one of the nautiloids.

a sequence of small ledges and slopes which is overlain by an upper cliff member nearly twice as thick as the basal unit. The Muav is greenish gray and when seen near the river it is very thinly bedded. Upon close examination one can see that individual limestone beds were broken into small fragments by ancient wave and current action immediately following deposition of thin beds, thus producing a somewhat heterogenous conglomerate-appearing rock type.

Fossil trilobites and ripple marks appear at various horizons within the Muav Limestone and indicate a relatively shallow marine environment of deposition for the formation. It is the youngest Cambrian formation within the Grand Canyon and is separated from the overlying Redwall Limestone by an erosional surface into which various channels were eroded. In various places within the Grand Canyon an additional Devonian limestone formation separates the Redwall and Muav limestones. This unit is inconspicuous, lensing, and relatively thin and is known as the Temple Butte Limestone. Where it is present it generally appears similar to the overlying Redwall Limestone.

Mile 36.0.—One can look up to the skyline and see a huge mass of rubble that has recently collapsed from the walls of the Kaibab-Toroweap sequence. This fall has produced an apron of debris which nearly blankets the Hermit Shale below in an excellent display of how the canyon widens. Large blocks collapse off the vertical cliff and are transported through mass movement to the river below where they are carried downstream. Several large open caverns and arches can be seen in the Redwall Limestone high on the side of the canyon.

Mile 36.5.—Redwall Limestone is beginning to respond to erosion typical of that in the park so that it develops large alcoves and reentrants.



TEXT-FIGURE 30.—Vertical aerial photograph showing Marble Canyon from Mile 32 to Mile 41. As a result of the greater depths of Marble Canyon in this vicinity, an intricate pattern of steps and ledges has developed in the canyon profile. Here the canyon is 2,750 feet deep and rarely exceeds one and one-half miles in width. Prominent roads seen on Tatahahso Point were constructed primarily for investigation of the proposed Marble Canyon Dam site.

Mile 36.9.—The basal contact of the Redwall is well exposed and is typically a horizontal surface with only a few slight irregularities. This is a classic example of a disconformity with essentially no structural discordance.

Mile 37.0.—TOP OF MUAV NEAR RIVER LEVEL. On the north wall the Muav Limestone is well exposed as a ledge and slope beneath the vertical cliff of the Redwall; but on the south wall differential erosion has not etched out this contact to any degree. It is difficult to pick but careful examination will reveal the disconformity and possibly some lenses of Temple Butte Limestone.

Mile 37.6.—ON THE EAST SIDE OF THE MAJOR BEND A DISCONTINUOUS LENS OF TEMPLE BUTTE LIMESTONE cuts into the well-bedded upper part of the Muav Limestone.

TEMPLE BUTTE LIMESTONE (DEVONIAN)

The Temple Butte Limestone is one of the most inconspicuous formations in the eastern part of the Grand Canyon. It was named by Walcott in 1889 for exposures in the vicinity of Temple Butte which is located 3 miles south of the junction of the Little Colorado River. (Text-fig. 45) Temple Butte Limestone occurs only as isolated lenses between the Redwall cliff and the underlying Muav Formation and often blends with the Redwall Limestone. In order to recognize Temple Butte beds from a distance one must carefully examine the exposures for structural breaks or erosional surfaces. The Temple Butte Limestone occurrence, however, does have very important connotations concerning the early geologic history of the Grand Canyon area, because of its unconformable relationship with the Cambrian rocks below and the Mississippian rocks above.

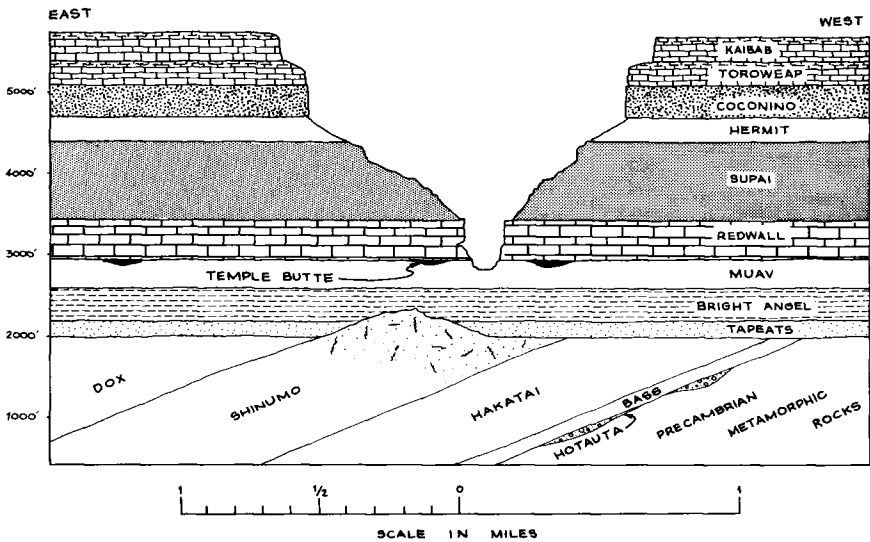
As seen from the river, the Temple Butte Limestone consists of large lenses of medium bedded limestone which has a characteristic purplish gray to pinkish gray color. These lenses vary considerably in dimensions, many are more than 400 feet across and 50 feet thick, but some only a few tens of feet wide also occur. They are eroded down into the underlying Muav Limestone and generally have a conglomeratic zone near their base. Stratification within the Temple Butte lenses is typically horizontal or with beds which parallel the lower concave surface of the channel. One lens is particularly well expressed and easily accessible at the mouth of Buck Farm Canyon, near Mile 41, where both the pink conglomeratic basal sequence and the overlying gray limestone are exposed. Fossils within the limestone indicate that the formation is of Upper Devonian age and is bounded by two significant unconformities in the Paleozoic sequence. The channeled base of Temple Butte Limestone indicates that after Cambrian sediments were deposited, but before Temple Butte sediments were laid down, this region of the Colorado Plateau was subjected to a period of erosion during which any Ordovician and Silurian rocks which may have been deposited were removed. The fact that the upper contact of the Temple Butte Limestone is also an erosional surface indicates that prior to deposition of the Redwall Limestone a younger period of erosion occurred in the Grand Canyon region.

Mile 38.0.—TEMPLE BUTTE LIMESTONE. Excellent channel fillings of Temple Butte Limestone beneath the Redwall Limestone. On the south side of the canyon Muav Limestone forms the ledgy material closer down to the river.

Mile 38.4.—Channels of Temple Butte Limestone approximately 30 feet deep locally separate the Redwall Limestone from the underlying Muav Limestone.

Mile 39.4.—Temple Butte channel, distinguished by a reddish color, cutting into the greenish cliffs of the Muav Limestone. It is approximately 40 to 50 feet deep and up to 400 feet wide.

Mile 40.0.—EXPLORATION TUNNELS FOR PROPOSED MARBLE CANYON DAM (Text-figs. 30 and 31). Exploration tunnels for the proposed Marble Canyon Dam can be seen on both the right and left in the sheer wall of the canyon. The scaffolding was removed but talus dumps scar the canyon wall. The tunnels were to test the foundation character of the limestone to see if a



TEXT-FIGURE 31.—Cross section showing the canyon profile and rock sequence at the proposed Marble Canyon Dam site at Mile 40. Vertical-walled inner gorge is developed upon the resistant Redwall Limestone with Muav Limestone encountered near water level. The total section of Mississippian, Pennsylvanian, and Permian rocks can be seen in the alternating cliff-slopes in the vicinity of the dam site. This section is almost 3,000 feet thick. The Mississippian to Permian rocks exposed in this part of the canyon represent a time span of approximately 300 million years.

major dam was feasible. Fortunately for river runners this proposed dam has been tabled for the present. Abandoned barges which were used in this operation can be seen near water level downstream below the scaffolding. The very knobby, shale beds of the Muav Limestone appear as distinct shaly breaks.

Mile 40.1.—Excellent Temple Butte channels cut down into the Muav Limestone. These are estimated to be about 200 yards wide and 60 to 70 feet deep. They are reddish maroon and are exposed on both sides of the canyon. The original trend of the channel was northeast-southwest.

Mile 40.3.—Temple Butte exposed on both sides of the canyon above the ledgy Muav beds and below the cliff-forming Redwall Limestone. This area is one of the most spectacular inner gorges within the entire distance of the Grand Canyon and would rival that of the Esplanade region of the Grand Canyon Monument to the west (Text-fig. 33).

Mile 40.5.—Excellent channel about 50 feet deep and perhaps 800 feet wide of Temple Butte Limestone overlies the Muav beds. Temple Butte Limestone can be seen separating the massive Redwall Limestone from the more prominently bedded Muav Limestone upstream from where Buck Farm Canyon empties into the Colorado River (Text-figs. 32 and 34). It is about 40 feet deep and may be as much as 400 feet across. The Muav Limestone forms ledges separated by small slopes because of limestone beds three to four feet thick which are separated by shaly partings from three inches up to a foot thick. The accessible channel of Temple Butte Limestone northeast of the fan is much more prominent and



TEXT-FIGURE 32.—Aerial photograph showing the Marble Canyon from Mile 40 to approximately Mile 50 in the vicinity of President Harding Rapids. The striking feature on this photo is the large bends around Point Hansbrough which is a classic example of entrenched meander. The steep-walled inner gorge cut in the Redwall Limestone forms a narrow passageway for the river. Minor faults have displaced the strata in the right hand of the photograph and have broken some of the steep-walled, cliff-forming units. This fault zone is essentially north-south.



TEXT-FIGURE 33.—Inner gorge of Redwall Limestone at Mile 40.7. The vertical cliff is largely cut in the Redwall Limestone whereas the lower knobby cliffs near water level are in the upper part of the Muav Limestone. At about the level of the gentle slope separating these two cliffs, one can find isolated channels of the Temple Butte Limestone.

massive. Ledges on either side of Buck Farm Canyon at the head of the fan show the characteristic texture of the Muav Limestone very well.

Mile 41.0.—Just around the first big meanders below Buck Farm Canyon, are three large caverns known as the Royal Arches (Text-fig. 35). They are reminiscent of limestone caverns seen upstream and occur at approximately the same stratigraphic horizon as Redwall Cavern.

Mile 41.4.—Bert Loper's boat is located on the right hand side of the river just upstream from the tributary. Excellent outcrops of middle Muav shaly beds at river level.

Mile 42.5.—The canyon begins to widen slightly because of the slope developed on the Muav Limestone.



TEXT-FIGURE 34.—View of a channel of Temple Butte Limestone separating the vertical cliffs of the overlying Redwall Formation and the underlying stratified Muav Limestone. Lenses of Temple Butte indicate a significant interruption, or break, in geologic processes separating the Cambrian Muav Formation from the Mississippian Redwall Limestone. In most of the canyon the contact between the Muav and the Redwall Limestones is simply a bedding plane. Here, however, the Muav Limestone has been eroded and channeled prior to deposition of the Devonian Temple Butte Limestone.

Mile 43.5.—Channel of the Temple Butte Limestone cut down into the Muav Limestone.

Mile 43.7.—**PRESIDENT HARDING'S RAPIDS (4) 4' DROP.** President Harding's Rapids was named on August 23, 1923, by the surveyors of the river who got word of President Harding's death here by radio. Stanton named the point in the meander core of the broad loop between Miles 41 and 47 "Point Hansbrough" for Peter Hansbrough, who drowned some ten miles above and was buried here near President Harding's Rapids.

Mile 43.8.—Northeast-trending faults parallel to the Eminence Fault have brecciated and dislocated the sequence of strata so that the entire face appears fractured and broken.



TEXT-FIGURE 35.—One of the Royal Arches developed in the Redwall Limestone in the vicinity of Mile 41.5. Development of caverns, arches, and alcoves within the lower part of the Redwall Limestone is seen throughout the Grand Canyon region and excellent examples are shown here, as well as at Redwall Cavern upstream. Cavern development is closely related to ground water activity and cascades of water from the tributaries over the Redwall Cliffs. The Muav Limestone forms the lower stratified ledges near water level in this photograph.

Mile 45.0.—Upper Muav Limestone forms nearly vertical walls 30 to 40 feet high extending down into the river. Downstream the Muav Limestone is well expressed on both sides of the stream. Weathering has etched out many structural details on the right hand side where the thin conglomeratic limestone nature is well expressed.

Mile 46.5.—Two additional large caverns are developed in the Redwall Limestone here and are similar to Redwall Cavern and occur at approximately the same horizon.

Mile 46.7.—Outcrops along the river banks are Muav Limestone.

Mile 47.0.—Triple Alcoves on the right-hand side of the stream are formed in the lower Redwall Limestone at the same horizon as Redwall Cavern upstream.

These occurrences further substantiate the hypothesis that the caverns developed from solution activity rather than stream erosion.

Mile 48.5.—Three distinct units are visible within the Muav Limestone: (1) an upper cliff, (2) a medial slope, and (3) a lower cliff about twice the thickness of the upper. A wall of Temple Butte Limestone is seen very close to the mouth of subtle canyon on the north.

Mile 49.2.—Large alcoves are developed within the Redwall Limestone, features typical of the formation in the park but developed here just above river level. Numerous alcoves develop where tributaries enter and form waterfalls over the Redwall cliff, and start in an even-bedded, pinkish unit low in the Redwall cliff.

Mile 49.5.—Small fault cuts diagonally across the canyon with a trend of approximately north-south, and fractured rocks allow tributary canyons to easily erode. Breccia shows particularly well in the Redwall Limestone on the north side and in the alcove carved between pillars of Muav Limestone. The Redwall forms a prominent fin on the left or west side of the canyon.

Mile 50.3.—Caverns can be seen in the Muav Limestone on the east side. Massive walls of the Redwall Limestone can be seen on either side with bedding poorly expressed above the prominent lower unit. Channels of Temple Butte Limestone can be seen cutting down into the more evenly bedded Muav Formation.

Mile 51.8.—Prominent Nankoweap and Little Nankoweap canyons, ahead, have developed one of the largest deltas seen on this section of the river (Text-fig. 36). Kaibab beds cap the cliff in views ahead. Notice how thick the Coconino Sandstone has become. The Redwall Limestone forms the characteristic wall of the inner gorge with the ledge and slope zone of the Muav Limestone leading down to the top of the MORE TAN AND BROWNISH GREEN-APPEARING BRIGHT ANGEL SHALE WHICH APPEARS AT RIVER LEVEL. Beginning from river level above the rapids at Nankoweap Canyon (Text-figs. 37 and 38) a cliff is formed in the upper part of the Bright Angel Shale, then a minor slope and cliff in the lower part of the Muav Limestone, overlain by a step-slope topography up through the middle part of the Muav leading to the upper massive cliff at the top of the formation. The step-slope of the Supai Sandstone is prominent below the narrow slope of the Hermit Shale. The massive columnar part of the upper cliff is the Coconino Formation which is overlain by the Kaibab and Toroweap formations that form the upper half of the highest cliff.

BRIGHT ANGEL SHALE (CAMBRIAN)

A sequence of fine-grained, mostly thin-bedded, light greenish gray silty shale beneath the Muav Limestone is referred to as the Bright Angel Shale. The formation ranges in thickness up to 450 feet. The shale is weak and very susceptible to erosion and as a result has been eroded back from the underlying Tapeats Sandstone to form a broad terrace known as the Tonto Platform in the park area. This terrace is one of the most significant topographic features within the national park area and is approximately 3,000 feet below the canyon rim, held up by the Kaibab Limestone. Three general types of fossils have been found within the Bright Angel Shale, all of which indicate it is of Cambrian age. Small, thin shells of extinct brachiopods are abundant, as are trilobites and many fossil tracks and trails. The latter are attributed to both trilobites and worms. The Bright Angel Shale is considered to be one of marine origin representing deposition of silty muds in a shallow sea environment.



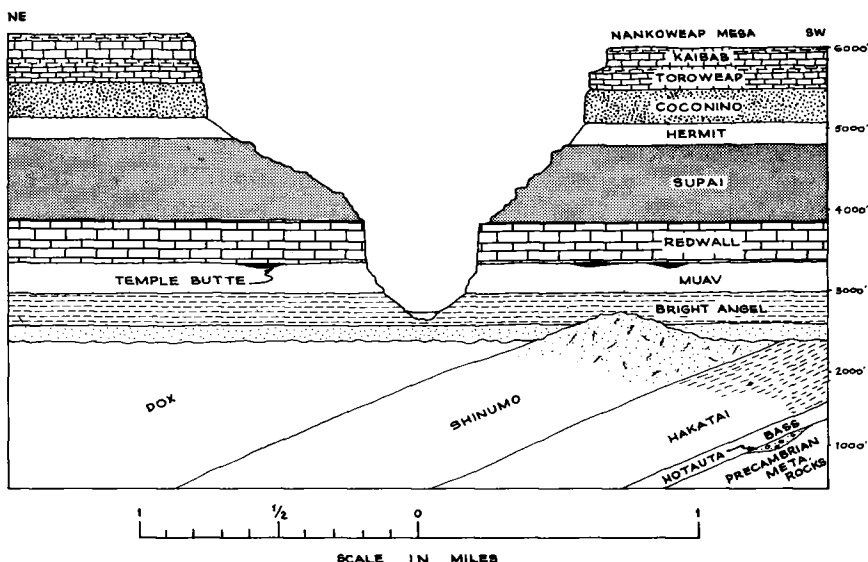
TEXT-FIGURE 36.—Vertical aerial photograph showing Marble Canyon from Mile 50 to approximately Mile 57, in the vicinity of Nankoweap Canyon. The boundary between Marble Gorge and Grand Canyon is in this vicinity. The Marble Platform to the right of the river is essentially flat and featureless. The area to the left has been uplifted along the East Kaibab Monocline and is highly dissected. The west rim of Grand Canyon is approximately eight miles from the river. Note the large alluvial debris fan at the mouth of Nankoweap Canyon. This deposit of sediment has caused a slight meander bend in the Colorado River in this vicinity.

The Grand Canyon National Park boundary comes in from the west along the crest of the spur north of Little Nankoweap Canyon and follows the east bank of the Colorado River to the Little Colorado River.

Mile 52.0.—NANKOWEAP RAPIDS (4) 27' DROP IN ONE MILE. At Nankoweap Canyon the river leaves the Marble Gorge and enters the Grand Canyon proper. From Lee's Ferry downstream to Mile 52 the river flows through Permian, Pennsylvanian, Mississippian, Devonian, and Cambrian rocks. Profiles of Marble Gorge range from less than one mile to two miles wide (Text-figs. 10, 17, and 31) and are characterized by steep nearly vertical walls. In Marble Gorge the canyon ranges up to 3,200 feet deep with elevation of the surrounding Marble Platform at approximately 6,000 feet above sea level. At Nankoweap Rapids the river encounters the great flexure of the East Kaibab Monocline (Text-figs. 1 and 8) which has lifted rocks to the west to a much higher elevation. West of the monocline the surface is more than 8,000 feet



TEXT-FIGURE 37.—View of canyon wall near Nankoweap Canyon at Mile 52. The Red-wall Limestone forms the vertical wall above low ledges of the Muav Formation. The step-like profile developed on the Supai is well expressed in this photograph. The Coconino, Kaibab, and Toroweap formations form a single cliff at the top of the canyon. Gravel terraces, several tens of feet above the present river level, are debris from Nankoweap Creek.



TEXT-FIGURE 38.—Cross section showing the sequence of rocks and profile of the canyon at Nankoweap Mesa at approximately Mile 54.5. Cross section shown here is only of the inner gorge of the canyon and the east rim. The northwest rim is some 2,000 feet higher as a result of flexing of the East Kaibab Monocline and is eight miles to the west and cannot be seen from river level. This section extends only to the crest of Nankoweap Mesa which is isolated from the main canyon rim by faulting and erosion.

high, permitting the river to cut an additional 2,000 to 3,000 feet deeper into the stratigraphic section than is possible at Marble Gorge. From Nankoweap Rapids downstream, the Grand Canyon is about eight miles wide and nearly one mile deep. The river runs parallel to the East Kaibab Monocline from Nankoweap Rapids to near Unkar Rapids and then swings abruptly westward and flows into the park region.

Although one cannot view these regional geomorphic relations from the river, reference to maps (Text-fig. 1 and maps inside cover) shows the very striking and abrupt change in the general characteristics from Marble Gorge into the Grand Canyon. Grand Canyon begins abruptly in the vicinity of Nankoweap Creek, with major characteristics that continue westward beyond the park into the Grand Wash Cliffs. In the vicinity of Nankoweap Rapids the canyon is extremely asymmetrical. The river is only one half of a mile from the east rim, whereas it is seven miles away from the west rim. In this vicinity the river flows essentially south, parallel to the east flank of the monocline.

For several miles below Nankoweap Rapids the river flows in the Bright Angel Shale which forms the prominent green and gray-green bluff at the base of the canyon wall. The shale is locally covered by slope wash which is tightly cemented with travertine, a spring deposit of calcium carbonate. This cemented layer forms a protective armor over the softer shale and, in most instances, protects it from rapid erosion. Here and there, however, the armor has broken through and excellent exposures of Bright Angel Shale can be seen.

Mile 53.0.—Excellent views of Bright Angel Shale can be seen on the east side of the river, where it forms the tan, brown, and olive drab slopes just above river level. Upper part of the cliff is formed of the greenish, knobby carbonates of the lower part of the Muav Limestone.

A tremendous panorama of stratigraphy from the Bright Angel Shale up to the Kaibab Limestone can be seen upstream east of Nankoweap Rapids (Text-fig. 37). The river terrace here might be correlative with those that can be seen down in the vicinity of Mile 66 near Lava Butte. Indian grain storage structures can be seen at the bottom of the cliff just south of Nankoweap Canyon on the west side of the river.

Mile 54.0.—East Rim and Nankoweap Butte (Text-fig. 38) expose rocks from the Bright Angel Shale to the Kaibab Limestone.

Mile 54.5.—Cemented slope wash and gravel which have buried the Bright Angel and the lower part of the Muav can be seen on the east side. Gray Castle is eroded in Muav Limestone above the tan and green-purplish olive drab shales of the Bright Angel Shale (Text-fig. 39). It stands as a high promontory out away from the Redwall Cliff.



TEXT-FIGURE 39.—Gray Castle, an erosional pinnacle of Muav Limestone, overlies the olive drab, green shales of the Bright Angel Shale at Mile 54.5. Fresh exposures of the Cambrian shales, shown here, illustrate very well the intricate stratification in these formations which is not usually seen where a weathered slope is produced.

Mile 56.0.—KWAGUNT RAPIDS (4) 7' DROP. Elevation of the river at this point is 2,760', and elevation of the canyon rim to the west on Walhalla Plateau is 8,501'.

Mile 56.3.—Relatively high cut exposes well-cemented alluvium. Coarse alluvium accumulated along the slopes and once extended much farther along the river than at present. This is one of the largest areas of cemented slope wash seen on the trip.

Excellent exposures of Bright Angel Shale can be seen just below Kwagunt Rapids, beneath the cemented gravel. Some of the tumbled blocks of conglomeratic debris have moved down to river level by rock creep.

Mile 57.8.—A pinnacle of rock formed on the Muav Formation is capped by Pleistocene gravel and forms a castle-like erosional remnant much like Gray Castle upstream.

Mile 58.0.—Excellent tracks and trails can be observed in the sandy units within the Bright Angel Shale just above river level. Some trilobite fragments occur here as well.

Mile 58.5.—Large remnants of slope wash cemented with travertine have been dissected by recent erosion. Alluvium here is upwards of 40 feet thick and contains many tremendous blocks of Upper Paleozoic rocks. In places it is cemented tightly with calcium carbonate (Text-fig. 40).

Mile 59.0.—TOP OF THE TAPEATS SANDSTONE APPEARS AT WATER LEVEL BELOW THE BRIGHT ANGEL SHALE. The coarse-textured, cross-bedded sandstone is well exposed in overhanging and undercut ledges at river level. This is the basal sandstone of the Paleozoic sequence and is approximately 600 million years old. It rests unconformably on older Precambrian rocks that appear at river level downstream through much of the rest of the trip.

TAPEATS SANDSTONE (CAMBRIAN)

The Tapeats Sandstone is the lowest Paleozoic formation and is 200 to 300 feet thick. This formation is one of the most persistent and prominent rock bodies in the canyon and is easily recognized because it characteristically weathers into a nearly vertical cliff immediately below the slope developed on the overlying Bright Angel Shale. It forms the ramparts at the top of Granite Gorge or rests on the upturned tilted edges of the red shales and sandstone of the Grand Canyon series.

Tapeats outcrops characteristically contain horizontal layers which have small-scale internal cross-stratification. The rock commonly weathers to a dark brown, but fresh surfaces are much lighter. It is composed mostly of coarse quartz sand grains, and like the Bright Angel Shale contains several varieties of marine Cambrian fossils. The Tapeats Sandstone can be traced through the entire canyon with only a few interruptions. Where it overlies the Precambrian metamorphic rocks it forms a striking contrast in development of land forms, but where it overlies the gently dipping sedimentary rocks of the Grand Canyon Series the contrast is somewhat less obvious. This is the only section of the canyon where one can see the Tapeats beds at river level between here and the end of Granite Gorge.

Mile 59.8.—Good exposures of Tapeats Sandstone on both sides of the river. Here the Tapeats is characterized by lenticular units of sandstone two to three feet thick, which pinch and swell and are characteristically cross stratified. They erode to form a very ragged cliff near the water level.

The remarkable development of slope wash (Text-fig. 40) on the east side is due in large part to preservation made possible by cementation with travertine.



TEXT-FIGURE 40.—Travertine-cemented slope wash in the center of the picture caps the Muav and Bright Angel formations at Mile 59.5. Details of stratification in bedrock below are well exposed. The slope wash has been stabilized by travertine cementation.

Travertine constitutes a significant part of the material and acts as a cement to hold the slope wash debris together from approximately Mile 53 down to the Little Colorado River.

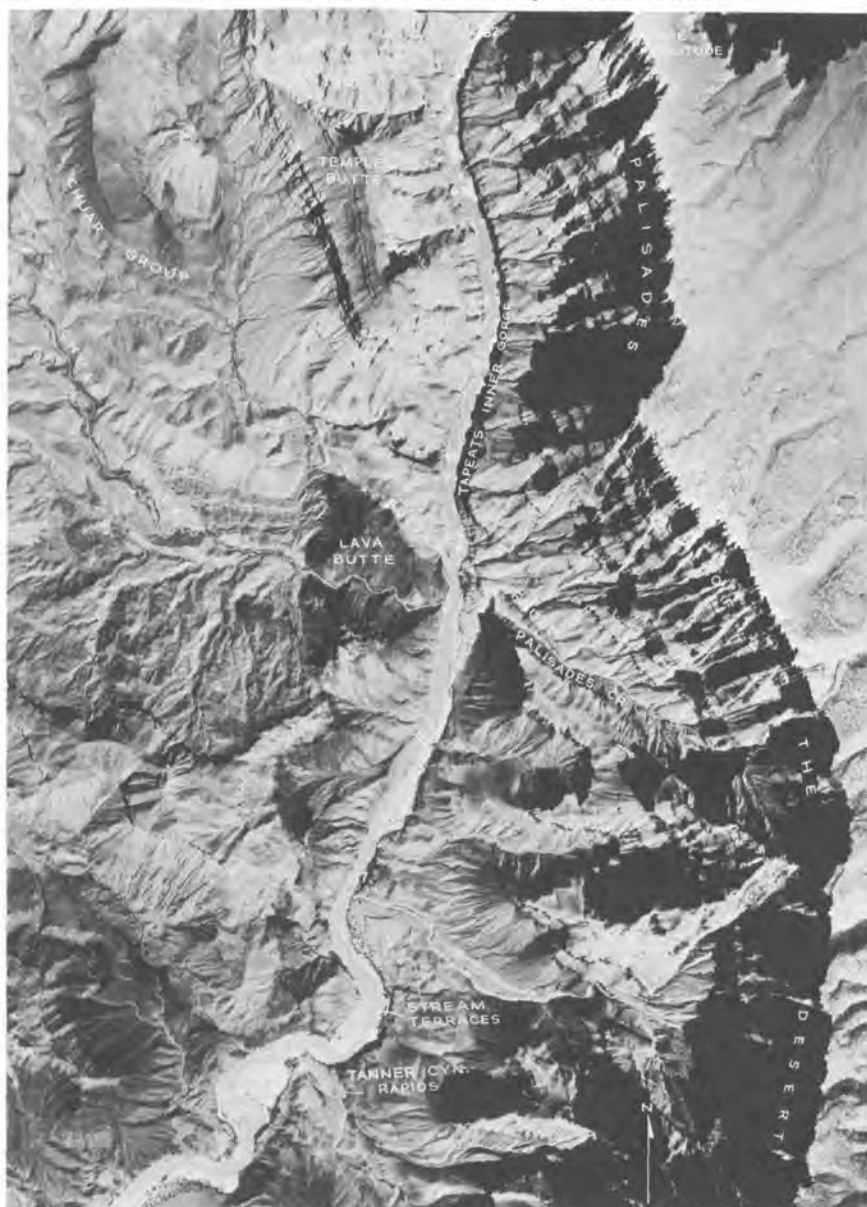
Mile 61.5.—JUNCTION OF THE LITTLE COLORADO AND COLORADO RIVERS (Text-fig. 41).

The Little Colorado River was bright red in 1869 when seen by Powell, and hence its name. However, it is usually a light azure blue, presumably as a result of algal action related to some of the small springs located up the canyon a short distance. These springs are considered to be sacred by the local Indians, for supposedly it was from here that their people emerged to the surface.

Although the Little Colorado River is a major tributary to the Grand Canyon, there are no significant rapids maintained at this junction. The reason for this is readily apparent when one compares the size of material being transported by the Little Colorado River—a stream with a relatively low gradient—with that of the material carried by the minor tributary streams with high gradients. Large boulders are transported by the minor steep streams but



TEXT-FIGURE 41.—Vertical aerial photograph of the Colorado River near the junction of the Little Colorado River, from Mile 56 to approximately Mile 62.



TEXT-FIGURE 42.—Vertical aerial photograph showing a segment of the Grand Canyon from Mile 62 to approximately Mile 70. Serrated, scalloped cliffs on the right are the Palisades of the Desert where very few slopes are developed on the Upper Paleozoic strata. Cape Solitude is located in the upper right corner. The dark toned areas in the center are basaltic sills injected in the Precambrian Grand Canyon Series near the Butte fault. These rocks are truncated and displaced by the Butte fault with the upthrown block to the west. Delicately stratified Chuar sediments are seen north-west of the sill. Palisades Creek is controlled to a large extent by the Butte fault.

only pebbles, cobbles, and sand are carried by the Little Colorado River. Instead of building a fan and rapids, the Little Colorado has built a prominent bar which is easily eroded and modified by waters of the Colorado River.

Just below the Little Colorado River the Bright Angel Shale begins to retreat back from the top of the Tapeats Sandstone to form the first expression of the Tonto Platform. Several channels of Temple Butte Limestone can be seen cut down into the Muav Limestone beneath the massive sheer wall at the base of the Redwall cliff on the east side of the river, north of its junction with the Little Colorado River. The river continues downstream through excellent exposures of the Tapeats Sandstone.

Two airlines' planes apparently collided in midair here, then crashed into Chuar Butte, the prominent butte immediately west of the junction of the rivers. With a pair of binoculars one can recognize impact marks on the faces of the butte. Considerable wreckage can be seen on the north slopes immediately above the sandbar at the junction. One airplane tire rolled down to near river level and still remains in the tributary canyon southeast from the butte. Fragments of the fuselage and wings still can be recognized on the slope of the tributary canyon.

Mile 62.0.—Relatively large exposures of Tapeats Sandstone form nearly vertical cliffs 150 feet high (Text-fig. 42). Retreat of the easily eroded Bright Angel Shale begins to define the Tonto Platform.

Mile 63.0.—The canyon broadens markedly here and one can see from the river the striking difference between this part of the Grand Canyon and Marble Gorge.

Mile 63.5.—THE GREAT UNCONFORMITY OR EROSIONAL SURFACE AT THE BASE OF THE CAMBRIAN TAPEATS SANDSTONE on the late Precambrian red siltstones and shales of the Nankoweap Formation rises above water level on the canyon wall (Text-fig. 43). Here the rocks are roughly parallel and only a slight angular discordance is evident. The boundary between Cambrian and Precambrian rocks is drawn at the base of the green and gray-green Tapeats Sandstone, on top of the varicolored massive siltstones. It separates younger Paleozoic strata which contain fossils from the older unfossiliferous Precambrian sequences below. The late Precambrian redbeds were deposited during an interval of time from approximately 700 million to 1.5 billion years ago.

THE GREAT UNCONFORMITY

The erosional surface at the base of the Tapeats Sandstone constitutes one of the most significant boundaries between rock bodies within the canyon (Text-figs. 8 and 38). This surface marks an important discontinuity within the sequence of rocks and is referred to as the Great Unconformity. In most unconformities there is a structural discordance between the rock bodies which indicates an interruption in geologic processes. The older rocks show evidence of deformation and erosion prior to deposition of the younger strata. This is clearly expressed in the Grand Canyon region where the Tapeats Sandstone is deposited on the tilted and eroded edges of either the Grand Canyon Series or on the older metamorphic rocks, so that a marked discontinuity is readily apparent. Geologically, an unconformity is significant because it shows an interruption in rock forming processes, usually accompanied by structural deformation, uplift, and erosion.

In the Grand Canyon, the Great Unconformity probably represents a time interval of many millions of years, for throughout most of the Grand Canyon a sequence of rocks, approximately 12,000 feet thick has been eroded and removed prior to deposition of the

Tapeats Sandstone. In most of the canyon the Great Unconformity appears as a nearly horizontal surface. At the junction between Marble Gorge and the Grand Canyon proper this erosional surface is carved upon the tilted red siltstones and shales of the Grand Canyon Series, but when the surface is traced westward and downstream, the Grand Canyon Series has been completely removed and the unconformity is developed upon the ancient metamorphic complex. In Granite Gorge the Tapeats Sandstone rests directly upon this erosion surface and removal of well over 12,000 feet of rock is represented by the unconformity. In several places the Tapeats Sandstone is absent and resistant units in the underlying Grand Canyon Series, such as the Shinumo Quartzite, are overlain directly by the middle units of the Bright Angel Shale. The Shinumo Quartzite obviously existed as erosional remnants or low mountain ridges, some of which were 800 feet high during the time the Tapeats Sea flooded the region. It was not until Bright Angel time that hills on the Precambrian Grand Canyon Series were completely covered. Close inspection of the unconformity will reveal an ancient "soil," or decayed rock, developed upon the Precambrian rocks. In some places this soil profile is more than 50 feet thick.

LATE PRECAMBRIAN ROCKS

THE GRAND CANYON SERIES

A very thick sequence of fine-grained sandstones, siltstones, and shale which have been tilted to angles ranging up to 15 degrees are exposed in the eastern part of the Grand Canyon and in isolated remnants to the west. These rocks stand out in marked contrast to the overlying horizontal Paleozoic strata and are referred to as the Grand Canyon Series. They are somewhat isolated and are seen in only a few places, hence these rocks have not received the same attention as that given to overlying Paleozoic units. The Grand Canyon Series is remarkable in that it represents a vast thickness of silt, shale, and sandstone over 12,000 feet thick, with little variation in rock type. These rocks are typically nonresistant and where considerable thicknesses of the series are exposed the canyon floor is characterized by a wide open valley with rolling hills.

The Grand Canyon Series is divided into two groups of rocks: the upper, or Chuar Group, is not seen on the river trip but is known in fault blocks west of Nankoweap Canyon (Text-fig. 42). The lower, or older Unkar Group is subdivided into the following formations listed from oldest to youngest: (1) Hotauta Conglomerate—the lowest unit in the Grand Canyon Series; (2) Bass Limestone; (3) Hakatai Shale; (4) the Shinumo Quartzite—a relatively clean quartz sandstone and the most resistant formation in the Grand Canyon Series; (5) the Dox Formation—which forms the great bulk of red shale and siltstone overlying the Shinumo Quartzite, and (6) the Nankoweap Formation.

Mile 63.7.—The Nankoweap Formation of the Unkar Group occurs beneath the Tapeats Sandstone with an angular discordance of about seven or eight degrees. The erosional surface here is a planar feature with very little relief. The Nankoweap Formation is the dark gray-brown, cross-bedded sandstone and siltstone which occurs beneath the light-colored massive cliffs of the Tapeats Sandstone. Nankoweap Formation consists of interbedded sand and fine silts that have developed a characteristic purple color which is bleached white along bedding planes so that stratification is commonly expressed by color changes. The sandstone is cross-stratified in sets ranging from one to two feet in thickness. The Nankoweap has been mildly metamorphosed so that mica flakes are abundant along the bedding planes and the sand grains are slightly welded together to form a very hard, dense rock. The Great Unconformity can be seen on both east and west walls of the canyon. White gypsum coats the base of the Tapeats sandstone here and upstream for a short distance.

Mile 64.0.—Desert View Tower can be seen ahead on the South Rim. The river continues through sandstones and siltstones of the Nankoweap Formation.

Mile 64.3.—Massive ledges of sandstone of the Nankoweap Formation exposed along both sides of the valley (Text-fig. 44). A panorama of the main part of the Grand Canyon opens up downstream through a gorge in the Nankoweap.



TEXT-FIGURE 43.—View of the entire Paleozoic sequence seen from Mile 64.1. The vertical-walled ragged inner-gorge in the foreground is carved on the Tapeats Sandstone which overlies the purplish Precambrian sandstones and siltstones of the Nankoweap Formation. The canyon rim shown here is 3,580 feet above river level and is at the north end of Palisades of the Desert. This is one of the steepest parts of the Grand Canyon, developed on the east and southern rim just below the Little Colorado River.

Mile 65.1.—THE BUTTE FAULT CROSSES THE RIVER AND DISPLACES THE PRECAMBRIAN SEQUENCE (Text-fig. 42). The dark basalts are faulted up against the redbeds. Upstream, ramparts of the Tapeats Sandstone show as a prominent cliff. Redbeds north of the fault are nearly horizontal; those in the fault blocks, in the vicinity of the basalt, are steeply dipping to the north. Nankoweap beds are well exposed on the north side of the fault. **PROMINENT LAVA-CAPPED MESAS AND UNDERLYING RED SILTSTONES OF THE DOX FORMATION** show very well on the southwest side of the fault, particularly on the east side of the canyon.

Strongly upflexed siltstone beds of the Nankoweap Formation have been deformed by drag along the fault. The prominent cliff of black basalt intruded as a sill into the Dox Formation. The bold rampart of the Tapeats Sandstone rests upon the truncated edges of the basalts; apparently the basalt was planed off as smoothly as the underlying red shales.

DOX FORMATION (LATE PRECAMBRIAN)

The great bulk of the Grand Canyon Series seen from the river consists of red, thin-bedded shales and siltstones known as the Dox Formation. These rocks are relatively



TEXT-FIGURE 44.—Exposure of the Great Unconformity seen at Mile 64.2. The unconformity separates the Cambrian Tapeats Sandstone from the underlying purplish red Nankoweap Formation of the Grand Canyon Series. The rocks dip toward the cliff, hence, only minor angularities are seen in this outcrop.

nonresistant to erosion and easily break down into gently sloping hills. Where a considerable thickness of the formation is exposed a very broad open area develops unlike any other region in the canyon (Text-figs. 45 and 46). Large intrusions of dark basaltic lava have been injected as sills within various layers of the Dox Formation and form very prominent, dark gray cliffs in the area below Desert View and west of Palisades of the Desert. In addition, a number of small, dark dikes also have intruded into the Dox beds, all of which indicate significant volcanic activity associated with the general period of deposition of the Grand Canyon Series.

Mile 65.4.—LAVA CANYON RAPIDS (3) 4' DROP.

*Mile 66.0.—*Looking back upstream the sequence of formations traversed from Lee's Ferry can be seen in profile (Text-fig. 43), beginning with the canyon rim composed of Kaibab, Toroweap, and Coconino formations which form the bold escarpment on the skyline known as the Palisades of the Desert (Text-fig. 46). Redbeds below are the Hermit Shale and Supai Formation and the



TEXT-FIGURE 45.—Panoramic view of the Grand Canyon seen from Desert View. Many features of the Grand Canyon are shown in this panorama and are indicated by the following numbers: (1) the Vermillion Cliffs in the far background; (2) the Marble Platform through which the canyon has cut Marble Gorge; (3) the steep cliffs of the Palisades of the Desert on the east rim; (4) Temple Butte; (5) exposures of the Chuar Group in Chuar Valley; (6) The Tapeat Sandstone below which is the Great Unconformity; (7) the gently dipping strata of the Unkar Group of the Grand Canyon Series; (8) the diabase sill in the Grand Canyon Series; and (9) terrace gravels

prominent Redwall Limestone forms the cliff halfway up the canyon wall. The Muav and Bright Angel formations form the cliff and slope beneath the Redwall Limestone, and the Tapeats Sandstone can be seen near river level through the narrow gorge. The dip in the Grand Canyon Series is relatively steep compared to the nearly flat-lying Paleozoic rocks above.

The East Kaibab Monocline crosses the canyon in the same vicinity as the Butte Fault (Text-figs. 1 and 8). This fold is reflected in the steep attitude of the Precambrian rocks.

The brilliant red shales and siltstones which are exposed immediately below the blackish green sill at Mile 66 are the upper part of the Dox Formation, which forms one of the thicker units in the Grand Canyon. These shales dip at a relatively low angle to the east so that downstream lower and lower rocks in the section are encountered. The homogeneity of the Dox Formation is one of its most outstanding characteristics. Layer after layer of alternating silts and shales constitute the only rock change throughout the entire sequence. These rocks continue to be the dominant exposures at river level to beyond Unkar Rapids. Upon close examination, micro-cross-bedding and innumerable ripple marks are the dominant internal structures of the Dox. On the right side of the



TEXT-FIGURE 46.—View of Palisades of the Desert from river level near Mile 66. The rolling hills in the foreground are carved on nonresistant siltstones and shales of the Dox Formation. Recent gravel terraces are shown close to river level. The vertical cliffs which rim the canyon at the skyline are in the Kaibab, Toroweap, and Coconino formations.

stream one can see mud cracks and ripple marks in the boulders of the Dox. Small anticlines and synclines are expressed in the stratification.

Mile 66.8.—Stream terraces capped by gravel are developed 20 to 50 feet above river level (Text-figs. 42 and 46).

Mile 67.0.—A flexure in the dip of the beds cause the Dox Formation to dip slightly upstream. The striking Palisades of the Desert are eroded on the Kaibab, Toroweap, and Coconino formations which form a vertical wall (Text-fig. 46). When one follows the basal contact of the Tapeats, the formation pinches out above the resistant basalt sill which here protrudes up into the overlying Bright Angel Shale.

Weak mineralization and high hopes prompted early prospectors to investigate the region in the vicinity of the sill and faults. However, the region has produced little but exceptional scenery.

Mile 68.4.—Vertical exposures of the diabase sill have been faulted down to river level. Note curvature of the fault plane and truncation of the Dox Formation against the fault (Text-fig. 47).

Mile 68.5.—TANNER CANYON RAPIDS (6) 20' DROP. Just below the rapids the Dox Formation is faulted up to the west again. The basalt sill forms a small graben separating exposures of the red Dox Formation. Excellent remnants of recent stream channels can be seen on the left.



TEXT-FIGURE 47.—Curved fault surface separating the cliff-forming diabase sill on the left from the lower beds of the Dox Formation on the right at Mile 68.4.

Mile 69.2.—A lower level of recent thick stream gravels can be seen on the outside bend in the river. These deposits are stratified, rounded, and sorted and are distinctly different from the slope wash seen upstream near the Little Colorado River. Folded Dox Formation is exposed beneath the gravels and dips as much as 30 degrees.

Mile 70.5.—Slope wash of basalt or diabase material veneers the upper level of the terrace above the older stream wash material. Small dikes trend toward the southeast, cut up through the Dox, and are expressed by very small, narrow ridges and also extend on up through the sill as the cockscomb ridge.

Mile 71.0.—Excellent exposures of the angular unconformity at the base of the Tapeats Sandstone can be seen to the north where the Tapeats rests on the Dox Formation and the basalt sill (Text-fig. 48). Photographs of this outcrop are used in many textbooks illustrating an angular unconformity.

The Precambrian redbeds, as well as the dark gray basaltic sill dip eight to ten degrees to the east and the eroded edges of these beds have been covered



TEXT-FIGURE 48.—View of Ochoa Point north from Mile 71.2 showing the diabase sill intruded into the Dox Formation, overlain with angular discordance by the Tapeats Sandstone.

by the overlying nearly horizontal Tapeats Sandstone. In places the contact is quite irregular with the more resistant segments of the sill forming buried hills beneath the Tapeats blanket. This contact can be traced from here throughout most of the national park area and it appears as a nearly straight line. It is difficult to estimate the time necessary to erode away a column of rock as thick as the Grand Canyon Series and to form such a flat surface over the metamorphosed "roots" of old mountains.

In this vicinity an impression of the great thickness of the Grand Canyon Series, as well as its remarkable uniformity, can be gained. These rocks are composed almost totally of ripple marked, weakly cross-bedded, laminated siltstone and shale which here have been eroded to form the open valley in the bottom the Grand Canyon. The Grand Canyon Series is approximately 12,000 thick, almost twice as thick as the overlying Paleozoic rocks through which the river has cut.

The profile and feeling or spirit of the canyon changes markedly where the river flows through the Grand Canyon Series because of the broad open rolling hills formed on the relatively weak and nonresistant red siltstones and shales (Text-fig. 49).

Mile 71.5.—A sandy bed within the middle part of the Dox Formation is a resistant unit making a rather narrow gorge in the vicinity of Unkar Creek. The lower Dox Formation forms a slope zone beneath the overlying sandy beds.

Mile 72.4.—UNKAR RAPIDS (10) 25' DROP IN .3 OF A MILE. Calm water above Unkar Rapids is typical of the main river where it has been partially dammed by debris from tributary streams (Text-fig. 49). Excellent exposures of the thin-bedded middle sandy units of the Dox Formation are visible in the



TEXT-FIGURE 49.—Vertical aerial photograph showing the Colorado River in the Grand Canyon from Mile 70 to Mile 76. The highway along the south rim is clearly shown connecting Lipan Point and Zuni Point. Bottom of the canyon is floored by weak nonresistant Dox Formation which responds to erosion to form rolling hills which are highly dissected by small ravines. This type of topography is unique within the canyon. Unkar Rapids has developed on the debris deposited in the river by Unkar Creek near the upper central part of the photograph. As the debris is brought in from Unkar Creek and deposited in quantities too great for the river to move on downstream the course of the river is forced to migrate away from the debris fan and has developed a minor meander bend. Intricate detail of the stratification shows in parts of the Dox Formation, expressed by light and dark tones, particularly north of Unkar Creek.

undercut bluffs which rise from the river over the rapids. The sandy bars of Unkar Creek were farmed by Indians. Village ruins can be seen on the north side of Unkar Creek at the base of the bluff near the head of the alluvial fan.

Mile 73.5.—The lower cliff-forming sandy unit of the Dox can be seen downstream. The visible rim of the canyon here is on the Redwall Limestone.

Exposures of a lower, more brownish unit of the lower part of the Dox Formation forms a rather narrow gorge. The lower Dox from here to Mile 74.5 forms a rather prominent cliff and a narrow gorge at least 500 feet deep.

Mile 74.4.—Shinumo Gorge. Light colored quartzite that forms the steep V-shaped narrow canyon can be seen downstream. The canyon rim formed on the Kaibab can be seen on the skyline directly down the river at this point.

Mile 74.7.—CONTACT BETWEEN THE REDDISH UNITS OF THE DOX FORMATION AND THE UNDERLYING SHINUMO QUARTZITE. The quartzite forms the narrow V-shaped gorge below the platform carved on the soft shale of the upper Grand Canyon Series (Text-fig. 50). One cannot help but wonder the thoughts which went through the minds of Powell's men as they left the pleasant wide open valley and entered into what must have seemed a dark, inhospitable section of the canyon on a river they did not know.

We are three quarters of a mile in the depths of the earth, and the great river shrinks into insignificance, as it dashes its angry waves against the walls and cliffs, that rise to the world above; they are but puny ripples, and we but pigmies, running up and down the sands, or lost among the boulders. We have an unknown distance yet to run; an unknown river yet to explore. What falls there are, we know not; what rocks beset the channel, we know not; what walls



TEXT-FIGURE 50.—View of Shinumo Gorge from approximately Mile 74. The Grand Canyon sequence dips upstream at a low angle. The resistant Shinumo Quartzite forms the steep walls of the gorge.

rise over the river, we know not. Ah, well! we may conjecture many things. The man talk as cheerfully as ever; jests are bandied about freely this morning; but to me the cheer is somber and the jests are ghastly. (Powell, 1875, p. 80.)

Top of the light colored Shinumo Quartzite is visible on the south side at river level, dipping to the east about 20 degrees.

SHINUMO QUARTZITE (LATE PRECAMBRIAN)

The most resistant formation in the Grand Canyon Series is the Shinumo Quartzite which directly overlies the Hakatai Shale and is well exposed in several localities within the canyon. This formation ranges up to approximately 1,100 feet thick and is characterized by almost pure quartz sandstone, tightly cemented with silica. On fresh exposure it is light gray but weathers to a dark gray-brown. It forms a very resistant cliff and in many places can be seen rising above the general surface of the Great Unconformity. The Shinumo stands out in marked contrast to the red sands and shales above and below, for it consists of metamorphosed grains which slightly interlock. Shinumo bedding consists of crude horizontal layers which range from a few inches to several feet thick.

Mile 74.9.—High bluff on the north side at the rapids is the Tapeats Sandstone resting on the Grand Canyon Series.

Mile 75.0.—The prominent white cliff formed on the upper Shinumo Quartzite shows well above the red siltstones and sandstones of the lower part of the formation.

Character of the canyon changes drastically as the soft easily eroded shale of the Dox Formation gives way to the hard resistant Shinumo Quartzite which here forms the narrow, nearly vertical-walled gorge.

Because the rocks dip upstream older and older rocks are encountered as one proceeds through this section where the chasm cuts into the lower part of the Grand Canyon Series. Certainly the area of Grand Canyon near Unkar Rapids is among the most cheerful and comfortable parts of the canyon because of the open floor and the bordering expanse of rolling hills. Contrast your feelings at Mile 75 when you look upstream with those when you look downstream.

The lowermost section of the Grand Canyon Series is exposed between

Mile 75 and Mile 78. The following rock units can be seen: (1) the Shinumo Quartzite which forms the major cliff; (2) the underlying red Hakatai Shale, similar in general character to that of the Dox redbeds seen upstream; (3) the siliceous Bass Limestone, a few hundred feet thick, which rests on top of (4) the patchy Hotauta Conglomerate which is at the contact with the older Precambrian metamorphosed, igneous and sedimentary rocks.

Mile 75.2.—SEVENTY-FIVE MILE RAPIDS (6) 15' DROP.

Mile 76.0.—THE HAKATAI SHALE APPEARS AT RIVER LEVEL, just below the basal ramparts of the red massive lower Shinumo Quartzite. The basal beds of the Shinumo Quartzite are reminiscent of the Nankoweap Formation and form the prominent sheer, massive cliffs above the very weak step-slope of the Hakatai Shale. The Hakatai Shale stands out in marked contrast to the overlying cliff of Shinumo, for it is the most brilliant red-orange shale formation of the Grand Canyon Series (Text-fig. 51).

HAKATAI SHALE (LATE PRECAMBRIAN)

The Hakatai Shale consists of a sequence of brown and red shale, 600 to 800 feet thick, which occurs below the Shinumo Quartzite and directly overlies the Bass Limestone.



TEXT-FIGURE 51.—Panorama view of the Grand Canyon from Lipan Point on the south rim. A number of unique features of the Grand Canyon are seen from Lipan Point and are indicated by the following numbers: (1) Tonto Platform; (2) V-shaped profile of the Granite Gorge; (3) white altered zone near the sill injected into the Bass Limestone; (4) Shinumo Quartzite; (5) Hakatai Shale; (6) unconformity between the Tapeats Sandstone and underlying Dox Formation.

Numerous ripple marks and mud cracks are obvious in this formation and indicate very shallow water deposition in which the sediments were repeatedly subjected to dessication. Best exposures of the Hakatai Shale are found in the vicinity of Hance Rapids (Text-fig. 52) where a basaltic dike and sill occur in the formation. The general character of the Hakatai is very similar to the Dox Formation but the two rock units are discriminated into separate formations because of the intervening Shinumo Quartzite.

Mile 76.5.—HANCE RAPIDS (9-11) 30' DROP IN $\frac{1}{2}$ MILE. The rapids are formed by an influx of sediments from Red Canyon to the south (Text-fig. 53). Hance Creek itself is located at Mile 78.5. Hance Rapids are particularly difficult because of the numerous rocks brought in from the creek to the south. The rapids are not exceptionally high but are very rocky over a long distance.

A dark basaltic dike has been injected into the Hakatai Shale at Mile 76.4, near the upper end of Hance Rapids (Text-fig. 52). Note that the dike near the rapids does not cut across the resistant Shinumo beds but becomes a sill and is injected parallel to bedding planes in the upper part of the Hakatai Shale. Difference between the very resistant quartzite sandstone of the Shinumo and the underlying weak redbeds of the Hakatai shows well at Hance Rapids.

Mile 76.8.—THE BASS LIMESTONE APPEARS ABOVE RIVER LEVEL AND FORMS THE LOWEST LEDGE OF THE GRAND CANYON SERIES, the cliff below the prominent red slope of the Hakatai Shale (Text-fig. 54).



TEXT-FIGURE 52.—Basaltic dike intruded into the Hakatai Shale just above Hance Rapids. Columnar jointing is expressed within the dike, perpendicular to its walls. The dike passes upward into a sill, parallel to bedding at the contact between the Shinumo Quartzite and the underlying Hakatai Shale. Minor dikelets can be seen cutting across the Hakatai beds in the same general zone as the major intrusion. Base of the Shinumo is etched out by differential erosion, near the top of the photograph, as are details in stratification of the Hakatai Shale.

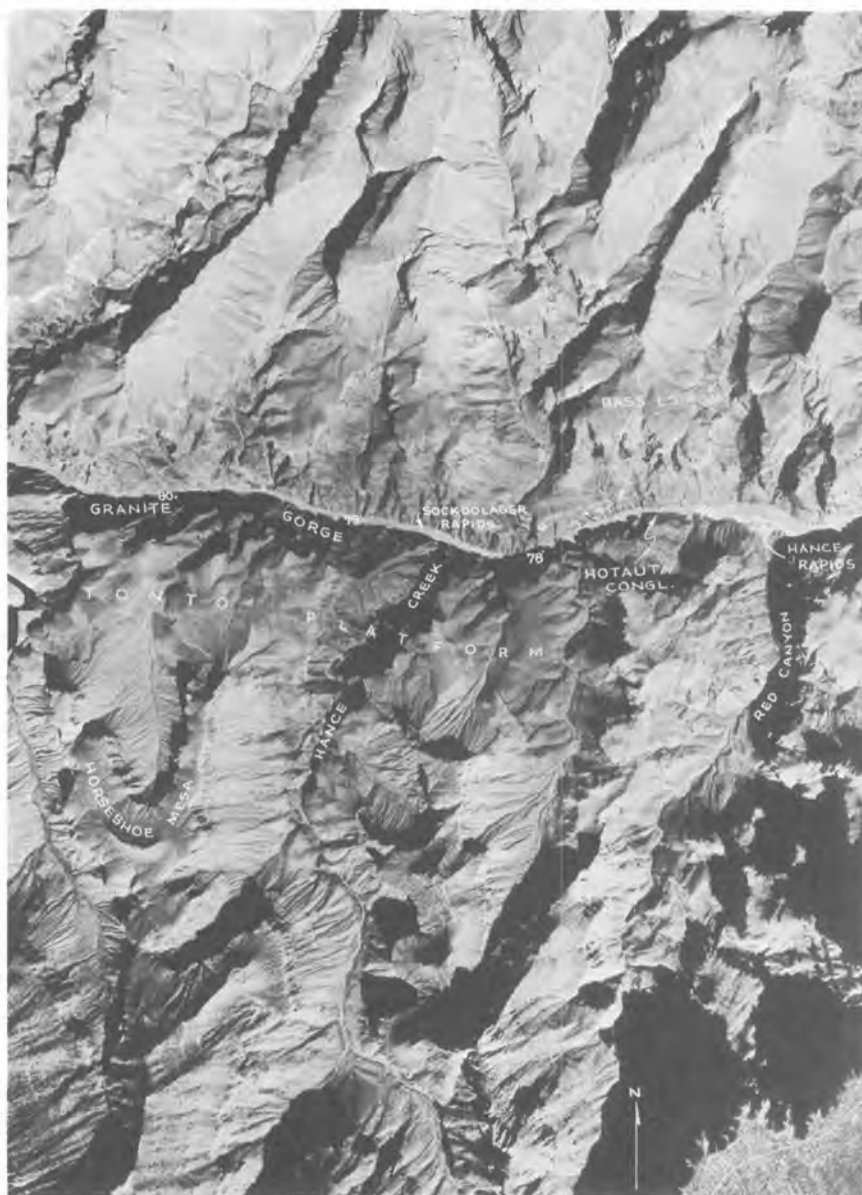
BASS LIMESTONE (LATE PRECAMBRIAN)

The Bass Limestone is a relatively inconspicuous formation within the Grand Canyon, but it constitutes a moderately resistant cliff approximately 250 feet high which can be seen just downstream from Hance Rapids. The Bass Limestone is a silty, reddish gray, obscurely bedded unit which contains impressions of organisms which are among the oldest direct evidences of life on earth. It is probably of marine origin. A thin sill, about as thick as the Bass Limestone separates the Bass beds from the underlying Vishnu Schist and Hotauta Conglomerate. The sill is typically green with crude columnar jointing. A prominent white zone, probably due to baking and marblization of the basal Bass Limestone forms a conspicuous layer (Text-figs. 51-53).

Mile 77.3.—Base of the Bass Limestone and the top of the sill are at river level. The sill is typically blackish green whereas the overlying Bass Limestone is red, separated by a prominent white bleached zone (Text-figs. 51 and 54). THE HOTAUTA CONGLOMERATE IS WELL EXPOSED ON THE LEFT SIDE OF THE RIVER (Text-fig. 55).

HOTAUTA CONGLOMERATE (LATE PRECAMBRIAN)

The Hotauta Conglomerate occurs in lenses and contains many of the various rock types found in the underlying Vishnu Schist. The most common are fragments of granite and quartz dikes, as well as some minor fragments of the schist. Most of the cobbles and boulders are well rounded in the upper part of the Hotauta, but near the base the fragments are highly angular and poorly sorted. The deposit is crudely stratified. The conglomerate is indurated and breaks across, rather than around, the gravels. It occurs as patches and lenses locally above the Vishnu Schist but is not a wide-spread unit.



TEXT-FIGURE 53.—Vertical aerial photograph showing the Colorado River in the vicinity of Granite Gorge from Mile 76 to approximately Mile 82. Many of the features shown in the oblique photograph in Text-figure 51 and in Text-figure 54 are seen here from a vertical view. The white altered zone associated with the Bass Limestone is clearly expressed in the central part of the photograph as is the prominent V-shaped Granite Gorge. The Tonto Platform is nearly a mile wide in this vicinity. The resistant Redwall Limestone responds to erosion to produce huge alcoves and amphitheatres.



TEXT-FIGURE 54.—View of the lower formations of the Grand Canyon Series at Mile 76.8.

The Shinumo Quartzite cliffs, in the upper right of the photograph are underlain by the Hakatai Shale which develops the smooth gentle slopes. The Bass Limestone forms the lower cliff which is crudely stratified and is underlain by a white layer which resulted from metamorphism associated with the intrusion of the basaltic sill. A small segment of the Precambrian metamorphic series can be seen where the river disappears around the bend.

Mile 77.4.—FIRST EXPOSURES OF THE EARLY PRECAMBRIAN UNCONFORMITY AND THE VISHNU SCHIST appear at water level, overlain by an excellent channel of the Hotauta Conglomerate.

THE EARLY PRECAMBRIAN UNCONFORMITY

A major erosional surface, similar in most respects to the Great Unconformity, separates the sediments of the Grand Canyon Series from the underlying metamorphosed rocks. Only limited exposures of this are preserved because the Grand Canyon Series has been removed in most areas prior to development of the Great Unconformity so that the early Precambrian Unconformity, the Grand Canyon Series, and the Great Unconformity are all represented by the surface beneath the Tapeats Sandstone. When seen along the river the early Precambrian Unconformity appears as a nearly plane surface or a straight line, parallel to bedding in the overlying Grand Canyon Series. A significant "soil" profile is developed on this surface and all physical evidence indicates that this discontinuity could well represent a time interval equal to that of the younger Great Unconformity.

Metamorphic rocks like these below the Early Precambrian Unconformity are interpreted to form only at great depth, under high temperatures and pressures. A considerable amount of uplift and erosion is therefore necessary to expose them at the earth's



TEXT-FIGURE 55.—View of the wall of the canyon at Mile 77.4, showing the Precambrian metamorphic complex at river level overlain by a thin lens of Hوتاута Conglomerate in the center of the photograph. Hوتاута Conglomerate is overlain by a basaltic sill which appears dark grey with crude columnar joints. A baked zone at the base of the Bass Limestone weathers light gray and separates the sill from the overlying limestone cliffs.

surface. The contact of sedimentary and metamorphic rocks clearly implies that the metamorphic rocks represent exhumed "roots" of very ancient mountains. The folding which produced these mountains took place approximately 1.5 billion years ago, prior to deposition of the Grand Canyon Series.

The early Precambrian Unconformity is one of the most important boundaries between major rock units within the canyon and even a person with little geologic background can recognize the sequence of events necessary for its development and can gain an insight into the immense magnitude of geologic time.

EARLY PRECAMBRIAN ROCKS

VISHNU SCHIST, BRAHMA SCHIST, AND ZOROASTER GRANITE

The oldest rocks within the Grand Canyon are exposed within Granite Gorge and are characteristically dark somber gray. They respond to erosion to form a steep-walled V-shaped gorge (Text-fig. 56) through which the Colorado River flows from Mile 77 downstream to beyond Phantom Ranch. These dark colored rocks are evidence of extensive deformation, during which they were subjected to intense heat and pressure and the



TEXT-FIGURE 56.—Upper end of Granite Gorge at Mile 77.5. The V-shaped character of Granite Gorge is well expressed below the dipping strata of the lower formations of the Grand Canyon Series. The white altered basal Bass Limestone is seen high on the right of the photograph. Weathered debris of this material is accumulating as light talus slopes. The Bass Limestone forms the skyline to the right.

effects of fluids and gases. The original sedimentary or volcanic characters have been extensively modified and in some cases obliterated. Early Precambrian rocks are not stratified but possess a planar structure known as foliation, resulting from reorientation of platy minerals, crystals, and grains in response to deformation. Foliation throughout most of Granite Gorge is nearly vertical which contrasts with the horizontal stratification of the overlying younger rocks.

Three major rock bodies are found within the Early Precambrian complex. The first encountered on the river trip consists of metamorphosed sedimentary rocks in which some relict sedimentary structures are preserved. This body of baked and altered rocks is known as the Vishnu Schist and is exposed downstream beyond Hance Rapids to near Zoroaster Canyon. They represent part of the older rocks of the earth's crust. Very little detailed information can be gained about their environment of deposition since the original character of the rock has been nearly completely obliterated.

Downstream from Zoroaster Canyon is a sequence of metamorphic rocks which differ in composition, color, and texture from the Vishnu Schist but superficially appear similar to it because of their degree of metamorphism. These rocks are known as the Brahma Schist and probably represent metamorphosed volcanic rocks. Numerous granitic dikes have intruded into both the Vishnu and Brahma schists. Most of these dikes are nearly vertical and parallel to foliation of the schists and stand out in marked contrast to the metamorphic material. Rocks of the dikes are characteristically pink, light colored, and composed of large interlocking crystals of feldspar and quartz, many of which are over a foot in diameter. These intrusions become very numerous in many areas and in some localities make up more than 50 percent of the rock body. Near Zoroaster Canyon dikes are particularly common and one large massive intrusion is dissected by the canyon.

Large granite bodies of the Inner Gorge are referred to as the Zoroaster Granite and represent a period of igneous activity after deposition and metamorphism of both the Brahma and Vishnu Schists but before deposition of the overlying Grand Canyon Series and Paleozoic formations.

The Vishnu Schist in the upper part of the gorge contains many pink pegmatite dikes. Many units within the schist are well foliated and may appear similar to a gneiss. Locally, relict bedding can be seen indicating a sedimentary origin. Foliation is nearly vertical. The gray-green walls of the Vishnu Schist are crisscrossed by dikes of pinkish

granite. The ragged, ledgy, V-shaped character of the inner gorge is evidenced downstream.

Mile 78.2.—The canyon makes a 60 degree bend. The rugged exposures of the Vishnu Schist form the Granite Gorge with Tapeats Sandstone exposed in ramparts in the high rim (Text-fig. 57).

Mile 78.6.—SOCKDOLAGER RAPIDS (8) 19' DROP. Sockdolager Rapids is among the most rigorous on the river. It occurs at the mouth of Hance Creek in Granite Gorge where the V-shaped canyon provides no opportunity to stop and survey the best course. Prepare to ride out a rather rigorous go. Batten down the hatches. Prepare to get wet.

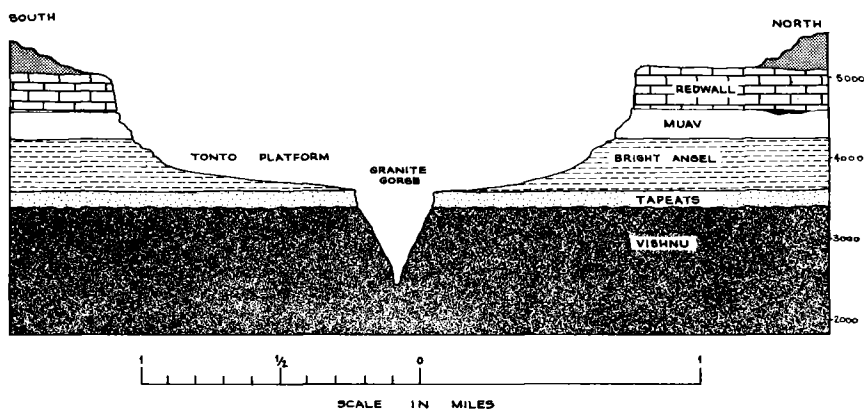
Mile 79.6.—Two small spurs of light-colored dikes on opposite sides of the canyon restrict the gorge.

Mile 80.5.—Very thick dikes of pink Zoroaster Granite cut vertically through the dark gray-green Vishnu Schist, parallel to foliation. These large dikes are as much as 100 feet wide.

Mile 80.9.—A wide pink granitic dike extends out into the river for a considerable distance.

Mile 81.5.—GRAPEVINE RAPIDS (10) 18' DROP. From Mile 81 to 83 dikes are very rare within the Vishnu Schist and one can see the vertical foliation and numerous potholes on either side of the canyon. In this part of the canyon foliation is very closely spaced, almost slaty-appearing, although the bedrock is a schist.

Mile 83.0.—The large valley on the right is probably eroded on a basic dike that is more susceptible to erosion, hence it formed a relatively broad valley 300 feet wide. The Tapeats Sandstone is occasionally visible capping the rim of the inner gorge. The white material seen locally within the Vishnu Schist is small



TEXT-FIGURE 57.—Cross section showing the rock sequence and canyon profile at approximately Mile 78. A V-shaped profile is developed on the Vishnu Schist forming Granite Gorge. The Tapeats Sandstone forms the bold cliff at the rim of Granite Gorge. The Tonto Platform is approximately 1.5 miles wide, carved on the Bright Angel Shale. Younger Paleozoic strata form the upper part of the canyon.

veins of quartz that have been twisted and crumpled by movements responsible for deformation of the schist. The Vishnu Schist appears almost jet black on weathered polished surfaces but where fresh exposures are available it is generally green with injections of white quartz parallel to the foliation.

Mile 83.6.—EIGHTY-THREE MILE RAPIDS (6) 7' DROP.

Mile 84.0.—The Tapeats Sandstone caps the Zoroaster Granite downstream. Zoroaster Granite stands out in contrast to the Vishnu Schist in that it is a pink, igneous, granitic intrusion which lacks foliation.

Mile 84.3 to approximately 84.6.—BRAHMA SCHIST IS EXPOSED ON THE NORTH AND SOUTH WALLS of the canyon above the Zoroaster Granite. The Brahma Schist is much more slaty appearing but still has a dominantly vertical pattern of foliation. On the north side of the canyon it forms a prominent, slaty-looking outcrop, in contrast to the more massive gneissic material of the Vishnu.

Mile 84.6.—ZOROASTER CANYON RAPIDS. THE ZOROASTER GRANITE IS EXPOSED AT RIVER LEVEL and is an excellent example of an igneous intrusive body. It has a sharp contact with the Brahma Schist near



TEXT-FIGURE 58.—Exposures of Zoroaster Granite in walls of the inner gorge at approximately Mile 85. Dark Brahma Schist is visible downstream, capped by Tapeats Sandstone.

Zoroaster Canyon. The granite is typically homogeneous, medium- to fine-grained, and pink with little internal structure, except a crude jointing system which is nearly vertical. Excellent examples of dissected potholes occur on the left bank in Zoroaster Granite.

Mile 85.3.—Excellent examples of sheeting developed in the granite downstream from the margin of the intrusive. Black dike cuts the rocks below the Tapeats high to the southeast. Pink granitic dikes are cutting the granite as well. Zoroaster Granite produces the relatively smooth exfoliated walls on both the north and south sides of the canyon (Text-fig. 58).

Mile 85.7.—The contact between the Zoroaster Granite and the Brahma Schist is exposed downstream. This contact slopes to the west at a high angle. The Brahma Schist is intruded by numerous dikes of granite undoubtedly associated with the large Zoroaster body. In many places it appears that most of the rock is granite with large inclusions of the dark Brahma Schist enclosed in the igneous material. Other major dikes trend nearly vertically whereas minor dikes zigzag in the canyon wall. A prominent side canyon from the south is near the contact zone.

Mile 85.8.—A view upstream to the southeast shows the sill-like structure of the granitic bodies as they parallel the foliation of the Brahma Schist and overlie the major contact with the granite. Large crystals of feldspar, some as much as two feet in diameter, can be seen in the pink rocks. These reflect sunlight



TEXT-FIGURE 59.—Brahma Schist cut by light granite dikes exposed in the walls of Granite Gorge.

from cleavage planes in the coarse-textured minerals in dikes cutting through the schist (Text-fig. 59).

Mile 86.9.—The sharp tributary canyon trending to the southeast is the result of faulting.

Mile 87.0.—The water gauging station at Phantom Ranch is visible on the right downstream. On the north side, complex folding can be seen in the massive light dikes that cut through the vertical Brahma Schist.

Mile 87.1.—Another small fault cuts the Brahma Schist parallel to the one seen at Mile 86.9. The north abutment of the suspension bridge over the Colorado River can be seen downstream, beyond the water gauging station.

Mile 87.2.—Gauging station cable over the river.

Mile 87.4.—Suspension bridge at the mouth of Bright Angel Creek connects trails from the north and south rims. Upstream from the bridge the Tapeats Sandstone rims the V-shaped inner gorge (Text-fig. 60).

Mile 87.5.—Landing at sand bar upstream from Bright Angel Creek. Phantom Ranch is a short distance upstream from the mouth of Bright Angel Creek. Reservations are necessary for accommodations. In the vicinity of Bright Angel



TEXT-FIGURE 60.—Granite Gorge as seen upstream from the upper suspension bridge at the mouth of Bright Angel Creek. Dark gray Brahma Schist forms the bedrock of the inner gorge of this region and is intricately laced with dikes and dikelets of characteristically pink granite. The top of Granite Gorge is capped with ramparts of horizontal Tapeats Sandstone. Granite Gorge is slightly more than 1,000 feet deep in this area, but total depth of Grand Canyon here is more than one mile.

Creek a small wedge of the Grand Canyon Series is preserved in an ancient Precambrian fault block beneath the Tapeats cliffs. In this area the Shinumo Quartzite dominates the sequence and evidently existed as an island in the seas where the Tapeats was deposited inasmuch as it protrudes through the Tapeats Sandstone up into the middle of the Bright Angel Shale.

If one chooses to walk up to the south rim, two trail are well maintained by the park. Bright Angel Trail leads to Grand Canyon Village. It is somewhat longer but has a more gentle gradient. In addition, water is available at Indian Gardens. The Kaibab Trail to Yaki Point is shorter but steeper. No water is available along the route. Transportation is not readily available from Yaki Point to Grand Canyon Village without prior arrangements. One should allow approximately eight hours for the hike out on either trail. Exit by mule train can be made with previous arrangements through the concessionaire at the park.

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