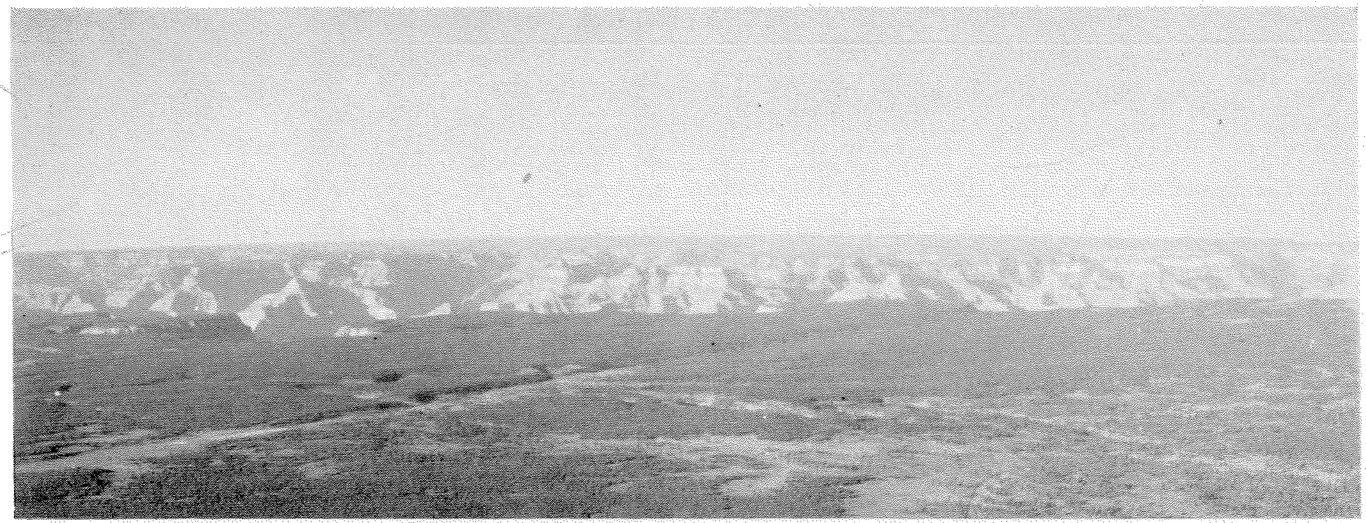

FIG. 1—General setting of the Grand Canyon. View looking northward over the Colorado Plateau in Grand Canyon National Park. The plateau to the north of the canyon is known as the Kaibab Plateau, and that to the south, as the Coconino Plateau.

RELATIONSHIP OF SCENERY TO GEOLOGY IN THE GRAND CANYON

By JOHN H. MAXSON

THE great canyon cut by the Colorado River for a distance of over 200 miles across the Colorado Plateau is one of the great sights of the world. It is a narrow, V-shaped stream valley with precipitous, stepped, side walls. Although it is relatively deep in proportion to its breadth, being nearly a mile deep near the village of Grand Canyon and only thirteen miles wide, there are other valleys in the world which are relatively more steeply walled, although not so deep. There are other valleys that are just as deep, although broader.

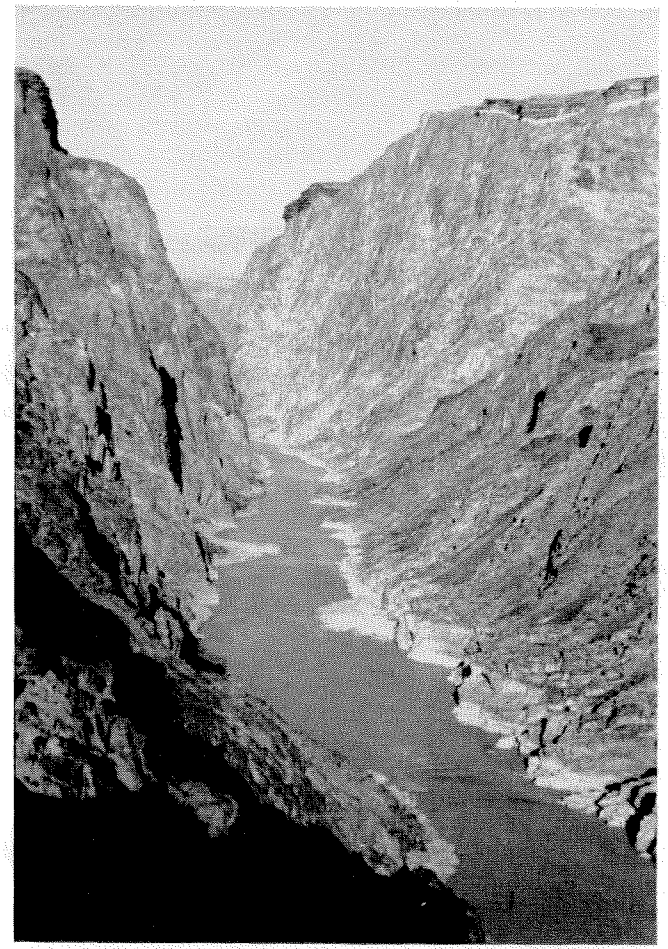

FIG. 2—Looking westerly down the deepest part of the Inner Gorge below the mouth of Zoroaster Creek.

What causes the Grand Canyon to have greater fascination for the human eye than other valleys and canyons? It is the fact that its geologic structure, faithfully revealed by processes of erosion, is on a large scale and produces interesting lineaments both vertical and horizontal. The regularity of the great and continuous cliffs with their subjacent benches is elaborated in plan into an apparent confusion of spired promontories and deep alcoves. To these lineaments is given a vivid and contrasting coloration by the geologic constitution of the rocks themselves. Since geologic circumstances are responsible for the peculiar attraction of Grand Canyon scenery, an analysis of the geologic and erosional history will contribute to the enjoyment of a visit by any scientifically minded person.

The Canyon has attracted many visitors, scientists and non-scientists alike, during the long period of time that has elapsed since its discovery by the Spaniard, Cardenas, in 1540. The first 200 years after discovery were ones of continued solitude so far as the historic records are concerned. During the later part of the eighteenth century the Canyon was visited by Spanish priests, and during the early part of the nineteenth century it was occasionally seen by pioneer herdsmen, hunters, and trappers. Through all these years of occasional visits, the depths of the Grand Canyon of the Colorado remained a mystery.

EXPLORATION OF THE GRAND CANYON

In 1869, the geologist, Major John Wesley Powell, a one-armed Civil War veteran, started down the river from Green River, Utah. He began the journey with nine men and four boats, and concluded it three months later a thousand miles down the stream after losing two boats on the river. Three men left the expedition en route at Separation Canyon. They thought that this canyon offered access to the north rim and were tired of the constant wettings and other hardships which the river trip entailed. Since no one had ever made the trip before, no one could be sure that even greater rapids than those through which they had managed to pass did not lie ahead. But the abandoning of the main party proved a mistake, for the three men were murdered by Indians when they reached the north rim, and the remainder of the party a short time later successfully passed the remaining rapids. Powell found the Grand Canyon to be replete with spectacular geological phenomena, and did not abandon his explorations after his first dangerous and difficult trip. In 1873, he again led an expedition down the Colorado River.

In considerable measure, because of the losses and difficulties experienced by the Powell expeditions, the Colorado River in the Grand Canyon district gained the reputation of being no place for a pleasure boat trip. However, many parties have passed through subsequently, and, when suitably equipped, the parties have suffered no losses. Some people have made the trip to obtain photographs, some to study botany, and some to study geology (including the California Institute of Technology--Carnegie Institution Expedition of 1937), and many have gone through just for the sake of adventure. Most people, however, will doubtless continue to visit the points on the rim where the mighty features may be viewed with ensemble effect. During good tourist years over 300,000 people visit Grand Canyon National Park. The Government, through the National Park Service, is attempting to provide visitors to all of our parks not only with recreation, but also to some degree with education. At the Grand Canyon this education is in large measure geologic.

EXPLANATORY DESCRIPTION OF LAND FORMS

The general explanation of land forms of the Grand Canyon is by no means complicated. Land forms are usually described genetically in terms of three factors: structure, process, and stage. Structure refers to the geologic structure of the materials constituting a given land form or region of land forms. It includes such things as stratification or non-stratification of the rocks, and their relative hardness, as well as the physical relations of rock masses to each other brought about by folding or faulting. Structure, in its geomorphic sense, is the major topic of discussion in this article. The other two factors will be briefly disposed of.

Process means the type of erosion actively operating on the given land form or in its vicinity. In the case of the Grand Canyon the only perennial streams are the Colorado River itself and a few major tributaries. Elsewhere in the valley the processes of erosion are those characteristic of an arid climate and they include weathering, which is mainly mechanical, leading to fracturing and disintegration of massive rocks, and, to a lesser extent, chemical decomposition. Occasional rains assist in transportation of debris down temporary stream courses and pick up calcium carbonate from the soluble limestones. As might be expected in a precipitous terrain, mass movement of rock fragments under the influence of gravity assists in the removal of the products of weathering. The third factor, stage, represents the point reached in the cycle of erosion. It is the degree to which the original high-lying area has been reduced to a land surface of low relief. In the vicinity of the Grand Canyon it is obvious that very little progress has been made, and that extensive, nearly flat highlands form the adjacent Colorado Plateau. The Grand Canyon, then, is a youthful geomorphic feature. Just how youthful we cannot say in terms of years, but it is likely that the canyon has been cut during the Pleistocene Epoch—that is, during the course of the last million years, more or less.

Cover Illustration

FIG. 3—Fluting and potholing of granitized schist in the Colorado River channel in the lower part of the Grand Canyon. (Photo by E. T. Schenk, U. S. National Park Service.)

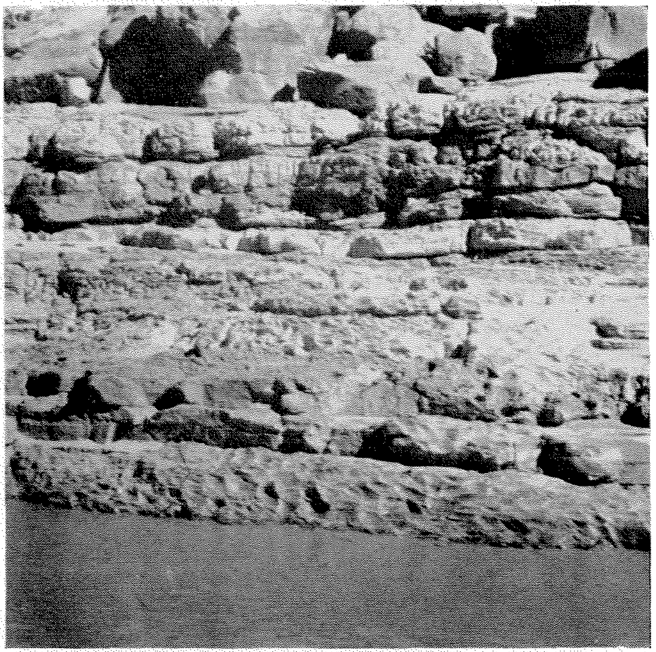

FIG. 4—Fluting developed on limestone strata of the Colorado River channel in Marble Canyon.

FIG. 5—California Institute-Carnegie Institution expedition of 1937 passing through the Inner Gorge.

STRUCTURE AND GEOLOGIC HISTORY

The detailed shapes of the land forms are controlled by structure which we can subdivide into two categories. First, is the structure which controls cross profile, and this may be termed vertical control. The second type is structure which controls distribution of feature in plan,

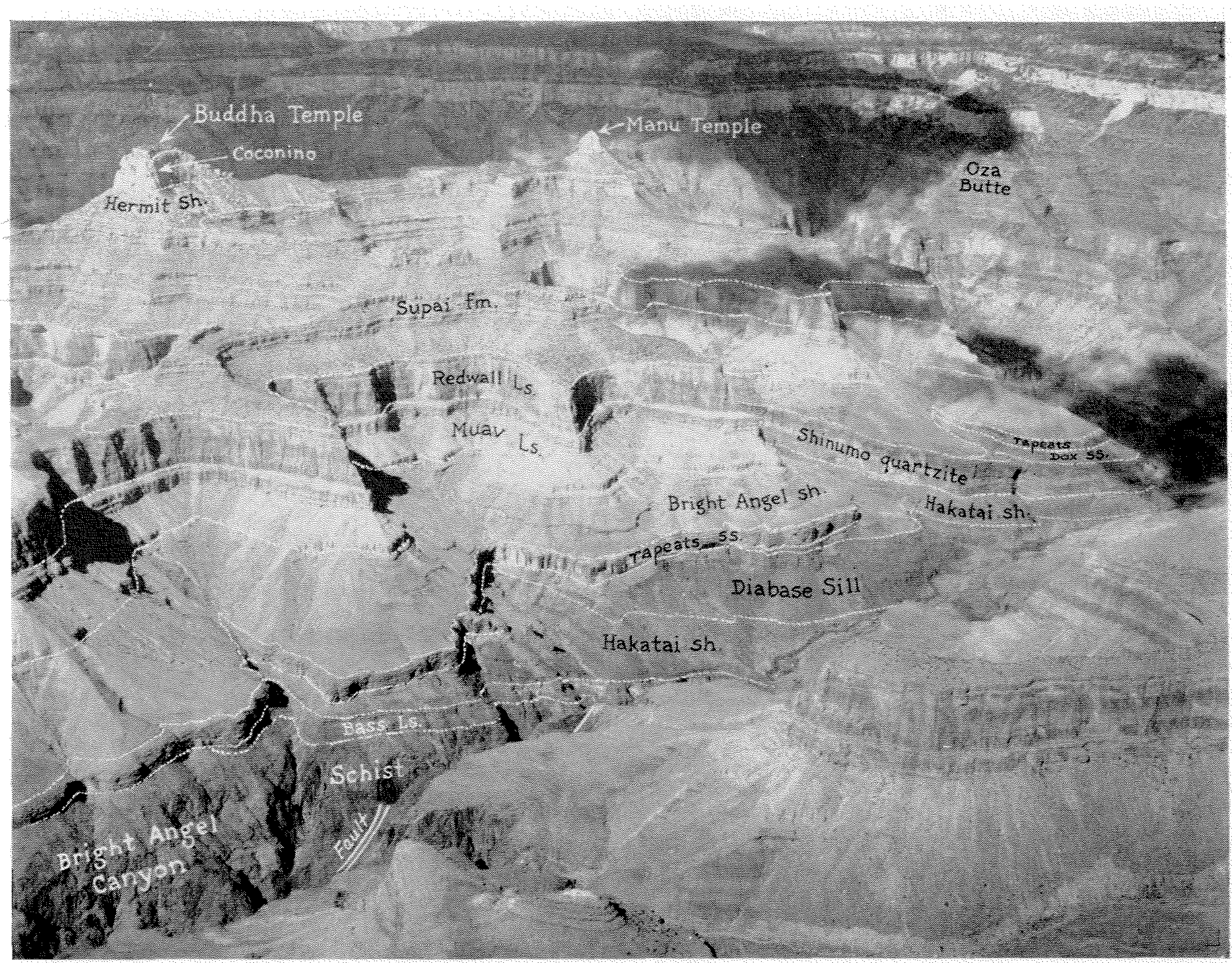

FIG. 6—This view shows the Wedge Series of Bright Angel Canyon sloping northward (to the right) and lying on a remarkably flat erosion surface cut on schist. The series is truncated, giving it wedge form, and overlain by the nearly horizontal Tapeats sandstone (basal member of the Horizontal Series) with angular unconformity.

and this may be termed horizontal control. The vertical control is dependent upon the sequence of rock types existing from the bottom of the Grand Canyon upwards to the rim. The horizontal control consists of the inherited direction of flow of the master stream, the Colorado River, and the direction of fault zones, shatter zones, and joint systems in the rock mass as a whole. The geologic history which offers the key to vertical control was simply described by the late Professor-Emeritus William Morris Davis, of Harvard, who was Professor of Physiographic Geology at the California Institute, 1930-1934, somewhat as follows: There are three major groups of rocks in the walls of the Grand Canyon: the Vertical Series of hard rocks at the bottom, the Wedge Series of tilted rocks at intermediate levels, and the Horizontal Series, consisting of alternating hard and soft, stratified, nearly flat-lying beds in the upper and outer canyon.

The Vertical Series is along the bottom where the Colorado River is cutting the Inner Gorge. It consists predominantly of vertically standing schists and pegmatite dikes. The sedimentary parts of this series were laid down as a part of the earliest geological record on the earth, in Archean times, possibly as much as a billion and a half years ago. Originally, they were sands and shales deposited in a broad and shallow sea. There came a period of crustal deformation and intrusion, believed to be a part of the Laurentian Revolution, which affected the whole earth. The sediments were

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FIG. 7—Looking westerly over Grand Canyon and Coconino Plateau from over vicinity of Trinity Creek. This view illustrates vertical control and topographic subdivisions within the canyon. 1. Vertical Archean schist; 2. Tapeats sandstone, lying on flat erosion surface and forming cliff separating Inner Gorge from Outer Canyon; 3. Bright Angel shale, eroding back to form prominent Tonto Platform; 4. Muav limestone, forming cliffs and slopes, the formation that is sapped from beneath the Redwall cliffs; 5. Redwall limestone, the major cliff-forming member of the Horizontal Series; 6. Supai formation, consisting of red sandstones and sandy shales; 7. Hermit shale, uppermost member of Supai formation is fine-grained, red shale, forming low slope or bench. Farther to the west the Esplanade (see FIG. 9) is cut as this level; 8. Coconino sandstone, prominent white, cliff-forming stratum of cross-bedded, wind-lain sandstone; 9. Toroweap formation of impure limestones and limey shales forms steep slope; 10. Kaibab formation of thick limestone strata forms cliff.

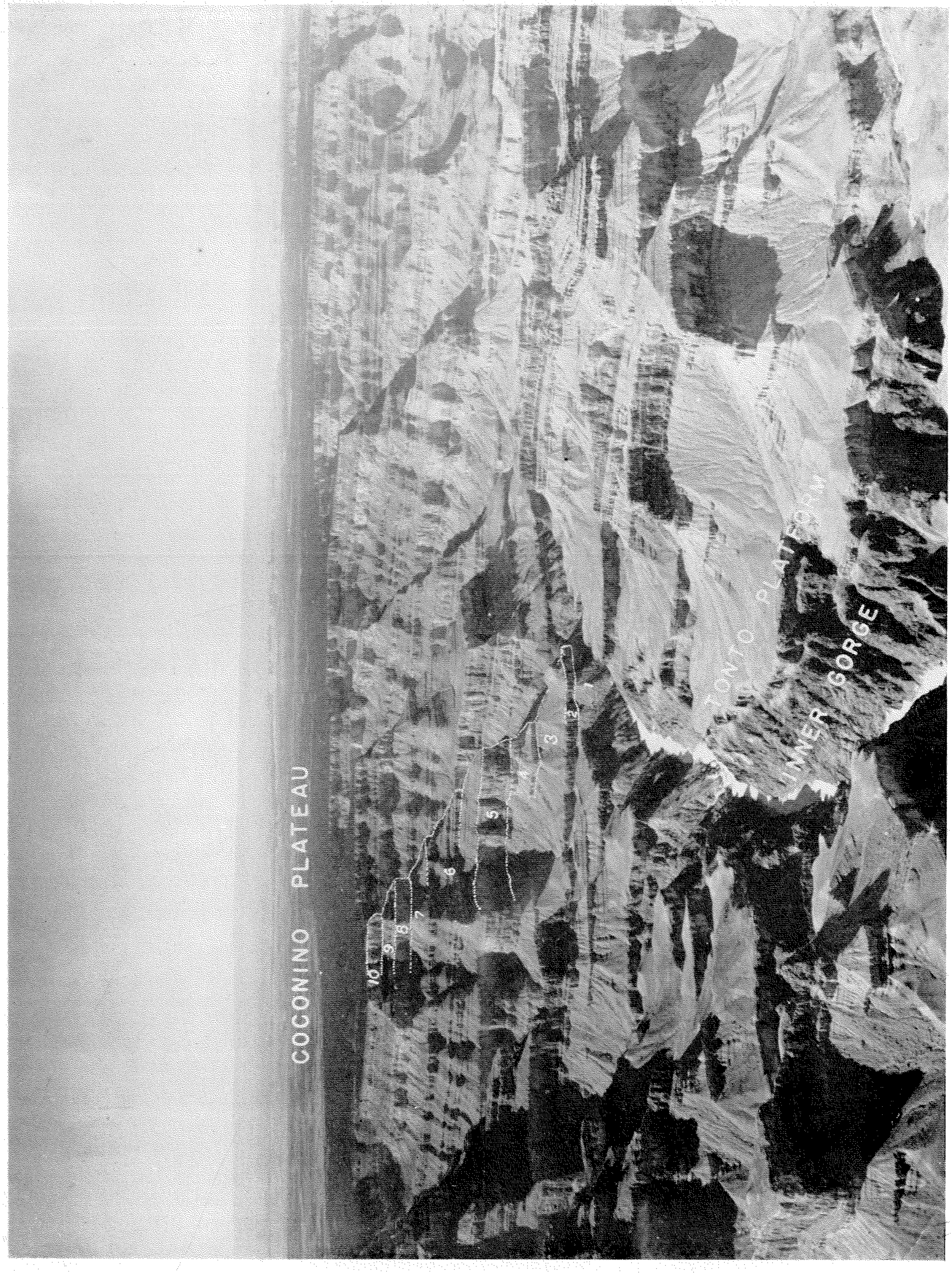

FIGURE 7

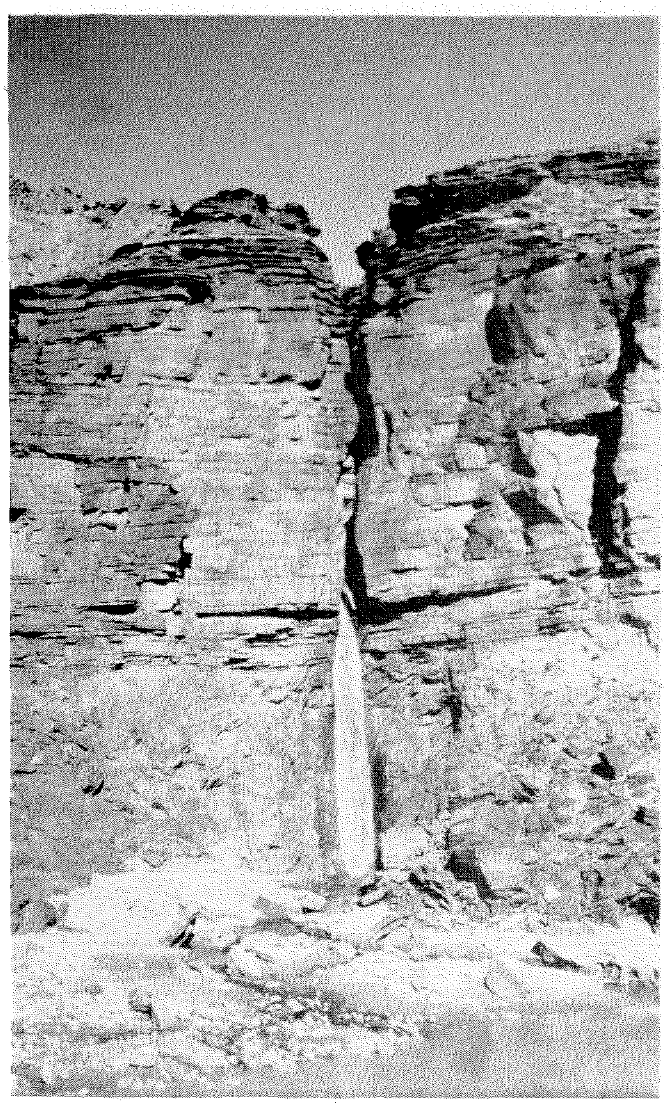

FIG. 8—Deer Creek Falls. Downcutting in Colorado River channel is so rapid that, although narrow slot has been cut in Tapeats sandstone cliff, Deer Creek has not been able to reach an accordant junction with the master stream. It constitutes one of the exceptions to Playfair's Law of Accordant Junctions.

compressed, and a great mountain system was built. The sediments were subjected to heat and pressure, and were metamorphosed into schists and quartzites. Juices from a deep-lying granite batholith worked their way up along the planes of foliation of the metamorphic rocks. Then followed a long period of erosion. The mountains were worn completely away, and an almost perfectly level surface was cut across the steeply dipping schists. From the cross sections of this erosion surface exposed in the walls of the Grand Canyon it had practically no relief whatever and therefore was more advanced than a peneplain. It was, in fact, a true erosional plain. No true erosional plain of such large extent is now known on the surface of the earth.

This plain was submerged beneath the sea and a great thickness of sandstones and shales accumulated. During the last phases of the accumulation of this series there was volcanic activity; basaltic lavas were erupted on the surface and injected as sills in the earlier strata. There followed another period of crustal deformation and erosion. This time, instead of being folded, the region was broken into blocks and faulted. Various blocks were tilted. Erosion led to beveling of these strata, and they may therefore be termed the Wedge Series. They are of Algonkian Age and may have been deposited between 500,000,000 and 1,000,000,000 years ago.

The erosion surface which was developed after the tilting of the Wedge Series was one of very low relief. Some fault block hills rising 500 feet above the general level remained, and it may therefore be termed a peneplain. This peneplain was submerged beneath the sea, and a sandstone accumulated in the seaways between the archipelago-like fault block islands. Later, shale was deposited on top of the sandstone and this accumulated to such thickness that the islands were buried. These and succeeding formations of the Paleozoic Era are almost flat-lying, having but a gentle slope to the south. This series may therefore be called the Horizontal Series.

Of the three components, the Vertical Series and the Horizontal Series have had the greatest influence on the topography because they are generally present throughout the Grand Canyon, whereas the Wedge Series occurs only in isolated localities.

LAND FORMS IN THE VERTICAL SERIES

The Vertical Series are, in a broad sense, geomorphically homogeneous—that is, the various rocks in the series have about equal resistance to stream erosion. They are compact and hard. Since the river is cutting downward in its channel rapidly in proportion to the erosion of the side walls, the valley is very steep-walled. From its position this chasm has received the name Inner Gorge. It is sometimes called the Granite Gorge, but this is a misnomer, since only a few relatively short stretches are cut in more or less homogeneous granite. The Inner Gorge is the scene of the most active stream erosion. The Colorado River can do an enormous amount of work during flood stages. During flood the discharge may total 125,000 sec. ft. in a single day, and

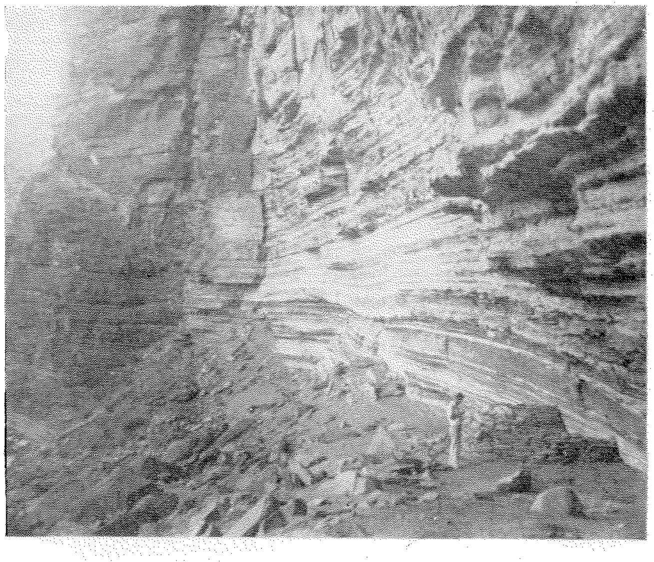

FIG. 9—Detail of Tapeats sandstone cliff showing accumulation of rubble by fall of joint blocks. Under overhanging ledge is ruin of an Indian shelter. Remains of Indian shelters and food caches are found in some of the most inaccessible parts of the canyon.

FIG. 10—Looking westerly down the Grand Canyon from above the vicinity of Havasu Creek. The origin of the meanders of the Colorado River shown by the dashed line is one of the geomorphic problems of the Canyon. They are believed to have been superposed from a surface higher than any in the photograph. The Esplanade itself is not a stream terrace, but originated by retreat of the Coconino cliffs through sapping of the relatively soft Hermit shale. The stripped surface is on thick-bedded sandstone of the upper Supai formation.

during such discharges the mean velocity in the total cross section of the river is about 10 ft/sec. In the upper part of its course, through Wyoming and Utah, the Colorado River picks up a great amount of sediment. During flood stage in the Grand Canyon as much as 27,600,000 tons of suspended matter has been recorded passing a gaging station in a single day. This does not include the bed load of the stream, which is carried along or near the bottom of the channel, although some estimates place this bed load as constituting 20 per cent of the total load. The endless barrage of silt particles, borne by turbulent high velocity stream currents, operates as a sand blast, actively abrading the channel walls and boulders in the channel. Soft rocks like limestone are fluted in accordance with the turbulence pattern. If it were not for the extremely effective reduction of boulders, the Colorado channel would be choked by huge deltas at the mouths of steep gradient tributaries. As conditions are, large boulder deltas accumulate, which produce the rapids forming the hazard to boat navigation.

The Inner Gorge is a dark and somber place, for the rocks are brownish-black, and the walls cut out much of

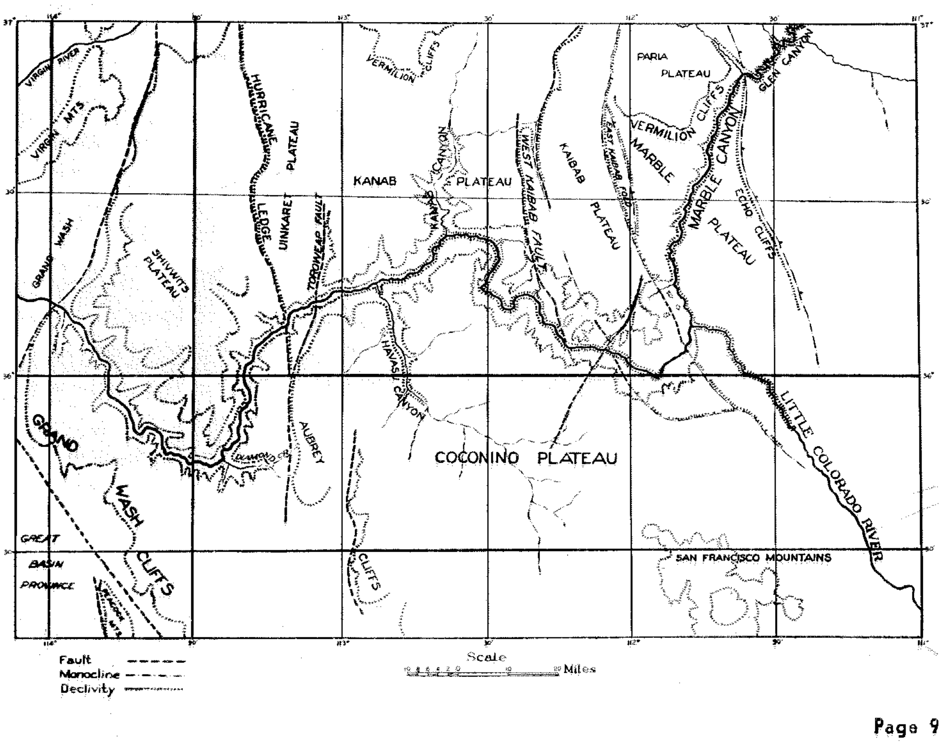

FIG. 11—Major structural lineaments in the Grand Canyon district.

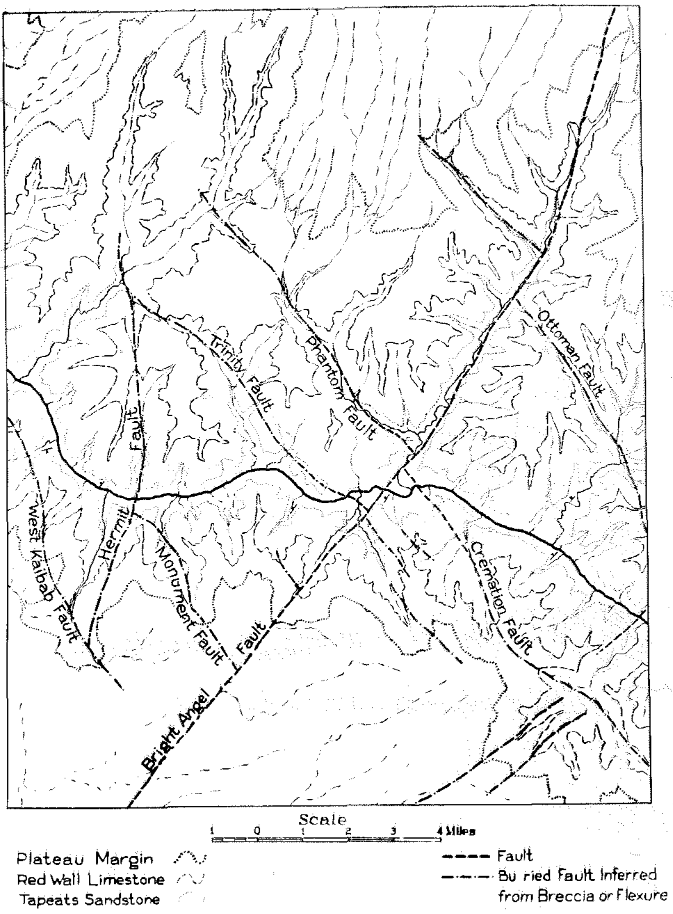

FIG. 12—Plan relationship of topographic features of the Bright Angel quadrangle to structural pattern.

the sunlight. Except at midday, the shadows are long and continuous. In the vicinity of the deltas the great rapids make a constant roar that reverberates through adjacent parts of the Inner Gorge.

VERTICAL CONTROL IN THE WEDGE SERIES

In some places a thin conglomerate (Hotauta) lies over the flat erosion surface cut on the Archean schists and granites. Elsewhere, this surface is overlain by a brown limestone (Bass) which forms a step-like series of low cliffs. This limestone is overlain in turn by a thick shale deposit (Hakatai) which is relatively easily eroded to form a bench, although small cliffs are formed by the more resistant sandy members. This shale is overlain by a very thick quartzite formation (Shinumo) which forms high cliffs wherever found. The quartzite is overlain by a very thick series of sandstones (Dox), some of which form cliffs, others of which form benches. This lower part of the Wedge Series (Unkar) may be seen in the headwaters area of Bright Angel Creek on the north side of the Grand Canyon opposite the village. Overlying this group is the upper Wedge Series (Chuar), which contains limestones and shales and erodes into cliff-bench topography. This series is found only in the upper end of the Grand Canyon and it can be seen to the northeast of Grandview.

Diabase dikes, sills, and flows are found at various places in the Wedge Series and generally form steep, but not vertical, cliffs. During the erosion period which followed tilting of the Wedge Series, fault block ridges capped by resistant Shinumo quartzite formed monadnocks.

VERTICAL CONTROL IN THE HORIZONTAL SERIES

The land forms in the Horizontal Series can best be understood by referring to *Fig. 7* in connection with the following discussion. The lowest and oldest formation of the Horizontal Series is a sandstone (Tapeats), which overlies the old erosion surface cut across the Archean metamorphics and the Wedge Series, and everywhere forms a precipitous cliff. This cliff marks the outer boundary of the Inner Gorge and the lower boundary of the Outer Canyon. It weathers to a dark brown in color. Overlying the sandstone is a shale formation (Bright Angel) which is everywhere bench-forming. The broad bench which has been formed by erosion back of the Bright Angel shales is one of the characteristic features of the Outer Canyon in the Bright Angel district, and to it is given the name Tonto Platform. An old Indian trail follows for many miles along the Tonto Platform on the south side of the river. Overlying the shale is a series of impure limestones (Muav), which in their upper portion form cliffs, in

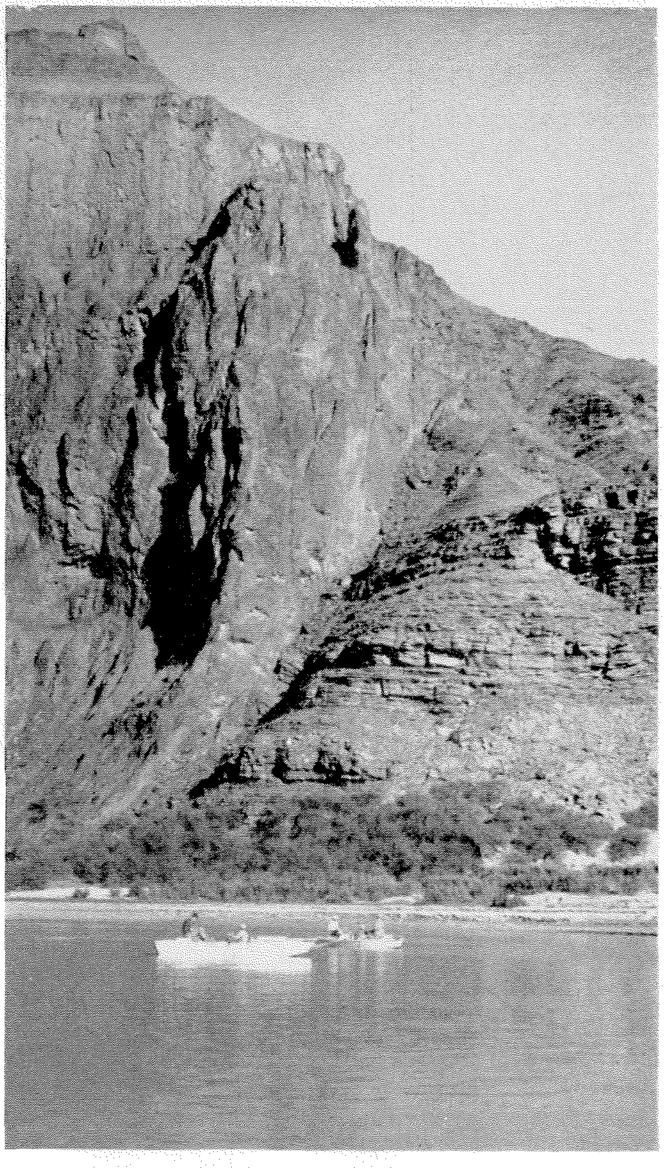

FIG. 13—West branch of Butte fault. During first epoch of movement left side is believed to have gone down. During last movement left side went up and flexed the overlying strata as shown in FIG. 15.

the middle portion form steep slopes, and in the lower portion form cliffs. The Muav limestone and Bright Angel shales have weathered to a pale yellowish green.

Overlying the Muav limestone in the eastern part of the Grand Canyon is the Redwall limestone which is everywhere cliff-forming, and which forms one of the most prominent topographic breaks in the Outer Canyon. The Redwall limestone is actually a compact grayish-white limestone whose outer surface has been stained reddish by iron oxide washed down from the overlying red Supai Formation. This latter formation consists of alternating sandstones and shale beds which form respectively cliffs and benches. The upper part of the Supai consists of red shale (Hermit), which overlies a rather thick red sandstone. The Hermit shale is a bench-forming member and in the western part of the Grand Canyon has been eroded back on the top of the heavy sandstone, forming a broad bench, known as the Esplanade. Overlying the Hermit shale is a thick, white, wind-laid sandstone (Coconino), which everywhere forms a prominent cliff. This in turn is overlain by a series of impure limestones and shales (Toroweap), which forms a steep slope resulting from alternating cliffs and benches. Resting on the Toroweap and forming the plateau surface to the north and south of the Grand Canyon is the Kaibab limestone, which forms prominent grayish-white cliffs.

The stepped topography of the outer part of the Grand Canyon, which is so important to cross profile form, is due to the fortuitous alternation of beds having widely different resistance to erosion. Also, by chance, there is an alternation of light-colored beds and dark-colored beds, with the striking red beds in intermediate position, which gives an effective color combination when seen from a distance.

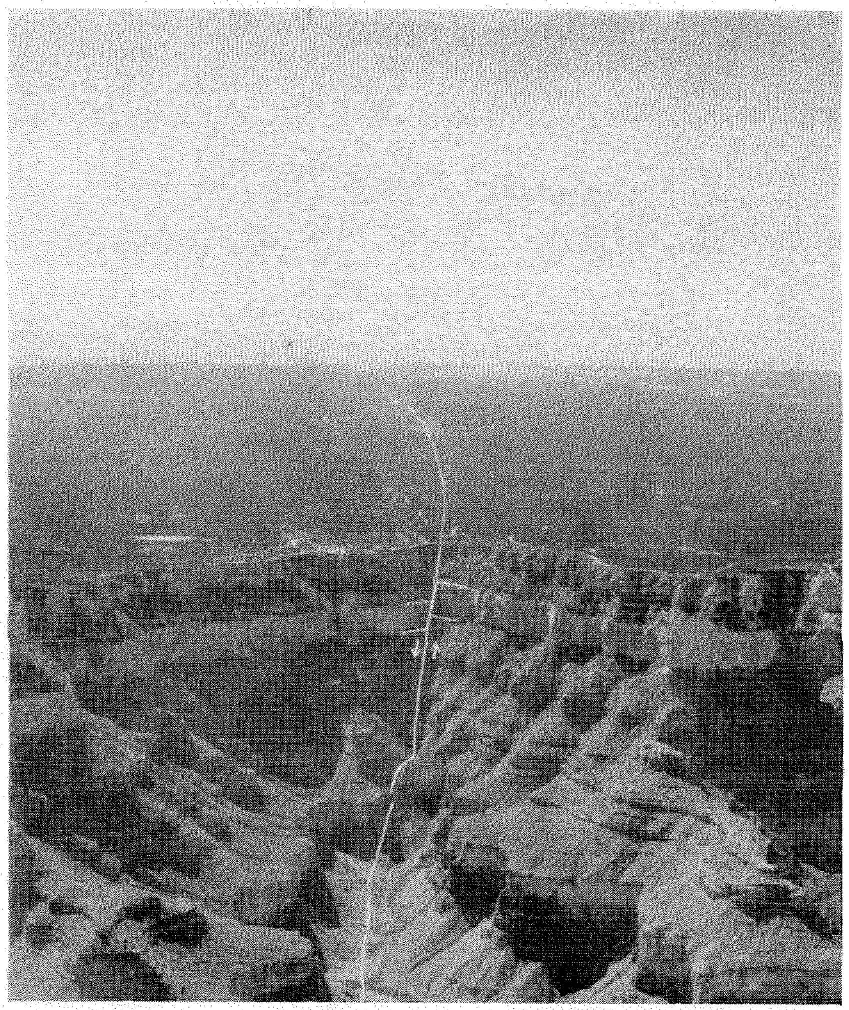

FIG. 14—Looking south along Bright Angel fault trace in Outer Canyon and on Coconino plateau. A post-Paleozoic normal fault of 180 feet displacement, it nearly overlies a post-Algonkian reverse fault of opposite directions of displacement. It illustrates V-shaped re-entrant in canyon walls where erosion has been facilitated by rock brecciation along the fault.

HORIZONTAL CONTROL

In plan, as shown in *Fig. 12*, the remarkable alignment of tributary valleys may be seen. These tributary valleys determine the principal amphitheaters in the Outer Canyon. One important system has a northeast-southwest trend parallel to the Bright Angel fault. This northeast-southwest trend is also possessed by the foliation of the underlying metamorphic rocks. A northwest-southeast trending series of faults also determines a tributary system with its group of amphitheaters. This fault system tends to be parallel to the major joint system in the underlying metamorphic rocks.

So, in plan, the basic control is inherited from very ancient structures. We may picture the underlying metamorphic basement as consisting of immense polyhedrons (in some cases roughly rhombohedrons) measuring several miles on a side. As compared with the mile of horizontal strata lying over them, they possess unlimited strength. Therefore, stresses within the crust have been adjusted by movement of the underlying blocks, accompanied by faulting and flexing of the weak overlying veneer, in cases of considerable movement, or just by shattering of the overlying veneer above the old faults, in cases of small displacement.

Crustal stresses developed in separated periods of geologic time in the Grand Canyon district and operated in different directions on two occasions. During the first period of stress, with which we are concerned, the northeast trending series of fractures were developed as reverse faults by compression acting in a direction normal to them—namely, southeast-northwest. The north and northwest striking faults were normal faults resulting from tension or lack of compression. The movement occurred at the end of Algonkian time, perhaps on breaks developed earlier at the end of Archean time.

Sometime after the Paleozoic series forming the Outer Canyon walls had been deposited, stresses were again applied to the underlying blocks, but in the opposite directions. Now the north and northwest striking faults were subjected to compression, and movement on them was reversed, forming thrust faults, and monoclinal structures in the overlying sediments. The Cremation fault is an example of this group. *Fig. 13* shows the

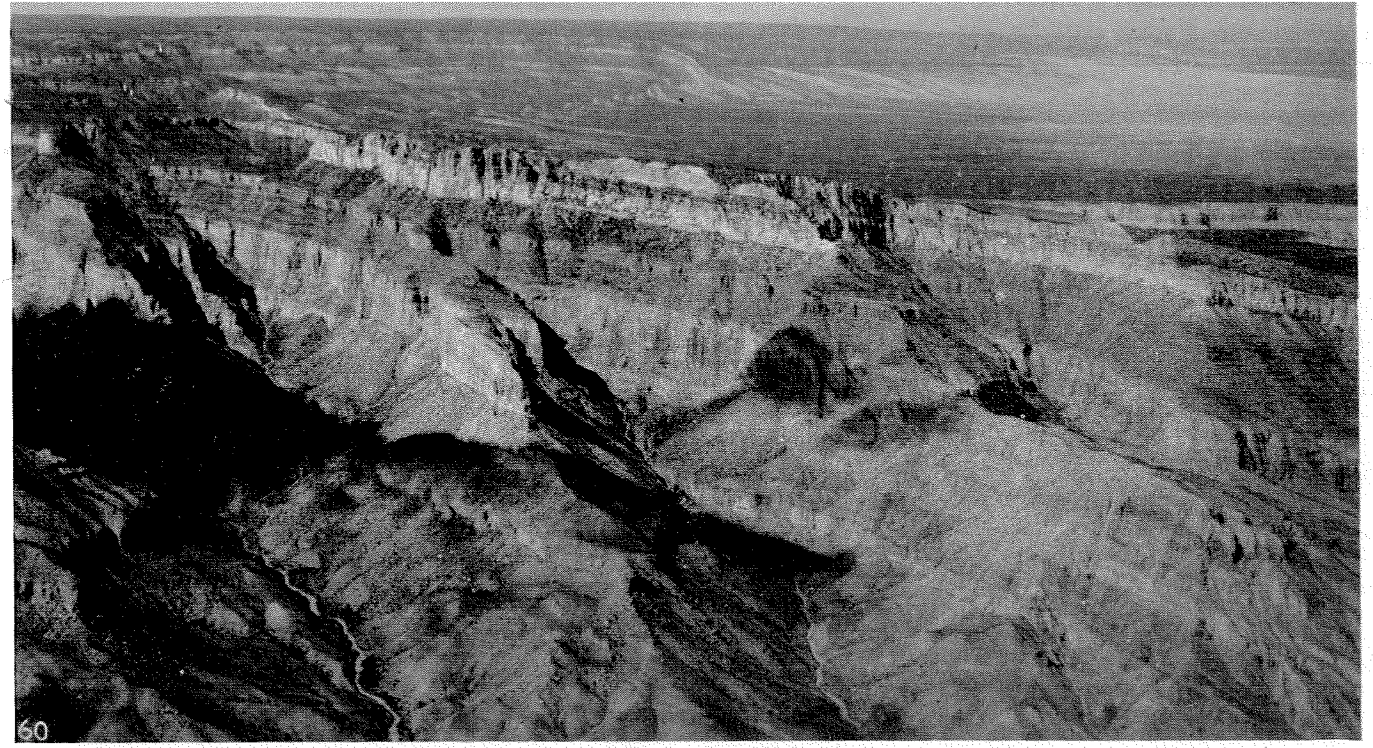

FIG. 15—East Kaibab monocline, a flexure in the strata of the Horizontal Series reflecting movement on underlying fault blocks.

north-northwest striking Butte fault, and *Fig. 15* shows the monoclinal folding of the Paleozoic strata overlying this fault. On the other hand, the northeast striking faults were relieved of compression and normal faults developed. In the case of the fault traversing Bright Angel Canyon, the plane of the late normal fault is close to, but not everywhere coincident with, the earlier thrust fault.

The intricate system of amphitheaters in the Outer Grand Canyon has been developed by headward erosion of streams along shatter zones or fault zones in the Paleozoic veneer, and by accompanying cliff retreat, influenced by joint zones, away from the stream channels. In the case of many tributaries, the brecciated zones have exercised predominant pattern control. In others, developed at right angles to the Colorado River where

TABLE SUMMARIZING GEOMORPHIC CHARACTERISTICS OF GRAND CANYON FORMATIONS

PALEOZOIC	Permian	Kaibab Limestone	400 ft	Cliff forming
		Toroweap Formation	250 ft	Cliff-bench
		Coconino Sandstone	300 ft	Cliff forming
		Supai Formation	1440 ft	Cliff-bench
	Mississippian	Redwall Limestone	600 ft	Cliff forming
	Devonian	Temple Butte Limestone	0-1000 ft	Cliff-bench
	Cambrian	Muav Limestone	450 ft	Cliff forming
		Bright Angel Shale	25-375 ft	Bench forming
		Tapeats Sandstone	0-300 ft	Cliff forming
ALGONKIAN		Chuar Series	9000 ft	Cliff-bench
		Unkar Series		
		Dox Sandstone	2000 + ft	
		Shinumo Quartzite	1000 + ft	
		Hakatai Shale	600 ft	
		Bass Limestone	350 ft	
ARCHEAN		Phantom Pegmatite		Hard basement, inner gorge-forming
		Zoroaster Granite		
		Alarcon Amphibolites	3000 + ft	
		Vishnu Paraschist	25000 ± ft	

it is oblique to major structures, jointing has influenced the detailed pattern. The tributary valleys of the Outer Canyon on the north side of the river are longer than those on the south because the south-sloping Kaibab Plateau collects rainfall and feeds streams and springs from the north. The streams on the south have relatively small collecting basins because the drainage divide is on or near the edge of the south-sloping Coconino Plateau. As first pointed out by Professor Davis, the cliffs of tributary valleys meet headward in acute-angled re-entrants because the channel in the cliffed re-entrant is the site of most effective stream erosion and transportation.

On the spurs between the tributaries there is very little rainfall, so that streams are developed at rare intervals. Reduction of these spurs proceeds through the sapping of the various cliff-forming members. The breaking and dropping of joint blocks proceeds in such a way as to form a rounded re-entrant. The larger the amount of water that flows over the cliffs, and the narrower the zone of streamlet channels, the greater is the curvature of this re-entrant. *Fig. 16* illustrates this point, the cirque at the right having greater curvature and more stream development than the cirque on the left. The more rapid enlargement of the cirque on the right might ultimately result in its cutting through the spur end and forming a butte. Where there is no concentration of streamlets the cirque enlarges concentrically, as illustrated by the left example in *Fig. 16.* An advanced stage in the development of cirques is shown in the Tower of Set in the lower right portion of *Fig. 7.* A cirque of large radius of curvature faces in the direction of the river. Other cirques expanding away from the tributary valleys meet in sharp cusps at the outer end of long narrow tongues of Redwall limestone. To the right of the Supai pinnacle, forming the Tower of Set, is a saddle caused by the reduction of the cliff-bench forming members above Redwall cirques on the two sides of the ridge which are approaching each other in their retreat.

In summary, as illustrated in *Fig. 12,* the general plan of the Grand Canyon in the Bright Angel quadrangle is one of long tributary valleys on the north and short tributary valleys on the south. The cliffs of these valleys meet headward in acute-angled re-entrants. Some of the tributary valleys are developed approximately at right angles to the Colorado master course; others are developed along the northeast trending and northwest trending shatter zones and fault zones. Where the systems intersect, amphitheaters on a large scale are developed, such as the Hindu and Ottoman amphitheaters on the north and the Cremation and Grapevine amphitheaters on the south. The detailed plan of the intertributary spurs, controlled by concentrically expanding cirques of cliff retreat, resembles dough from which cookies have been punched. Dependent upon the intersection or approaching intersection of circles of cliff retreat are the various stepped buttes and step-spired temples of the Outer Canyon.

The geologic story of the Grand Canyon is told by the landscape so plainly that any visitor can understand it. Its separate chapters and paragraphs are coherent and succinct. It is colorful and fascinating. It is rich, not only as a source of scientific facts, but also in features elucidating them. The Grand Canyon is certainly one of the great heritages of the American people.

FIG. 16—Vertical view of cliff-bench topography near Indian Gardens. Heavy shadows are caused by Redwall limestone cliff which is controlling factor, virtually a temporary base-level, in the recession of cliffs in the overlying Supai sandstones. Note their parallelism with the Redwall cliff. Where there is no continuous drainage from above, sapping operates with equal effectiveness about the periphery of a re-entrant, and it is expanded in sub-circular outline to form a cirque or amphitheater.