BRIGHAM

YOUNG

UNIVERSITY

GEOLOGY STUDIES

Volume 18: Part 3 — December 1971

CONTENTS

Brigham Young University Geology Studies

Volume 18, Part 3 — December, 1971

Contents

A publication of the
Department of Geology
Brigham Young University
Provo, Utah 84601

Editor

Jess R. Bushman

Brigham Young University Geology Studies is published semi-annually by the department. Geology Studies consists of graduate student and staff research in the department and occasional papers from other contributors.

Distributed February 15, 1972

Price $4.00

The Nature and Development of the Esplanade in the Grand Canyon, Arizona*

WILLIAM L. CHESSER
Brigham Young University, Provo, Utah

ABSTRACT.—The Esplanade platform constitutes the major terrace in the western Grand Canyon region as it extends approximately 175 miles along the Colorado River in the western part of the canyon and ranges up to six miles in width. Although various interpretations have been made regarding the development of the Esplanade over the past century, no attempt has been made to study the feature throughout its entire extent. Field data and the study of vertical and oblique aerial photos and new topographic maps provide the basic framework of this study.

Variations in the nature of the surface of the Esplanade are attributed to (1) slope retreat, creating small step-slopes, (2) differential weathering of joint systems, (3) solutions basins, (4) exhumed pre-Hermit erosion surface, (5) drainage dissected topography, (6) faults, (7) folds, and (8) differential weathering of rock units in the Esplanade Sandstone, producing hummocky surface features.

Regional variations in the expression of the Esplanade terrace have been classified in the following subdivisions: (1) the step-slope, Eastern Park Section, (2) the transitional, Powell Plateau Section, (3) the broad, Esplanade Section, (4) the lava-covered Volcanic Cascades Section, (5) the fault-controlled, Hurricane Fault Section, (6) the one-sided, deep, Lower Granite Gorge Section, and (7) the fault-bounded, Western Margins Section.

Variations in the width of the Esplanade were compared with such possible controlling factors as the thickness of the overlying Hermit Shale, thicknesses of various units in the Supai Formation, gross lithologic types in the Hermit-Supai sequence, and physiographic expressions of the Hermit and Supai profiles. All but the last of these variables were analyzed with a computer. Results of this investigation indicate that the significant controlling factors of the development of the Esplanade terrace are (1) the westward thickening of the Hermit Shale and (2) a change in the physiographic expression of the cliffs of the Supai Formation. The computer analysis also strongly suggests a relatively high correlation of increasing sand content of the Hermit Shale to the west with the development of the Esplanade.

CONTENTS

ILLUSTRATIONS

*A thesis submitted to the faculty of the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree of Master of Science.

ACKNOWLEDGMENTS

The writer wishes to express appreciation to Dr. W. K. Hamblin, who not only served as the thesis committee chairman but also sparked an interest in Grand Canyon geology. He constantly encouraged the writer throughout the project and allowed the use of many of his original photos and materials in support of this study.

Thanks are also given to Dr. L. F. Hintze, who served on the thesis committee and, along with Dr. H. J. Bissell, offered many helpful suggestions. Special thanks are extended to Mr. Richard Beesley, who assisted in the field work, and to Mr. Gary Lawyer, who helped with the photographic work.

Appreciation is extended to the Brigham Young University Department of Statistics and to Computer Center personnel, though unnamed, who rendered valuable assistance in accomplishing the objectives of this project. The writer is deeply indebted to Dr. E. D. McKee of the U.S. Geological Survey, who offered many helpful suggestions and generously made available to the writer a large volume of yet unpublished field notes and measured stratigraphic sections which have made the objectives of this project feasible.

Special appreciation is given to the writer's wife, Sally, who gave constant encouragement and support and helped in the transcription of field notes.

INTRODUCTION

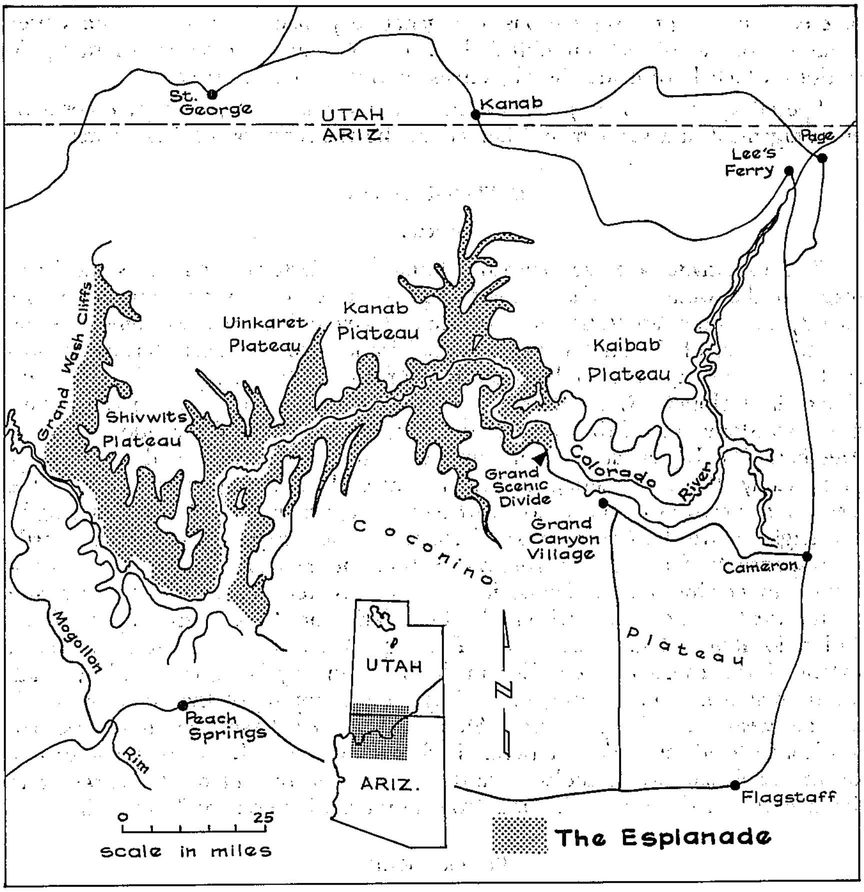
General

The Esplanade, a broad structural terrace or platform, dominates the landscape in the western Grand Canyon region. It is perhaps best known in the vicinity of Toroweap Valley in the Grand Canyon National Monument, some 30 miles west of Grand Canyon National Park. The Esplanade terrace is situated at a level approximately two-thirds of the vertical height of the canyon above the Colorado River. It is the erosional surface developed on the uppermost sandstone unit of the Supai Formation, known as the Esplanade Sandstone Member. The Esplanade is approximately 2 to 6 miles wide and extends approximately 175 miles along the river course. It is cut symmetrically by the steep, inner canyon of the Colorado River for approximately half of its length. Its height above the Colorado River changes in an irregular manner, primarily in response to faulting and folding. While the Esplanade is not the largest terrace in northwestern Arizona, it is the largest terrace, both in breadth and areal extent, to be found within the boundaries of the Grand Canyon of the Colorado River. The index map (Text-fig. 1) shows the approximate areal extent of the Esplanade. The Esplanade is continually being enlarged by headward erosion in tributary canyons and by lateral sapping of the outer rim cliffs as the weak underlying Hermit Shale is stripped from the more resistant Esplanade Sandstone. The National Park visitor sees only an incipient profile of the Esplanade as he looks toward the far western end of the views from Pima Point on the South Rim and from Point Sublime on the North Rim.

Previous Work

C. E. Dutton and W. H. Holmes (Dutton, 1882) combined their individual talents to produce literary and artistic descriptions of the Grand Canyon scenery that have remained unequaled by any other witness of the canyon's grandeur. Dutton's word pictures evoke such vivid mental images of the Grand Canyon that when one actually visits the areas described, the experience is simply a confirmation. Holme's portrayals of the Grand Canyon are some of the finest and most accurate examples of landscape sketches to be found anywhere in the world. The reader is referred to these works in Dutton's (1882) *Tertiary History of the Grand Canyon* and its accompanying atlas.

G. W. James (1910) named the easternmost promontory of the incipient Esplanade the Grand Scenic Divide, "because it is the point where the granite of the inner gorge disappears from the Grand Canyon, and this disappearance makes as vast and wonderful a difference in the canyon scenery as it is possible to find in its whole 217 miles of length. To the right (east) of the divide one can see the temples, buttes, and towers that make the view from El Tovar and Grandview Point so interesting. Looking westward, the whole aspect changes so markedly indeed that one can scarcely believe it to be the same canyon, hence the appropriateness of the name."



TEXT-FIGURE 1.—Index map showing areal extent of the Esplanade. Irregular solid line on either side of the Colorado River marks the cliff line of the outer rim.

In comparing the views to the east and to the west in the proximity of Grand Scenic Divide, he further states, "the view, to the westward . . . is uninteresting. The reason for this is clear. The granite of the inner gorge has disappeared. Here is the Scenic Divide, the natural line of demarcation between two distinctive portions of the canyon the scenery of which is markedly diverse. Where the granite is in evidence, the stratified rocks resting upon it are carved into varied forms. Where the river flows through the stratified rocks and no granite appears, there are few or no buttes, no towers, no monuments. Nowhere else in the accessible portions of the canyon is this difference seen."

Although James's observation that at the Grand Scenic Divide the scenery change is so vast as to seem to be the demarcation line between two canyons of entirely different natures, his reasons for the change are completely inaccurate. The fact that the granite gorge disappears at the Grand Scenic Divide is strictly fortuitous with regard to the change in scenery. It bears no relationship to the development of the Esplanade, which is primarily responsible for the dramatic change in canyon scenery and profile.

J. W. Powell (1875, p. 92), in his trip down the Colorado River in 1869, saw and described the terrace, which was later named "the esplanade" by Dutton (1882). His account is as follows:

> August 22—
>
> . . . I climb the wall on the northeast, to a height of about two thousand five hundred feet, where I can obtain a good view of a long stretch of cañon below. Its course is to the southwest. The walls seem to rise very abruptly, for two thousand feet, and then there is a gently sloping terrace, on each side, for two or three miles, and again we find cliffs, one thousand five hundred or two thousand feet high. . . . The effect of the terrace is to give the appearance of a narrow winding valley, with high walls on either side, and a deep, dark meandering gorge down its middle (1875, p. 92).

Dutton (1882) named and described the Esplanade and offered the following interpretation for its origin:

> At the close of the Miocene . . . the country was situated at a level not far above the sea, and was at a base level of erosion. . . . At length a new epoch of upheaval set in hoisting the country from 2,000 to 3,000 feet, and somewhat unequally. . . . At length the uplifting action paused for a time. . . . The river sought and quickly found a new base-level at the horizon of the great esplanade of the Grand Cañon. . . . The process of erosion was occupied in . . . sapping the newly formed cliffs of the cañon. The cliffs, thus attacked receded away from the river, gradually developing the broad avenue of the outer chasm (the Esplanade). . . . Again the country was hoisted . . . the corrasion of the river bed was renewed. The faults were increased. The volcanic fires were rekindled. Swiftly the river gorge was scoured out, and the chasm assumed its present condition.

Thus the origin of the Esplanade was explained as an incipient peneplain. This interpretation remained apparently unchallenged for almost 20 years, until W. M. Davis (1901) challenged the "pause in an uplift" theory of Dutton's and proposed that all of the events could have taken place in a single cycle of erosion. He further declared that the Esplanade was a structural terrace, which is in contrast to Dutton's peneplain concept. Geologists such as L. F. Noble (1914), N. M. Fenneman (1931), E. D. McKee (1969), and W. K. Hamblin and J. K. Rigby (1969) have generally adhered to the basic concepts proposed by Davis.

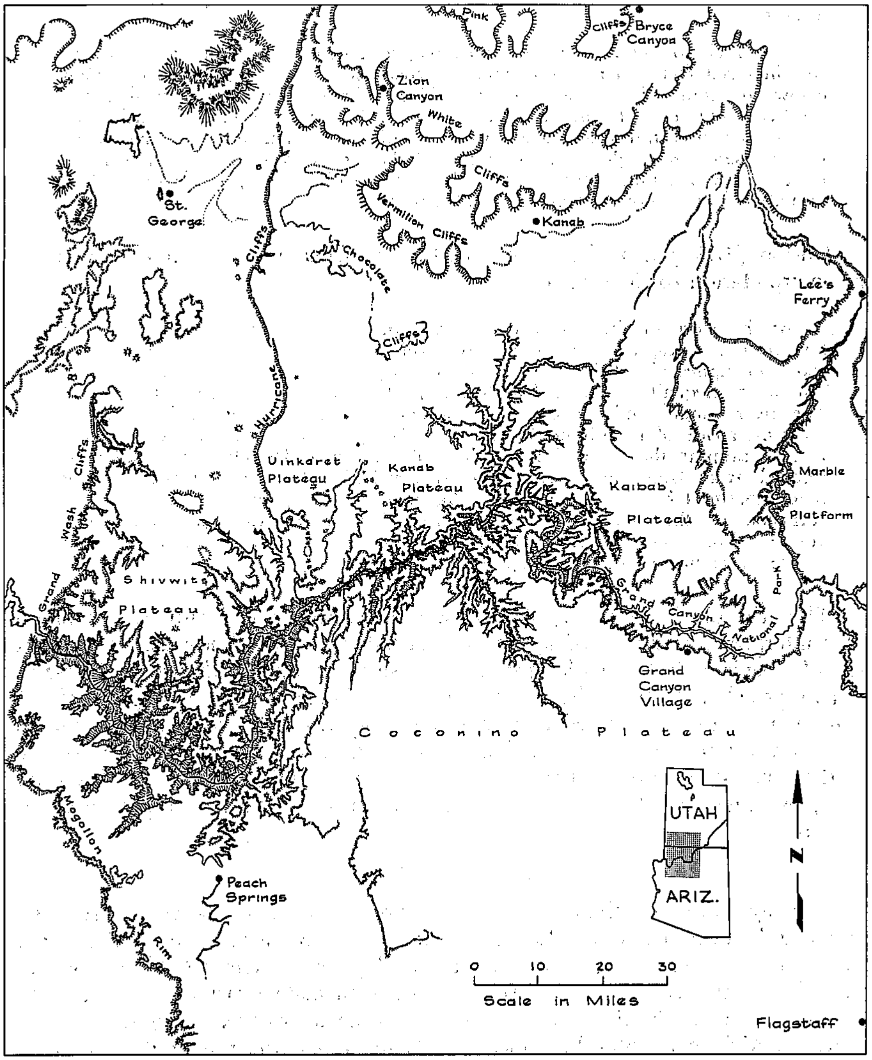
Purpose and Scope

Although most of these investigators have offered explanations for the origin and development of the Esplanade, none have attempted to determine the significant controlling factors in its development. Many questions have remained unanswered, such as: "Why is the Esplanade situated where it is?" "Is the Esplanade development related to a westward thickening of the Hermit Shale, as McKee (1969) has stated?" "Is its development related to a facies change in the Supai Formation?" and "What conditions were necessary for the Esplanade to develop?" The object of this study, therefore, is to attempt to determine the significant factors and/or conditions which contributed to the development of the Esplanade platform.

GEOLOGIC SETTING

General

Most of the sedimentary rocks in northwestern Arizona and southwestern Utah are expressed physiographically as cliffs and slopes. This is the natural response to erosion of alternating "hard" and "soft" horizontal rocks. As shown on the physiographic map (Text-fig. 2), a series of broad steps or cliffs sup-



TEXT-FIGURE 2.—Physiographic map showing regional setting of the Esplanade. Esplanade terrace is lightened area within the canyon that can be identified by comparing to Text-figure 1.

ported by upper Paleozoic and Mesozoic formations lead up to the High Plateaus of Utah. This series of cliffs forms the well known Grand Staircase.

The western Grand Canyon is dominated by the broad platform of the Esplanade. This part of the canyon is also characterized by a double rim, which consists of a broad outer chasm that is cut almost equally in its middle portion by a steep-walled, winding, inner chasm. One of the unique features of the western Grand Canyon is the abundant evidence of spectacular Pleistocene volcanic activity. The volcanics are expressed by the many well-preserved cinder cones, lava cascades, and features that are associated with this type of igneous activity. Excellent papers have been published on the volcanics of this area, and the reader is referred to those by McKee and Schenk (1942) and Hamblin (1969).

Stratigraphy

The formations that primarily effect the development of the Esplanade terrace are the Hermit Shale and the underlying Supai Formation. Although these units are essentially horizontal, the contact is marked by a topographic unconformity, considered by White (1929) to be the result of a pre-Hermit erosion surface on the top of the then-unconsolidated Supai sandstone. Conspicuous variation from the essentially horizontal attitudes of beds in the Hermit-Supai are directly related to faults and flexures throughout the region.

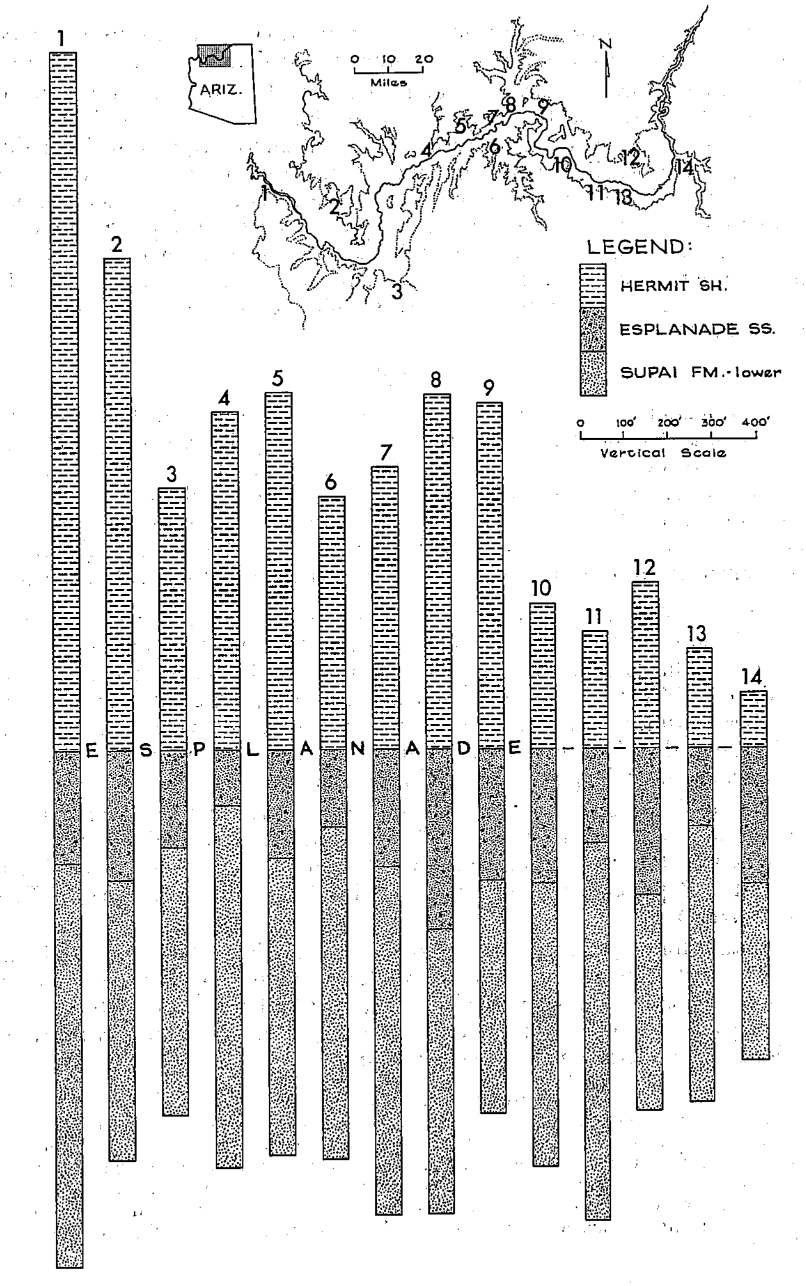
Hermit Shale (Permian).—The Hermit Shale consists of dark, reddish-brown, silty sandstones and shales. White (1929) stated that the environment for deposition of the Hermit was far removed from any highland source for rock material, as evidenced by the lack of conglomeratic pebbles and/or boulders. He further considered the condition of the rock units as evidence for a semi-arid climate with a long dry season. This environment, according to White, is further evidenced by the plant life found in the Hermit.

This unit thickens conspicuously to the west in the Grand Canyon country. Variations are from approximately 125 feet in the eastern end of the Grand Canyon National Park to approximately 1,600 feet in the west at the Grand Wash Cliffs. Representative unit thicknesses for 14 localities are given in Text-figures 3 and 4.

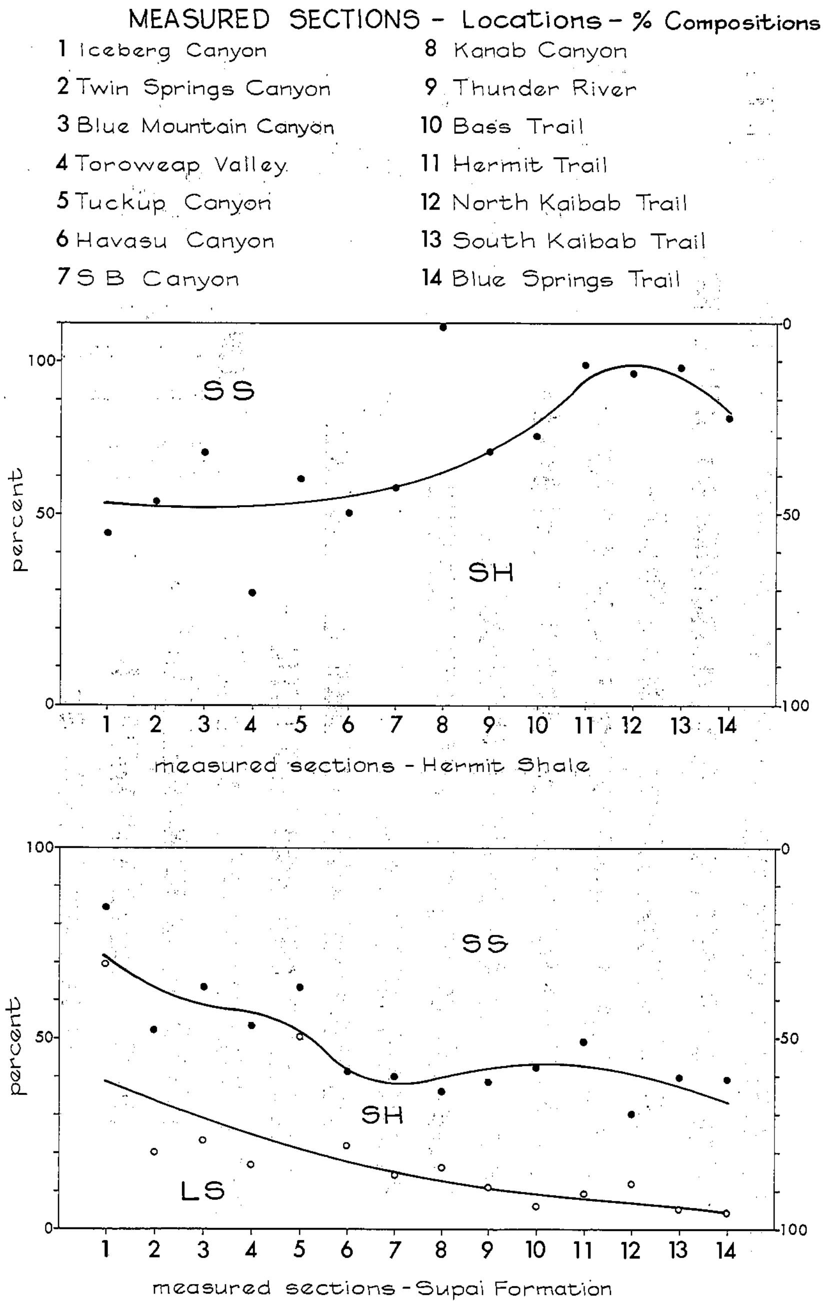
Silty sandstones are the primary constituent of the ledges in the Hermit Shale. The distribution of the diminutive ledges in the Hermit are shown in a series of representative sections (Text-figs. 5, 6). The nature of these sandstones plays an important role in the development of the characteristic single long slope of the Hermit. White (1929) states:

> Thin sandstones, irregularly bedded and soft, occur at several levels, especially in the hollow-fillings on the Esplanade, and in the next 50 feet of beds above the Esplanade level; also three or four soft sandstones are found near the top of the formation. All appear to lack continuity and though the grains are generally thickly coated with iron, and more or less cemented by carbonates, the sands are soft and easily eroded. This accounts for the sloping surface from the top of the Esplanade to the foot of the light buff cliffs of the Coconino Sandstone.

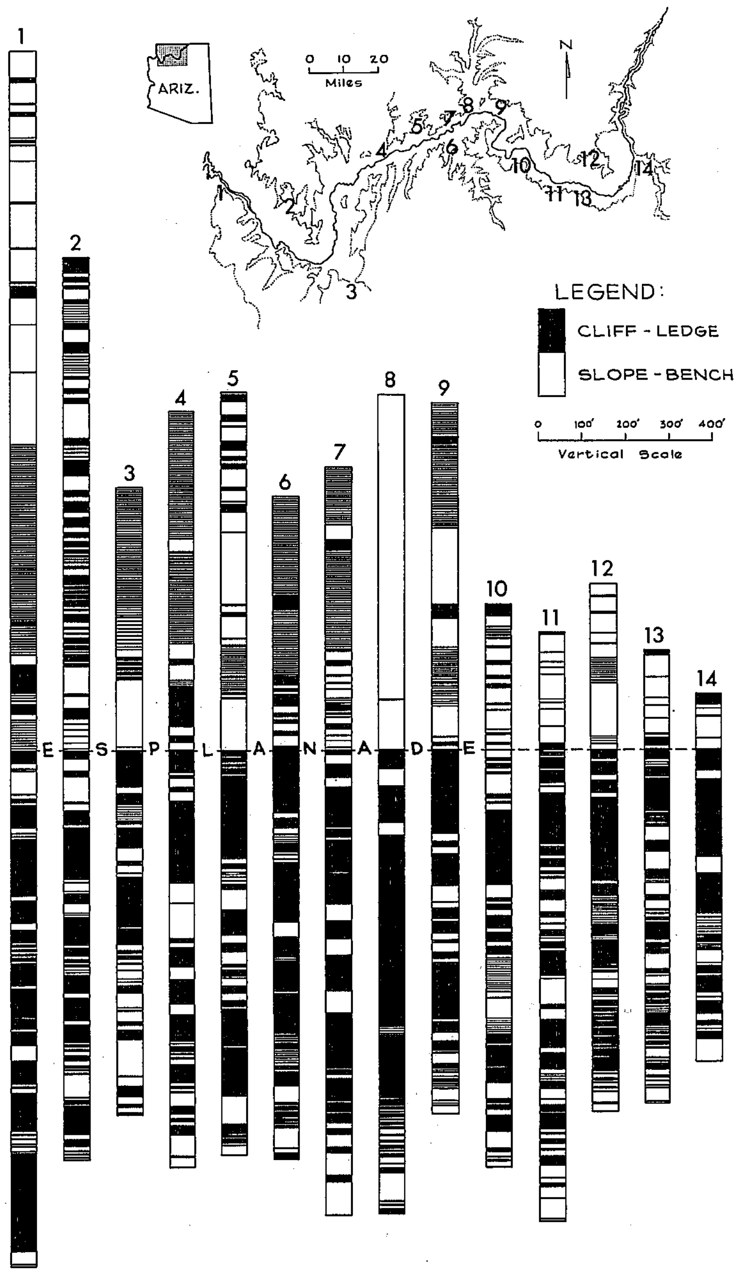
As previously discussed, a buildup of sands in the Hermit accompanies the westward unit thickening of the Hermit Shale. Therefore, despite the fact that in detailed observation, the Hermit has many small ledges throughout its section, it is expressed as one long slope.



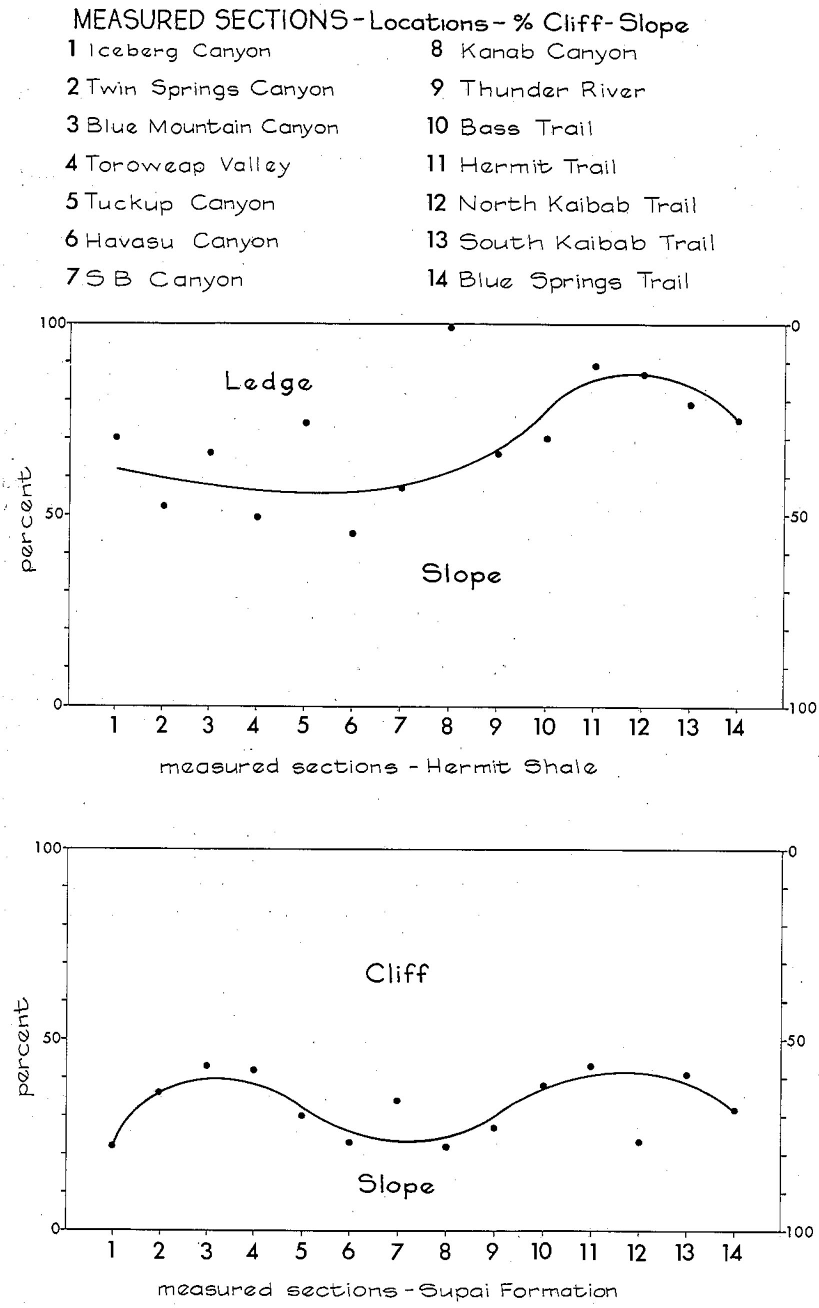
TEXT-FIGURE 3.—Generalized stratigraphic columns showing unit thicknesses of the Hermit Shale, the Esplanade Sandstone, and the Supai Formation. Esplanade horizon is also indicated. Section identifications are shown in Text-figure 4.



TEXT-FIGURE 4.—Graphs showing percentage composition of sandstone, shale, and limestone for the Hermit Shale and the Supai Formation. Section distribution is shown on Text-figure 3.



TEXT-FIGURE 5.—Columns showing thicknesses and distribution of cliffs and slopes in the Hermit Shale and the Supai Formation. Esplanade horizon is also indicated. Section identifications are shown on Text-figure 6.



TEXT-FIGURE 6.—Graphs showing percentages of cliffs and slopes for the Hermit Shale and the Supai Formation. Section distribution is shown on Text-figure 5.

Supai Formation (Pennslyvanian-Permian).—Havasu Canyon is designated as the type locality for the Supai Formation. Darton (1910) named the Supai Formation for the Indian village of Supai which is situated in Havasu Canyon. As originally defined by Darton, the Supai included the red shales which Noble (1922) later redesignated the Hermit Shale.

The Callville Limestone, the Pakoon Formation, and the Queantoweap Sandstone in the western part of the Grand Canyon represent the same interval of time as the Supai Formation in the eastern areas of the canyon. McNair (1951) discussed the relationships of these formations. He said that the Queantoweap Sandstone is the lithologic equivalent of the Esplanade Sandstone Member of the Supai Formation. The Callville Limestone intertongues with and grades into the Lower Supai. Finally, the Pakoon Limestone forms a large wedge between the Callville Limestone and Queantoweap Sandstone which thins eastward and disappears beneath the Shivwits Plateau. As a group these formations are overlain by the Hermit Shale, and they overlie the Redwall Limestone.

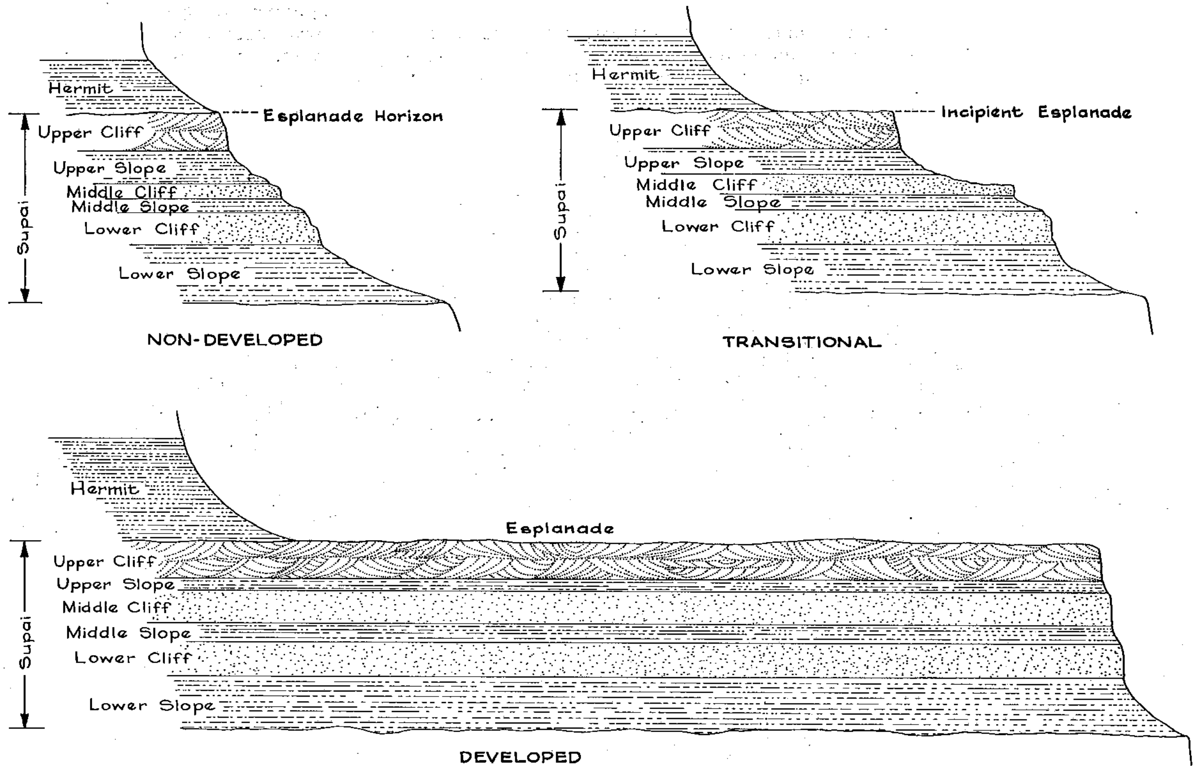
Notwithstanding the stratigraphic divisions imposed by stratigraphers upon nature, the Supai Formation and its physiographic equivalents throughout the canyon are all classed under the single name "Supai Formation" for the purposes of this study. The Supai, so designated, varies in thickness from approximately 700 feet to 1,200 feet in the Grand Canyon. Even though these two extremes are at opposite ends of the canyon, the Supai does not gradationally thicken to the west (Text-fig. 3).

Lithologically, the Supai is typically composed of red-to-pink-to-buff calcareous to noncalcareous sandstones interlayered with red-brown, silty shales. Near the base of the Supai are a number of dolomitic limestone units which form ledges, cliffs, and some high angle or rubbly slopes. The majority of the ledges and cliffs of the Supai are made of sandstone, but the cliff-forming dolomitic limestones are located near the base and increase in importance toward the west (Text-figs. 4, 5).

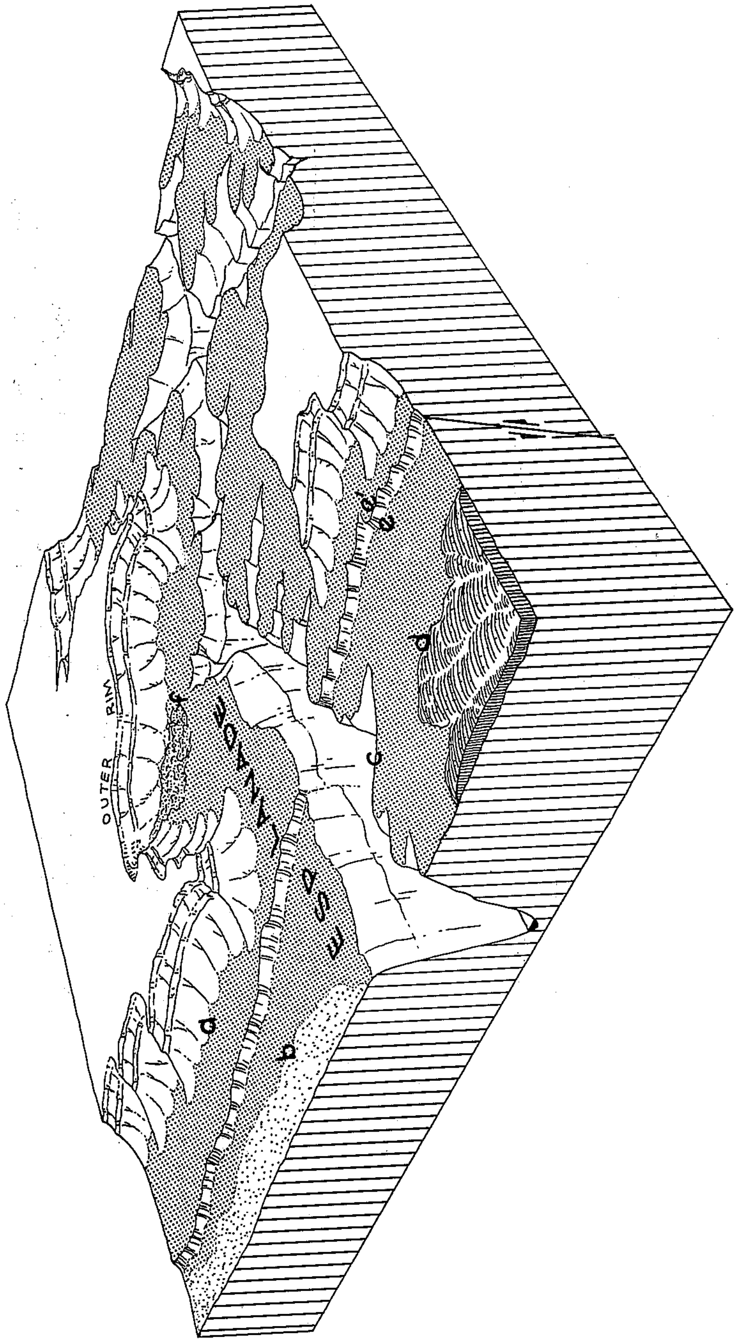
Detailed cliff-slope relationships (Text-fig. 5) suggest a multitude of terraces, but typically the Supai is characterized by three major cliffs and three major slopes. McKee (personal communication) referred to them as the Upper, Middle, and Lower cliffs and the Upper, Middle, and Lower slopes. Noble (1922) also used a three-part designation, but this writer finds McKee's nomenclature preferable, and references to the Supai cliffs and/or slopes will closely follow his designations.

Despite the fact that these cliff-slope units are expressed somewhat differently in various sections of the canyon, the discriminating observer should have little difficulty in identifying the individual units. Representative expressions of the cliff and slope units described are shown in the idealized diagram (Text-fig. 7) for areas in which the Esplanade has not been developed, for transitional areas, and for areas in which the Esplanade is well developed. Note the differences in cliff profiles, as related to the Esplanade development. Where the Esplanade is well developed, the cliffs "stand up" to make a high angle, or near vertical "total" profile. Where the "total" profile reclines, the Esplanade either appears only as an incipient terrace or not at all. One can see this same general relationship throughout the canyon.

Esplanade Sandstone Member.—This member forms the Upper Cliff of the Supai Formation. It was so designated by White (1929, p. 11) because the Esplanade terrace is developed on its upper surface throughout a large portion



TEXT-FIGURE 7.—Idealized profile sections showing generalized morphology and nomenclature of the Supai-Hermit cliffs and slopes. Various stages in the development of the Esplanade and their physiographic relationships to the Hermit-Supai sequence are also indicated.



TEXT-FIGURE 8.—Conceptual block diagram showing boundaries of the Esplanade. a—toe of Hermit slope; b—edge of alluvial covering; c—rim of inner gorge; d—edge of volcanic features, i.e., cinder cones and lava flows; e, e'—fault escarpments; f—edge of landslide debris.

of the Canyon. This cliff-forming unit is relatively continuous and makes a convenient and useful reference for this study. It is a reddish-pink-to-buff calcareous to noncalcareous sandstone cliff with red shale partings. This cliff unit is present throughout the canyon and varies in thickness from approximately 50 to 400 feet (Text-fig. 3).

One of the unique characteristic features of the Esplanade Sandstone is the abundance of large cross bedding (Text-fig. 7). Sorauf (1962, p. 94) states that, "It is probable that the uppermost beds of the Esplanade Sandstone were deposited in the main part of the longshore bar or barrier beach, and these intertongue with gypsiferous, sandy lagoonal deposits of the lower Hermit Formation. . . . The massive, cross laminated sandstones are thus thought to represent the beach and foreslope environments related to a longshore-bar and beach complex."

Prior to the deposition of the Hermit Shale, channels up to 70 feet deep were scoured into the sands of this cliff unit. These channels and their accompanying surface of erosion create the topographic unconformity that exists between the Supai and Hermit formations. This unconformity is particularly well expressed in Hermit Basin where the Hermit Trail descends through one of these channels at "Red Top." White (1929, pp. 13-14) discusses their significance, and the reader is referred to his paper, which also contains a photograph of the channel mentioned above (White, 1929, Plate B, opposite p. 8).

THE ESPLANADE

General Description

Dutton's (1882) description of the Esplanade from Toroweap Valley follows:

> Climbing among the rocky ledges . . . we at length obtain a stand-point which enables us to gain a preliminary view of the mighty avenue. To the eastward it stretches in vanishing perspective forty miles or more. Between symmetric walls 2,000 feet high and 5 miles apart is a plain, which in comparison with its limiting cliffs might be regarded as smooth, but which in reality is diversified by rocky hummocks and basins, and hillocks where patches of soil give life to scattered cedars and piñons. . . . As we move outward towards the center of the grand avenue the immensity and beautiful proportions of the walls develop. . . . On either side its palisades stretch away to the horizon. Their fronts wander in and out, here throwing out a gable, there receding into a chamber, or gaping widely to admit the entrance of a lateral chasm. The profile . . . is definite, graceful, architectural, and systematic.

Unlike the broad fault-bounded plateau terraces that form the outer rims of the western Grand Canyon, the Esplanade is a broad, sinuous terrace that follows the serpentine course of the Colorado River. The platform is approximately two to six miles wide. The impression that the platform is broader is more apparent than real. What the viewer sees and attributes to a broad outer chasm of the Esplanade is nothing more than an extension of the Esplanade surface into one or more of the many side canyons found throughout the region.

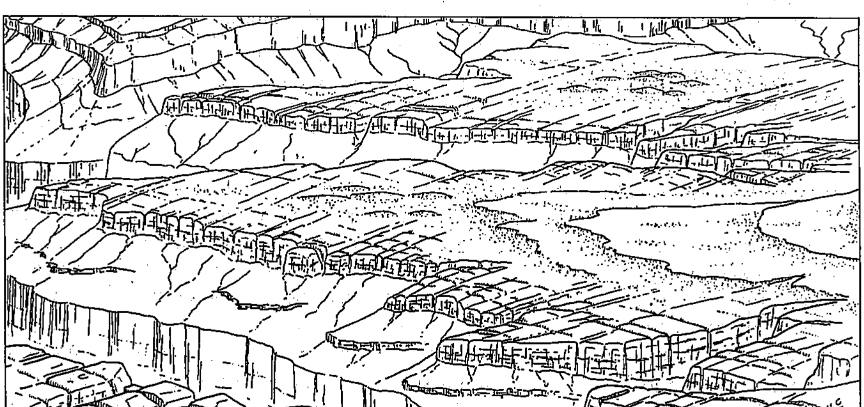
The Esplanade is a surface of erosion. It extends approximately 175 miles along the course of the Colorado River and extends laterally up tributary canyons to a distance exceeding 50 miles. However, it is not simply a horizontal planar surface. It is tilted, disrupted, and displaced by monoclinal flexures, erosion, faults, and fault-related features such as the "reverse drag" phenomenon treated by Hamblin (1965). "Reverse drag" tilts the Esplanade along several faults in the canyon, most notably along the Hurricane and West Kaibab Fault Zones. Displacements and inclined strata cause the Esplanade to be situated at varying elevations, ranging from approximately 3,000 to 5,600 feet above sea level.

By definition, the Esplanade is that surface of erosion that is developed on the upper surface of the Esplanade Sandstone Member of the Supai Formation. The features which mark its boundaries are summarized on the idealized block diagram (Text-fig. 8). This diagram shows the nature of each feature and its physical relation to the Esplanade platform.

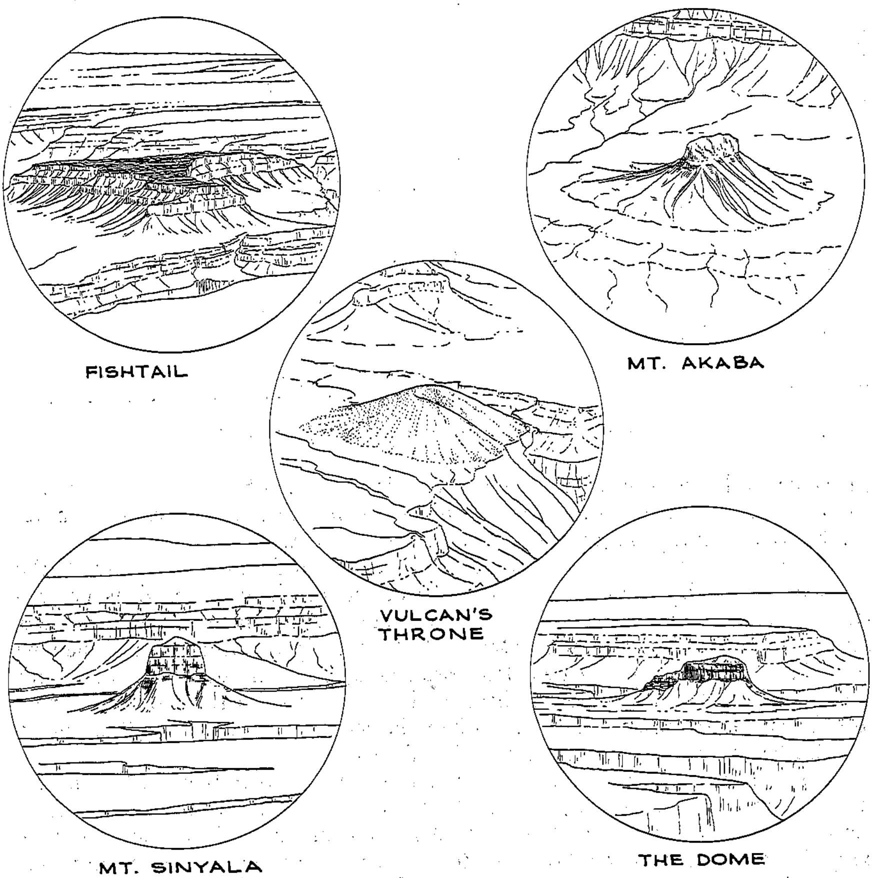
On a regional basis, the Esplanade appears flat, but on closer examination it is a rough, irregular surface. The irregular topography of the Esplanade can generally be attributed to one or more reasons. Cliff retreat produces a series of staggered, step-like, small terraces within various thin rock layers of the upper Esplanade Sandstone. The overall impression created by these terraces is that of an inclined surface that slopes gently towards the river. The expression of three such terraces is shown in the right central portion of the sketch (Text-fig. 9), which shows only a relatively small portion of the Esplanade.

Differential weathering associated with the joint systems prevalent on the Esplanade surface creates an unusual topography. Billingsley (personal communication) states that the joint patterns in the area around Tuckup Canyon have two dominant trends of N 27°-32°W and N 54°-60°E. He suggests that these are not related to present structures in the area, but are perhaps an upward extension of Precambrian joint systems. Regardless of their origin, joints greatly influence the topography of large areas of the Esplanade. When differently-trending joint systems intersect, weathering creates a "breadloaf" topography such as is illustrated in Text-figure 9. Joints tend to produce a rectilinear drainage pattern on the surface of the Esplanade near the inner gorge.

Drainage patterns have partly dissected the Esplanade with valleys ranging from the tiniest rivulet creases to the larger tributary canyons. The drainage profiles of these intermittent and perennial streams are greatly accentuated around the river edge periphery of the Esplanade and diminish in magnitude as



TEXT-FIGURE 9.—Sketch of a small portion of the Esplanade, showing surface irregularities.



TEXT-FIGURE 10.—Sketches of erosional and depositional forms perched on the Esplanade.

they retreat from the Colorado River. Joint systems, faults, and inclination of strata all affect the specific configurations of the drainage patterns and the resultant topographic expression of the partly dissected Esplanade surface.

Hummocky mounds of the Hermit Shale remain on the surface of the Esplanade as a result of differential erosion along joints or the intersection of tributary streams. The intersection of tributary streams by headward erosion isolates portions of the outer rim. This creates buttes and mesas such as Mt. Sinyala, The Dome, Mt. Akaba, and Fishtail (Text-fig. 10). As features such as these degenerate by the constant wear of erosion, they eventually arrive at a stage in their evolution where nothing remains but a hummocky mound of the Hermit Shale. Also, as talus accumulates from the cliffs overlying the Hermit, a blanket is formed that, when consolidated, is more resistant to erosion than the Hermit Shale. Consequently, this talus forms an inclined caprock which preserves the Hermit immediately beneath it. As the major cliff retreats, remnants are left stranded beneath the talus cones. Excellent examples of this phenomenon can be seen in Havasu Canyon from Topocoba Hilltop. Although

TEXT-FIGURE 11.—Sketch showing solution basins in the Esplanade.

many examples of this phenomenon in various stages of detachment are seen in the Grand Canyon, they are not unique to this area. Many such examples can be found throughout the southwestern United States.

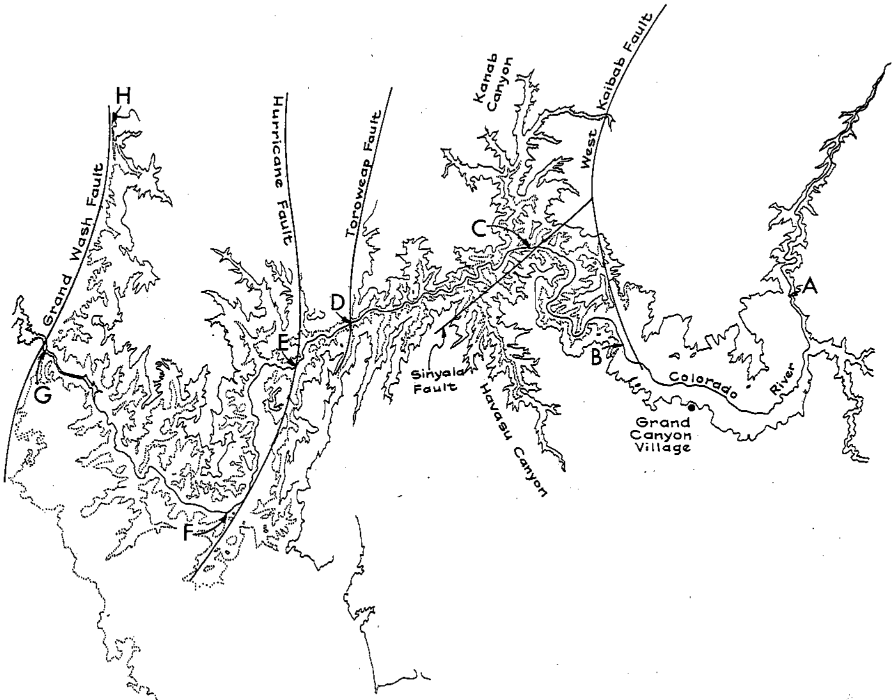
Solution basins, such as those illustrated in Text-figure 11, pockmark the surface of the Esplanade. The wide distribution of these basins does not become apparent until one has the rare opportunity to see them filled with water after a rainshower has passed. Dutton (1882) aptly described them when he said, ". . . we find its surface [the Esplanade] to be mostly bare rock, with broad shallow basins etched in them, which hold water after showers. There are thousands of these pools, and when the showers have passed they gleam and glitter in the sun like innumerable mirrors."

The exhumed pre-Hermit erosion surface which correlates with the Esplanade horizon undoubtedly affects the present configuration of the Esplanade terrace. Noble (1922) and White (1929) point out that this surface has topographic relief of between 50 and 70 feet, with channels not exceeding one-half mile across. Irregularities of this dimension produce some structural control of the erosive forces at work on the Esplanade.

As previously indicated, faulting (Text-fig. 12) and fault-related features, and folds cause disruption and/or inclination of the Esplanade surface. Hamblin (1965, pp. 1148, 1155; Plates 1 and 2) points out that the "reverse drag" phenomenon is well expressed in the Grand Canyon, and specifically on the Esplanade. Numerous small monoclinal flexures are dispersed throughout the canyon, which create undulations in the Esplanade surface.

Regional Variations

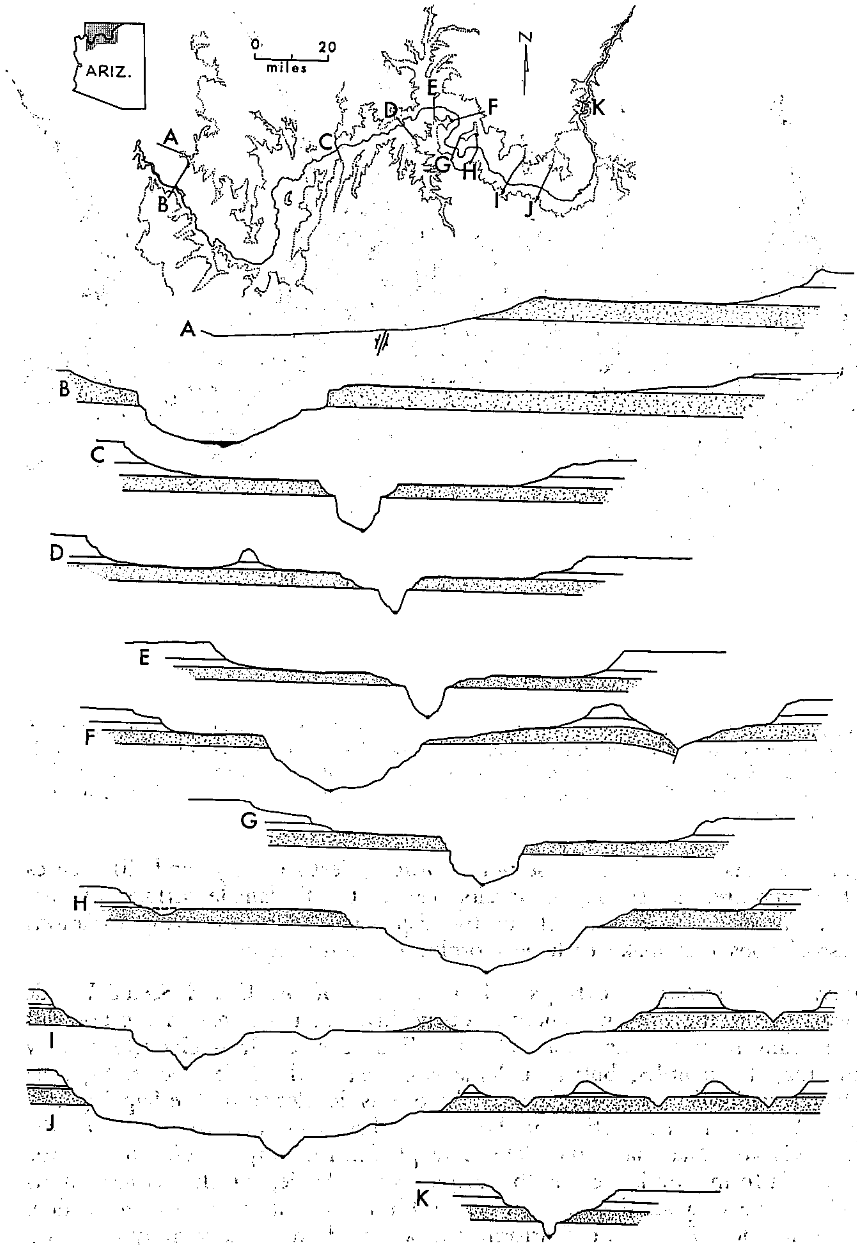
Frequently, writers of Grand Canyon geology have subdivided the canyon into several divisions as an aid in discussing the various aspects of their subject. This writer also finds this approach useful in discussing the regional variations of the Esplanade platform. For this purpose, geomorphic divisions of the Esplanade were adopted and modified from those proposed by Chesser (1969). The general boundary locations for the sections so designated are shown on the map (Text-fig. 12). Generally, the descriptions of each section are limited to Hermit-Supai physiography, geologic phenomena related to the



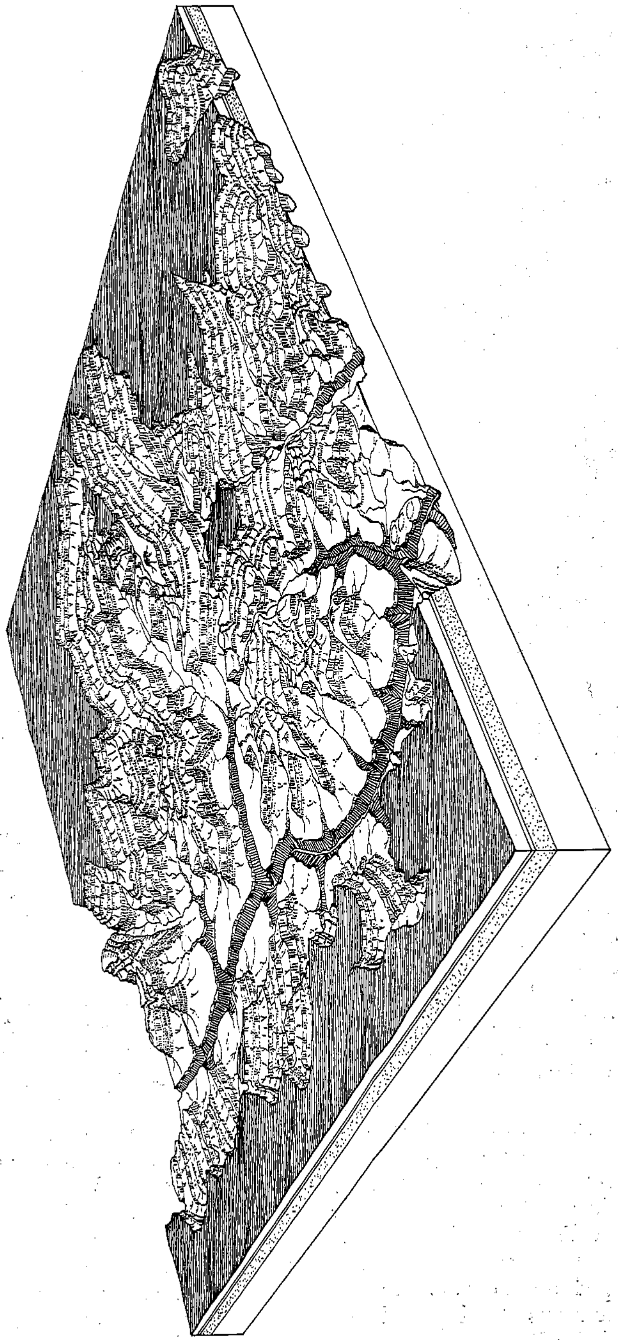
TEXT-FIGURE 12.—Map showing major faults that cut the Esplanade and boundaries of geomorphic divisions of the Esplanade. A–B—Eastern Park Section, B–C—Powell Plateau Section, C–D—Esplanade Section, D–E—Volcanic Cascades Section, E–F—Hurricane Fault Section, F–G—Lower Granite Gorge Section, G–H—Western Margins Section.

Esplanade, characteristic cross section profiles (Text-fig. 13), and differences in the exposure, expression, or development of the Esplanade surface. Despite the consistency of some aspects of the Esplanade, there are many variations or associations that make each geomorphic division unique.

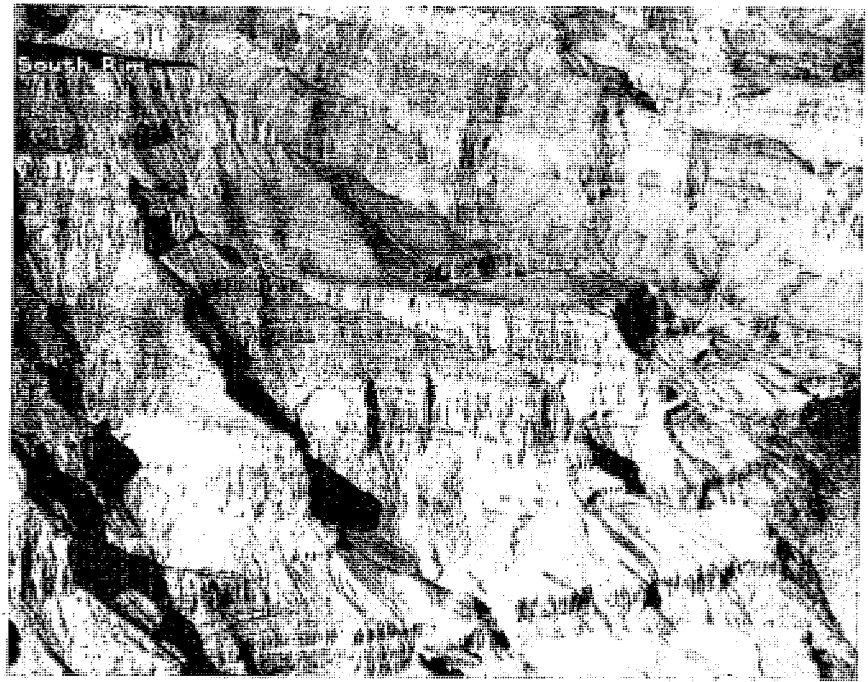
Eastern Park Section (Text-figs. 14, 15).—East of the Grand Scenic Divide (Text-fig. 1), the canyon scenery is vastly different from that in the portions of the canyon where the Esplanade is well developed. It is characterized by many majestic temples, buttes, and mesas carved in the Paleozoic stratigraphy in the canyon (Text-fig. 14), but no platform is developed on the Supai (Text-fig. 15). This is the portion of the canyon that is familiar to visitors of the Grand Canyon National Park. The only platform of any broad extent is the Tonto Platform developed on the Bright Angel Shale, which, because of its depth in the canyon, does not present itself in an imposing manner as does the Esplanade. The Tonto Platform can be traced from the vicinity of Havasupai Point eastward to the end of the inner gorge below Lipan Point before the canyon reaches the confluence of the Little Colorado River. It is approximately 2,000 feet down-section from the stratigraphic horizon of the Esplanade platform. This is in contrast to the implication by Dutton (1882) that the Tonto Platform was the eastern equivalent of the Esplanade erosion surface.



TEXT-FIGURE 13.—Cross sections showing development of the Esplanade. Esplanade is indicated by heavy line drawn on top of Supai Formation (stippled). The Hermit Shale overlies the Supai and is left blank. Section A is oriented so that east is right. Sections B–K are oriented so that the viewer is looking downstream, as indicated on the small index map.



TEXT-FIGURE 14.—Eastern Park Section—block diagram. View is to the northwest. Supai is stippled and the overlying Hermit is left blank.



TEXT-FIGURE 15.—Eastern Park Section—aerial photo. E indicates the Esplanade horizon. View is to the west, of a portion of the South Rim below Pima Point in the Grand Canyon National Park. (Photo by W. K. Hamblin)

Because of its seven-mile-wide expanse and one-mile depth, the observer is impressed with the immense spaciousness of the canyon. The canyon cuts across the southern end of the Kaibab uplift and has structurally adjusted itself downdip. The resultant profile is asymmetrical, and the critical observer realizes this as he takes note of the position of the river in the canyon gorge (Text-fig. 14 and cross sections I, J in Text-fig. 13).

Typically, the Supai profile reclines in this portion of the canyon (Text-fig. 4, nondeveloped profile) and is characterized by step-slope topography. The Hermit Shale is much thinner and in many areas is difficult to distinguish from the Supai Formation. Upon casual observation, it appears only as the uppermost slope of a series of shale units interbedded in sandstones (Text-fig. 15).

The thickness of the Hermit Shale in the Eastern Park Section varies from 100 feet near the confluence of the Little Colorado and Colorado rivers, westward to roughly 300 feet in the vicinity of Hermit's Basin. However, as one goes northward from the mouth of the Little Colorado River to the gorge in the Marble Platform (Text-fig. 2), the Hermit increases in thickness to more than 600 feet. Because of this increase in thickness, an incipient Esplanade is developed on the Supai headlands which are on the inside curves of the several meanders developed there. At the same time, as the Hermit thickens northward the Esplanade horizon approaches and then plunges below the base level (Colorado River). This would partly explain why only an incipient Esplanade has been developed here.

The Esplanade Sandstone Member and the Supai Formation in this section do not differ greatly in total thickness from their total thicknesses in other parts of the canyon (Text-fig. 3).

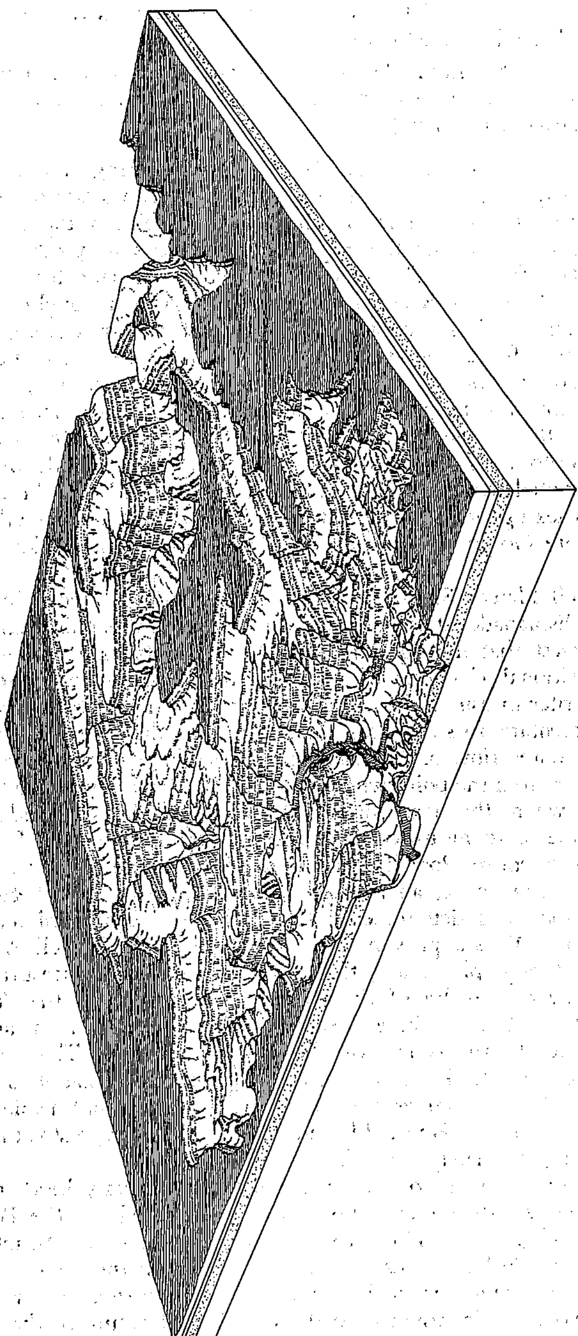
Powell Plateau Section (Text-figs. 16, 17).—Beginning at the Grand Scenic Divide (Text-fig. 1), the major profile of the canyon starts to change (Text-fig. 13, cross section H). The Hermit begins to thicken appreciably, and the physiographic expression of the Supai cliffs changes to produce an incipient Esplanade (Text-fig. 7). The smaller incipient Esplanade terrace follows the course of the Colorado River around Powell Plateau roughly in a reverse "S" configuration. This section marks the easternmost development of the Esplanade except for a few small discontinuous terraces developed at the Esplanade horizon in the Eastern Park Section. In this section, the Esplanade begins to assume the proportions of a prominent terrace, such as the Tonto Platform. In the whole of the western Grand Canyon the Esplanade surpasses the Tonto Platform in size and dominates the profile of the canyon. It should be noted that the Tonto Platform disappears below Havasupai Point, due to downflexing of the stratigraphy by the West Kaibab Fault Zone. The Middle Granite Gorge and the Tapeats Sandstone plunge below the level of the river.

The Powell Plateau Section is, in essence, a transition zone in the development of the Esplanade. It is not until the canyon leaves this section and turns to the southwest that the "grand avenue" attains its magnificent proportions.

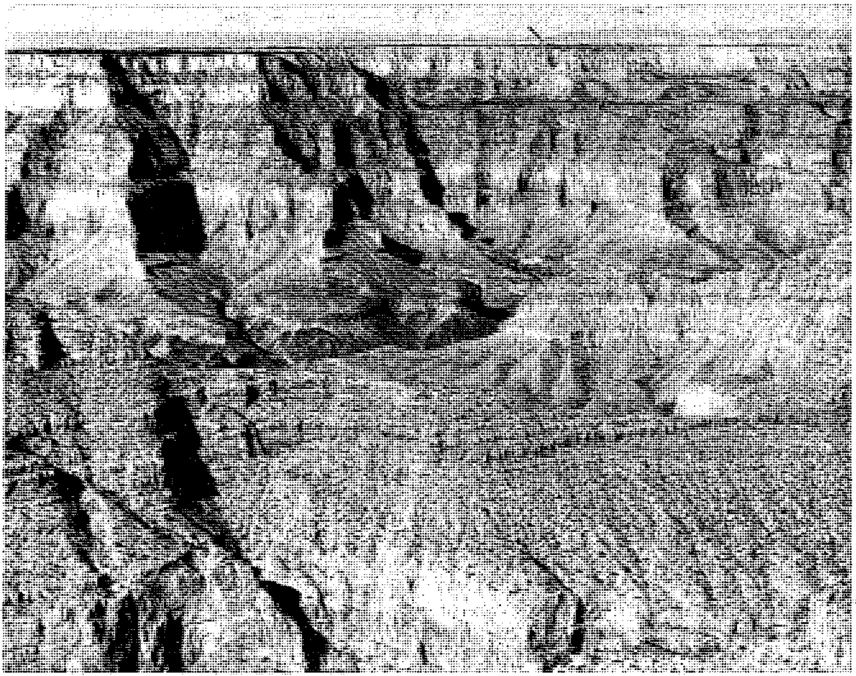
The transitional character of the Esplanade can be expressed in several ways. The writer measured the distances between "major" tributary canyons that cut the sedimentary rocks at least half the map distance from the Colorado River to the outer rims of the canyon. These measurements were along the Colorado River from the point where one "major" tributary entered the Colorado to the point where the next "major" tributary on the same side of the river entered. These were measured in succession on both sides of the Colorado throughout the entire Powell Plateau and Esplanade sections. After these measurements were made, an average value for the distance between "major" tributary canyons was determined. The average "major" tributary separation distance (AMTSD) is approximately 5,700 feet for the Powell Plateau Section.

From the topographic maps, the writer also collected measurements of the approximate average width of the stream divides between the "major" tributaries described above. These measurements were taken in an orientation roughly parallel to the course of the Colorado River. These measurements were made only of the Esplanade terrace to the extent that it is developed in each section. Average values for the Powell Plateau and Esplanade sections were determined. In the Powell Plateau Section, the average stream divide width (ASDW) is approximately 2,250 feet.

An idealized cross section of an average intertributary headland, which incorporated the two dimensions above, was constructed for the Powell Plateau Section (Text-fig. 18). This cross section becomes significant only when compared to an idealized cross section constructed in the same manner for the Esplanade Section which is in the same figure. The smaller distances between tributary canyons are in response to the transitional nature of the geologic conditions prevalent in the Powell Plateau Section. The cliffs of the Supai have



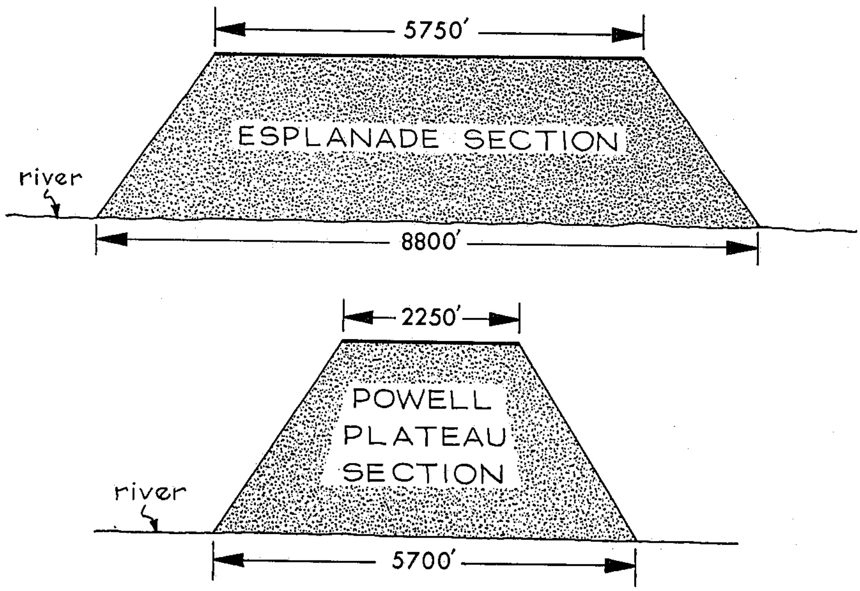
TEXT-FIGURE 16.—Powell Plateau Section—block diagram. View is to the southwest. Powell Plateau is the large isolated mesa in the middle of the diagram. The Supai is stippled and the overlying Hermit is blank.



TEXT-FIGURE 17.—Powell Plateau Section—aerial photo. View is to the southwest. In the middle distance, one can see Mt. Huethawali (long arrow) perched on the Darwin Plateau, which is an arm of the Esplanade. The short arrow points to the Grand Scenic Divide (Text-fig. 1), which marks the easternmost development of the Esplanade. (Photo by W. K. Hamblin)

not changed completely from their physiographic step-slope form of the Eastern Park Section to the more massive straight-walled cliffs of the Esplanade Section. This section, therefore, has a higher drainage density than does the Esplanade Section. The transitional character of the Powell Plateau Section is also shown by the "rounded" nature of the intertributary divides (Text-fig. 16).

In this section of the canyon, the cliffs of the Supai are in a transitional mode that has an erodibility factor somewhere between that of the Supai cliffs in the Eastern Park Section and those in the Esplanade Section. Although it has not been confirmed by concrete data, other than observation in the field, this changing physiographic expression of the Supai cliffs is due, not to a significant increase in sands or cliffs of the Supai, but to a thinning of its Upper and Middle slopes to the west. One can see the reasoning behind this point of view when it is seen that Text-figure 6 shows no significant buildup in the percentage of cliffs to the west, except locally. Further, Text-figure 5 shows, upon critical observation, that there are fewer slopes or partings in the cliffs of the Supai in its upper portions west of section 8 at the mouth of Kanab Canyon. Sections 9 and 10 in the Powell Plateau Section are transitional. The evolution of the Supai cliffs to the west would therefore follow this

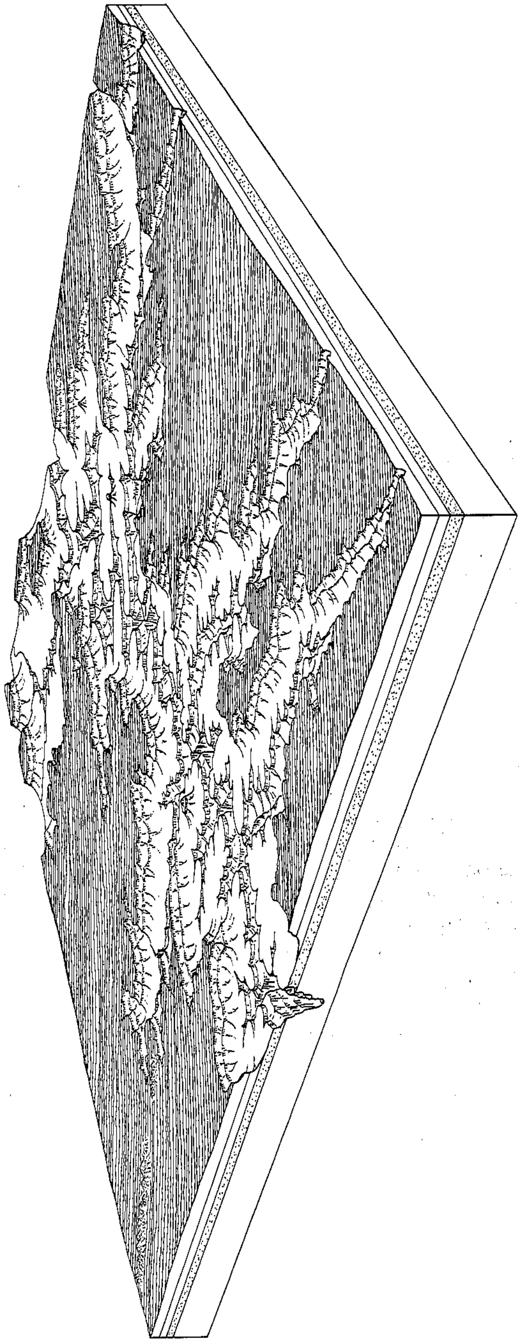


TEXT-FIGURE 18.—Idealized cross section of two intertributary headlands. The Esplanade terrace is represented by the heavy horizontal lines.

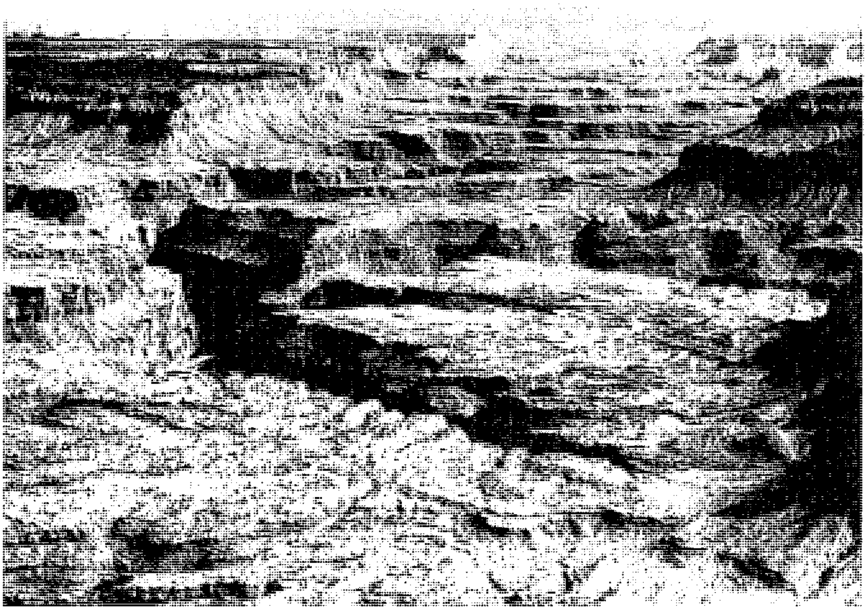
sequence: (1) The Eastern Park Section Supai profile lays down because the Upper, Middle, and Lower slopes have sapped the Upper, Middle, and Lower cliffs, so that the rim of the cliffs roughly coincides with the toe of the overlying slopes. (2) The Supai profile in the Powell Plateau Section starts to stand up as the Upper and Middle slopes thin, so that their ability to sap the overlying Upper and Middle cliffs is reduced. The thinner shale units, however, are stripped from the upper surfaces of the underlying cliffs, creating broad steps or benches at several horizons throughout the Supai section (Text-fig. 16). (3) Finally, in the Esplanade Section the Upper and Middle slopes thin sufficiently to drop to their lowest influence in undermining the overlying Upper and Middle cliffs. Consequently, the profile stands nearly vertical, and, except to the critical observer, all three cliffs act almost as one (Text-fig. 7, developed profile). It should be noted that as the Upper and Middle slopes diminish to the west, the Lower Slope maintains its thickness. However, the Lower Slope's influence in sapping the overlying cliff is reduced not by thinning, but by the changing configuration of the overlying cliffs, which overpowers its influence on them. Locally, where the two upper slopes thicken somewhat, there is a breakdown in the vertical cliff profile.

Esplanade Section (Text-figs. 19, 20).—This is the most familiar section of the Esplanade, due in large measure to its accessibility by roads down Toroweap Valley in the Grand Canyon National Monument. The relatively uncluttered view eastward for approximately 30 miles (Text-fig. 23) from the mouth of Toroweap Valley inspired the works of Dutton and Holmes.

A typical profile of this section, such as profile C (Text-fig. 16), gives an excellent concept of most of the Esplanade. It shows a double-rimmed can-



TEXT-FIGURE 19.—Esplanade Section—block diagram. View is to the northeast. The Supai is stippled and the overlying Hermit is blank. The Esplanade is the lightened terrace that dominates the canyon profile.



TEXT-FIGURE 20.—Esplanade Section—aerial photo. View is to the east from the vicinity of Toroweap Valley and shows the broad expanse of the Esplanade. Mt. Sinyala is in the upper right. (Photo by W. K. Hamblin)

yon that is dominated by the platform of the Esplanade. This simple profile characterizes the majority of the canyon where the Esplanade has been developed. Variations from this profile are primarily due to evolution of the Esplanade or extraneous geologic phenomena, such as faulting, and vulcanism having been superimposed on this simplified setting.

This section of the canyon is further characterized by the seven large tributary canyons that extend from five to twenty-five miles from the main gorge (Text-fig. 12). Havasu Canyon is located in an asymmetric structural trough that trends roughly southeastward from the Colorado River. Its restricted situation in this trough has caused the smaller tributaries feeding it to be relatively short. This is in marked contrast to the long, branching tributaries of Kanab Canyon on the north side of the river, which is restricted only on the east by the Kaibab Uplift. The block diagram (Text-fig. 19) shows the dominating influence of the Esplanade on the character of this portion of the canyon. It also shows the configuration of the large tributary canyons into which the Esplanade is extended. Because of the broad platforms developed in these tributary canyons, the width of the major course of the Esplanade is more apparent than real.

Text-figure 18 showes an idealized cross section of an intertributary headland of the Esplanade Section. It is compared to one drawn for the transitional

Powel Plateau Section. Incorporated in the diagram is the average "major" tributary separation distance (AMTSD) of approximately 8,800 feet. Also included is the average stream divide width (ASDW) of approximately 5,750 feet. The methods used to obtain values for the AMTSD and ASDW are discussed in the Powell Plateau Section. In the diagram (Text-fig. 18) the vertical and horizontal scales are the same. Relative heights above base level (Colorado River) are also drawn to scale.

Perched on these obviously broad stream divides are isolated buttes, mesas, and cinder cones (Text-fig. 10). Buttes and mesas such as Mt. Akaba, Mt. Sinyala, The Dome, and Fishtail have all been isolated by the headward erosion of tributary side canyons. In the case of Mt. Sinyala, headward erosion has been accelerated and partially controlled by the Sinyala Fault.

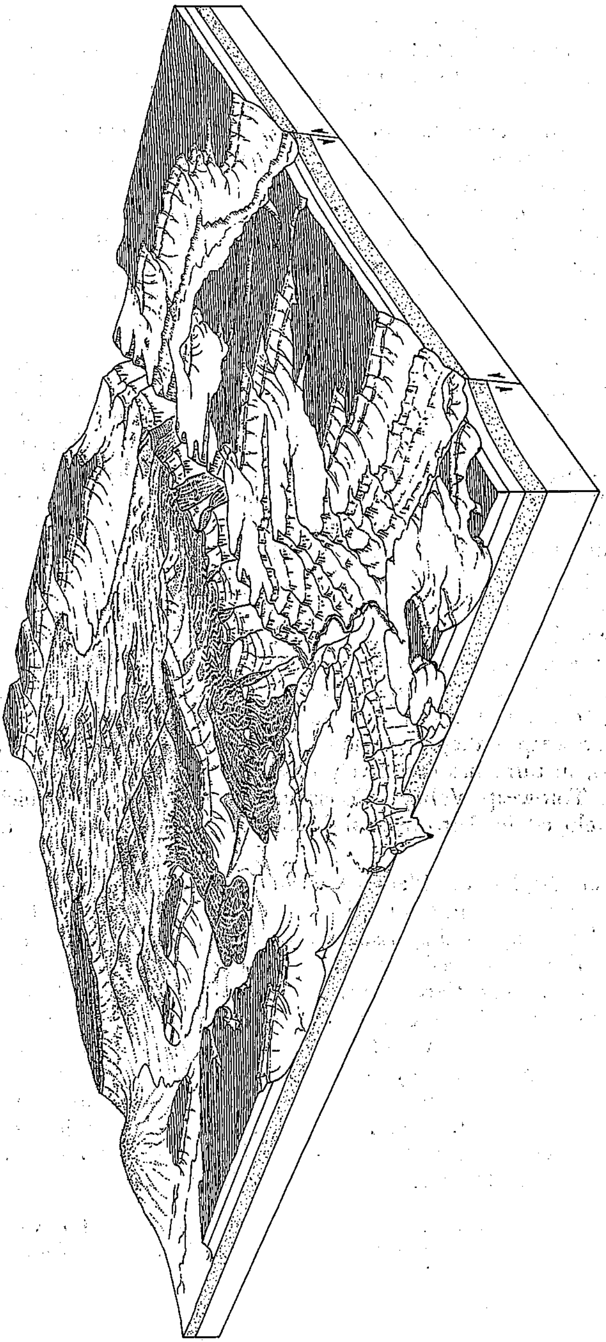
Volcanic Cascades Section (Text-figs. 21, 22).—In this section, the Esplanade's expression and the canyon profile are similar to those described in the preceding Esplanade Section. The section has been down-dropped approximately 800 feet by movement on the Toroweap Fault. The escarpment thus created marks the easternmost boundary of this section. On the south side of the river a few cinder cones dot the surface of the Esplanade. On the north side, the Esplanade is covered by a thin veneer of Pleistocene volcanics and is exposed only as headland patches (Text-fig. 22).

The floors of Toroweap and Prospect valleys arrive at the inner canyon rim at the level of the Esplanade. McKee and Schenk (1942) and Hamblin (1969) have shown that the Toroweap Valley was originally cut appreciably deeper, almost to the depth, possibly, of the present canyon. The valley was then filled with lava flows and thereafter with a generous covering of alluvium. Vulcan's Throne (Text-figs. 10, 22), a cinder cone approximately 600 feet in height, and the Toroweap Valley lava flows have protected the alluvial cover from erosion. This, in turn, has effectively obscured such details as the extent of the prevolcanic Toroweap Valley. Consequently, the extent to which the Esplanade was developed in Toroweap and Prospect valleys remains a matter of conjecture.

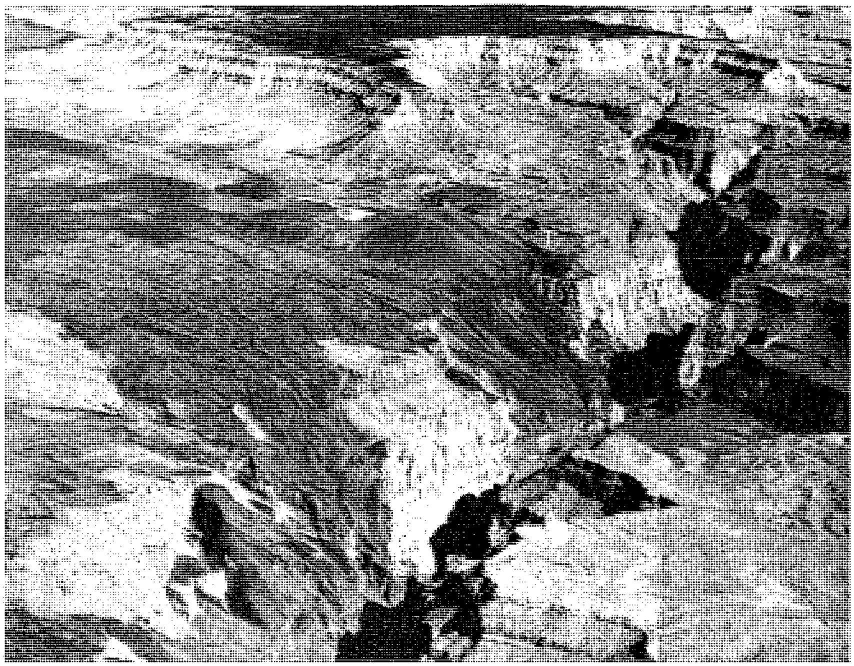
The magnificent display of Pleistocene volcanics in this region would make one wonder if he had just missed a scene of—billowing, black clouds of volcanic ash fill the sky as they issue forth from the vents scattered over the plateau. Piles of volcanic ash and debris soon grow into cinder cones which dot the landscape. The fiery glows of molten rock surging forth from the rumbling depths below fill the sky and landscape with a fearful iridescence. Numerous serpent-like flows of molten lava slowly crawl across the broad terrace of the Esplanade only to plummet 3,000 feet below into the cold waters of the Colorado. An explosion of white steam fills the inner gorge and shoots skyward with seething fury. Soon, the volcanic fires are cooled and the winds clear the air to reveal the landscape that one can now see spread before him on the Uinkaret Plateau (Text-fig. 21).

Hurricane Fault Section (Text-figs. 23, 24).—The course of the Colorado River turns southward near the mouth of Whitmore Wash and follows the Hurricane Fault Zone to Diamond Peak. Peculiarities created by this situation set this stretch of the canyon apart as distinctively as any other.

East and south of the river along this portion of the canyon, the Esplanade is offset by faulting and has developed a series of inclined steps



TEXT-FIGURE 21.—Volcanic Cascades Section—block diagram. View is to the northeast. This section is bounded by the Toroweap and Hurricane Faults, which run roughly parallel to the left front edge of the block diagram. Fault locations are indicated on the right front edge of the diagram: Toroweap Fault—back, right (east); Hurricane Fault—front, left (west). The Supai is stippled and the overlying Hermit is blank.



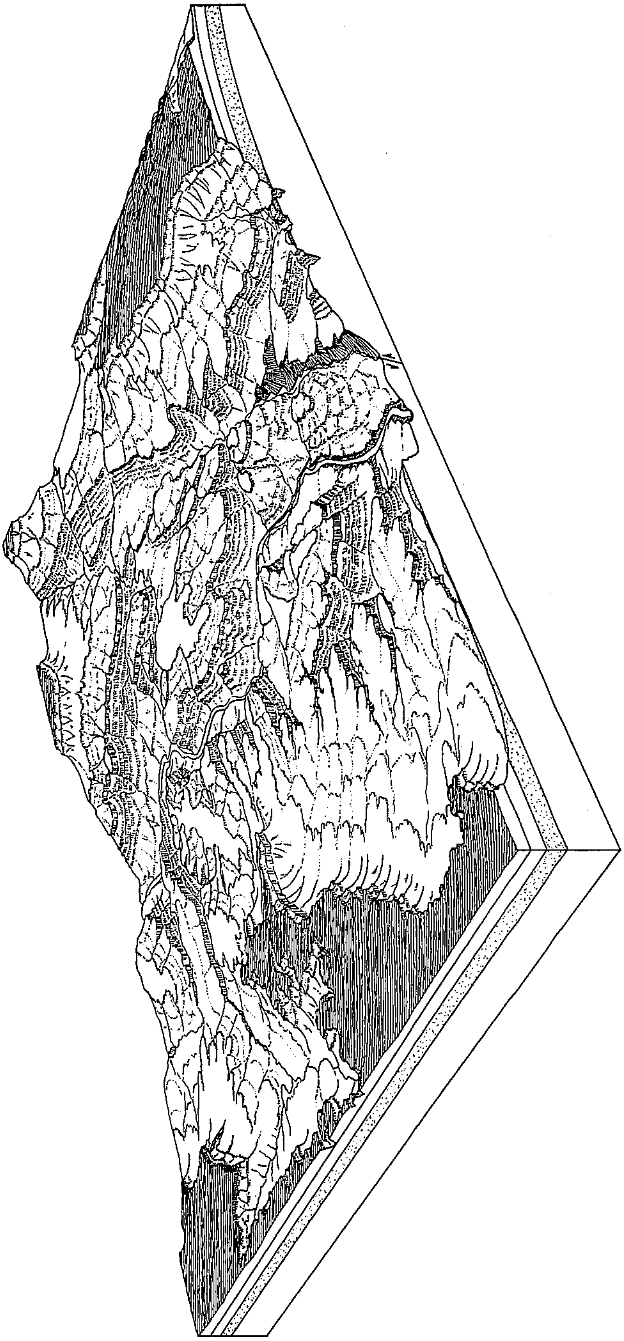
TEXT-FIGURE 22.—Volcanic Cascades Section—aerial photo. View is to the northeast. E—headland patch of Esplanade, T—Toroweap Fault escarpment. Large cinder cone in center of photo is Vulcan's Throne. Lava cascades fill the tributary canyons. (Photo by W. K. Hamblin)

(Text-fig. 24). The eastward inclination of strata is attributed by Hamblin (1965) to the effect of a "reverse drag" phenomenon, and not to monoclinal folding, as some have thought. On the west or north side of the river, the Esplanade has developed "normally" and becomes wider as the Hermit thickens. The cliffs of the Supai, while still very thick, recede slightly because of the less resistant nature of the limestones and sandstones that are present in this section. The Supai forms a slightly reclined profile, which is somewhat similar to that in the Powell Plateau Section.

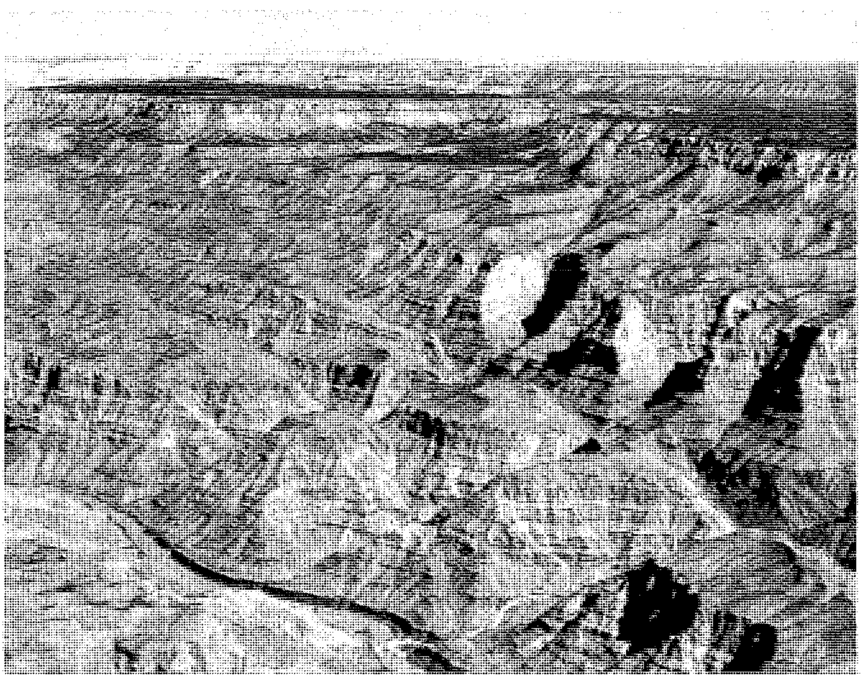
The Granite Gorge reappears in this stretch of the river as a low inner gorge. Text-figure 23 shows the geologic configuration of this section of the canyon along the trace of the Hurricane Fault Zone.

Lower Granite Gorge Section (Text-figs. 25, 26).—Diamond Peak marks the approximate eastern limit of the lower Granite Gorge Section (Text-fig. 12). The Hermit Shale attains its greatest thickness—about 1,600 feet—near the Grand Wash Cliffs (Text-fig. 3). This section is uniquely characterized by its single outer rim, shown in cross section B (Text-fig. 13). Here, the Esplanade is developed on only the north side of the river (Text-fig. 1).

On the south side of the river is an erosion surface that topographically corresponds to the level of the Esplanade (Text-fig. 25). However, it differs



TEXT-FIGURE 23.—Hurricane Fault Section—block diagram. View is to the northeast. The Supai is stippled and the overlying Hermit is blank.

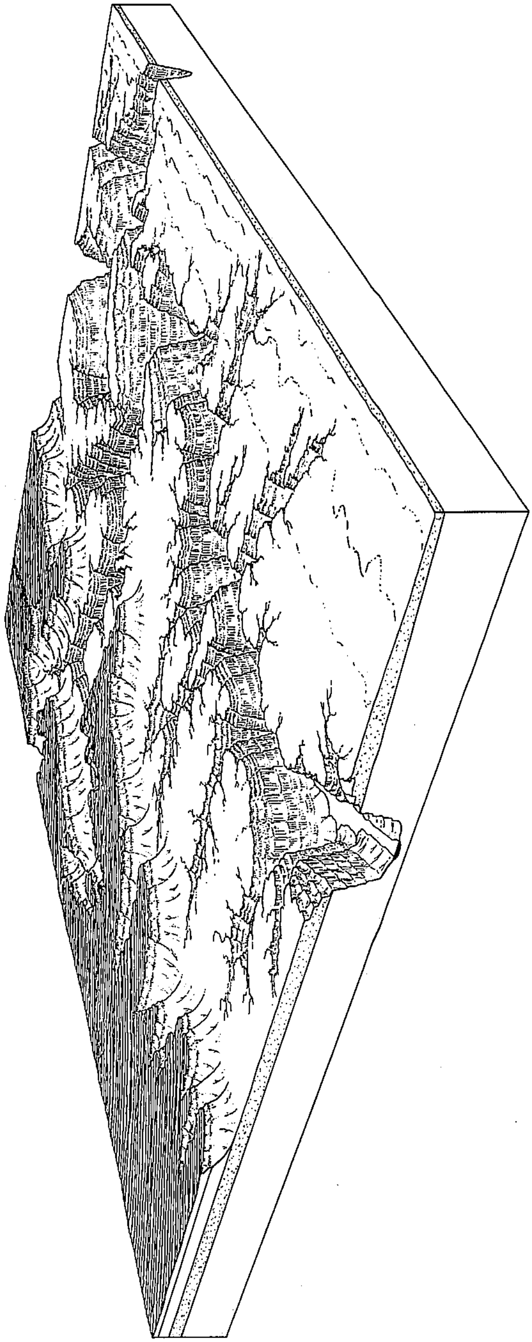


TEXT-FIGURE 24.—Hurricane Fault Section—aerial photo. View is to the northeast. This is the right middle portion portrayed in the block diagram (Text-fig. 23). Dotted lines indicate trace of Hurricane Fault Zone. (Photo by W. K. Hamblin)

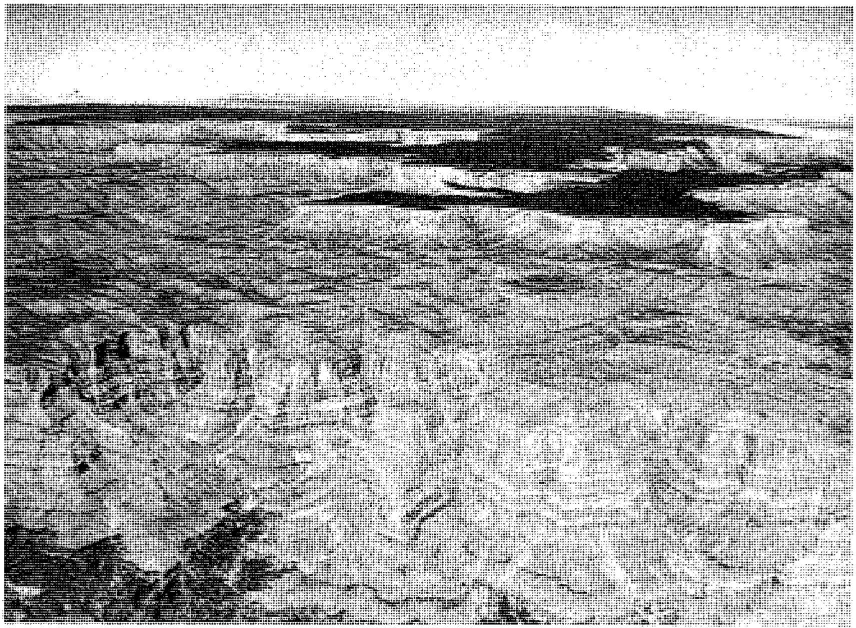
from the Esplanade in stratigraphic position, genesis, and physiographic expression. This surface cuts across several formations that dip gently to the northeast, namely, the lower Supai equivalent, Callville Limestone (McNair, 1951); the Tonto Group; and Precambrian rocks. This surface extends southward until it reaches the Mogollon Rim, where it ends against the Basin and Range. It is not considered by this writer to be an extension of the Esplanade platform but that it involves processes other than canyon development in its origin.

Western Margins Section (Text-figs. 27, 28).—The Esplanade has developed approximately 35 miles northward along the trace of the Grand Wash Fault to the vicinity of Jump Canyon, where its tapering shape disappears. The eastern boundary is formed by the high cliffs of the Shivwits Plateau. Unlike the other sections of the Esplanade, this section is not cut along its major axis by the Colorado River; rather, the western boundary of this section is the rim of the Grand Wash Cliffs (Text-fig. 1). Cross section A (Text-fig. 13) shows the characteristic configuration of the Esplanade as it is developed along the Grand Wash Cliffs.

Text-figure 27 shows the trace of the Grand Wash Fault, which cuts through the left front edge of the diagram. One can see how the face of the upthrown block has retreated away from the fault and forms the Grand Wash



TEXT-FIGURE 25.—Lower Granite Gorge Section—block diagram. View is to the northeast. Esplanade is developed only on north (left) side of the river. The Supai is stippled and the overlying Hermit is blank. Notice that strata on the south (right) side of the river dip gently to the north (left).



TEXT-FIGURE 26.—Lower Granite Gorge Section—aerial photo. View is to the north. Dark upper surface is the Shivwits Plateau, which is capped by basalt. Notice the dissected character of the Esplanade terrace. The Lower Granite Gorge is shown in the lower left corner of the photo. (Photo by W. K. Hamblin)

Cliffs. The Esplanade forms the terrace on top of the Grand Wash Cliffs, with the Shivwits Plateau forming a higher step-like terrace to the east. The southern boundary of the Western Margins Section (Text-fig. 12) is located where the Colorado River emerges from the Grand Canyon (Text-fig. 28). The terrace on top of the cliffs (Mogollon Rim) south of the river is part of the erosion surface discussed in the Lower Granite Gorge Section.

COMPUTER ANALYSIS

Sources of Data

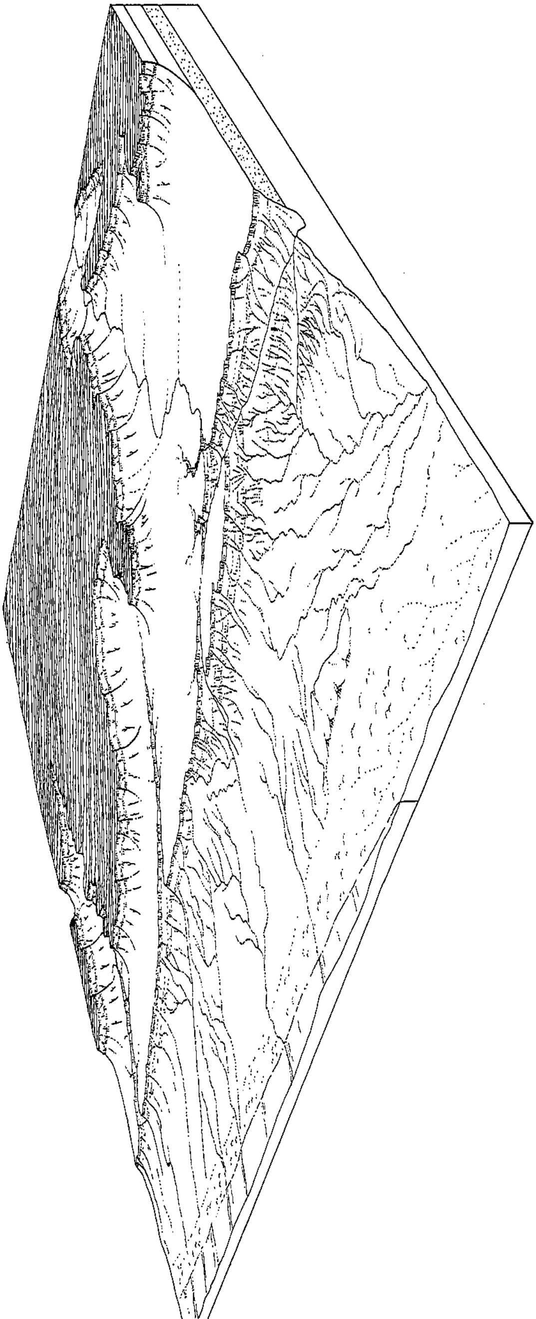
The basic method of accumulating data on the Esplanade was to measure sections of the Hermit-Supai sequence and to relate the rock types to the profile of the canyon. In addition to the original field work, published sections by Noble (1914, 1922) and McNair (1951), and unpublished sections by Billingsley (1970), Sorauf (1962), Fisher (1961), and E. D. McKee (personal communication) were studied and utilized. E. D. McKee, who is currently completing a comprehensive treatment of the Hermit and Supai Formations throughout the entirety of the Grand Canyon, has graciously allowed the writer the use of much information found in 30 of his measured sections.

Subsequently, much of the information obtained from the measured sections was converted to a number system so that it could be analyzed by a computer. The computer produced a regressive correlation matrix (Table 1) which suggested various trends and values for the data analyzed.

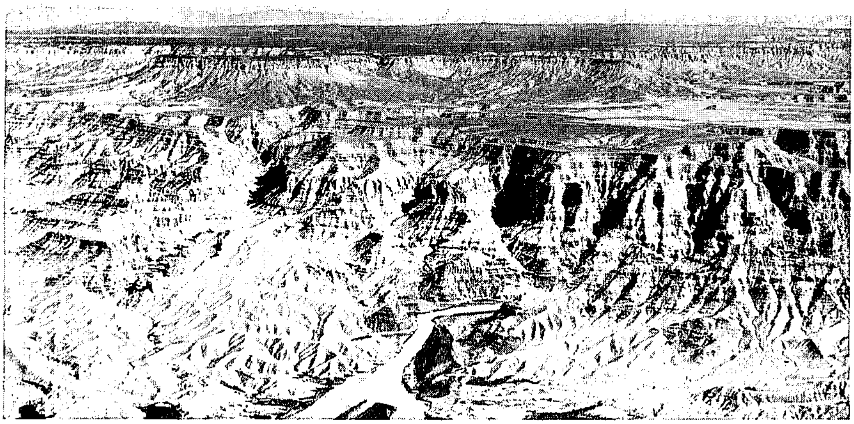
TABLE 1

CORRELATION MATRIX

	Esplanade (width)	Esplanade SS (thickness)	Supai (thickness)	Hermit (thickness)	Supai (sandstone %)	Hermit (sandstone %)	Supai (shale %)	Hermit (shale %)	Supai (limestone %)	Supai (cliffs %)	Hermit (ledges %)	Supai (slopes %)	Hermit (slopes %)
Esplanade SS—thickness	0.03												
Supai—thickness	0.41	0.02											
Hermit—thickness	0.86	0.06	0.59										
Supai—sandstone %	-0.65	0.35	0.00	-0.49									
Hermit—sandstone %	0.78	-0.31	0.47	0.88	-0.64								
Supai—shale %	-0.12	-0.33	0.07	-0.35	0.12	-0.19							
Hermit—shale %	0.67	0.49	0.53	0.81	-0.14	0.43	-0.42						
Supai—limestone %	0.72	-0.07	0.59	0.82	-0.69	0.78	-0.46	0.60					
Supai—cliffs %	0.42	0.33	0.80	0.67	0.02	0.44	-0.49	0.72	0.68				
Hermit—ledges %	0.74	-0.33	0.33	0.79	-0.46	0.92	-0.10	0.36	0.54	0.28			
Supai—slopes %	-0.02	-0.49	0.32	-0.13	-0.03	0.05	0.87	-0.30	-0.15	-0.32	0.08		
Hermit—slopes %	0.75	0.30	0.62	0.92	-0.40	0.66	-0.43	0.92	0.82	0.77	0.48	-0.23	



TEXT-FIGURE 27.—Western Margins Section—block diagram. View is to the northeast and shows the fault trace of the Grand Wash Fault (left front edge of diagram) and the retreated escarpment that constitutes the Grand Wash Cliffs. The upper surface is the Shivwits Plateau. The Supai is stippled and the overlying Hermit is blank.



TEXT-FIGURE 28.—Western Margins Section—aerial photo. View is to the northeast and shows the southern boundary of this section where the Colorado River emerges from the Grand Canyon. (Photo by W. K. Hamblin)

The writer used a large number of vertical aerial photographs taken by the U.S. Geological Survey and large aerial oblique photographs taken by the U.S. Air Force. Numerous aerial oblique and ground photographs taken by W. K. Hamblin were made available to the writer and were used extensively.

Recent U.S. Geological Survey topographic maps with scales of 1:24,000 and 1:62,500 were used in studying the topographic expressions of the Esplanade surface. These maps proved to be valuable information sources, since it was not possible to study the Esplanade expression in such detail before they were available. From these maps, 41 accurate cross sections showing the profile development of the Esplanade in the Grand Canyon were drawn.

A survey was made of the lithologic and cliff-slope relationships within the Hermit and Supai formations. These were studied in individually measured sections throughout the Grand Canyon area to determine which factors or relationships were correlative to the development of the Esplanade. The major emphasis was on the central portion of the Grand Canyon, where the transitional development of the Esplanade takes place.

At the outset, differences in the classification of rock types and cliff-slope identifications in the detailed measured sections by various authors made exact correlations of these components impossible. In order to accommodate these differences, much broader classification schemes were used (Text-fig. 29). These classifications were based on the genetic and/or rock relationships observed in the field.

"Best fit" curves were drawn which show overall trends for the lithologic and cliff-slope relationships throughout the canyon (Text-figs. 3-6). In Text-figures 3-6, one can see a buildup in the sand of the Hermit to the west, which contributes to the erodibility of the Hermit Shale. This undoubtedly is signifi-

SS	SH	LS
SANDSTONE SILTSTONE (cliff or ledge forming) CONGLOMERATE CALCAREOUS SANDSTONE (< 50 % limestone)	SHALE SILTSTONE (slope or bench forming) MUDSTONE	LIMESTONE DOLOMITE DOLOMITIC LIMESTONE SILTY LIMESTONE SANDY LIMESTONE (< 50 % sandstone) CHERT

CLIFF	SLOPE
CLIFF (vertical; straight; massive; recessive) LEDGE (ledgy) LAYERED BEDDED	SLOPE (high angle; long; low) BENCH RECESS RUBBLY

TEXT-FIGURE 29.—Classification schemes used for lithologies, cliffs, and slopes. Nomenclatures used by various authors are listed under broader classifications.

cant in the development of the Esplanade. Also, while one can see that there is no appreciable change in the percentage of cliffs or shale in the Supai, the lower sandstone cliffs of the Supai are simply replaced by limestone in the west. These apparently have little or only localized effects on the development of the Esplanade.

Analysis of Data

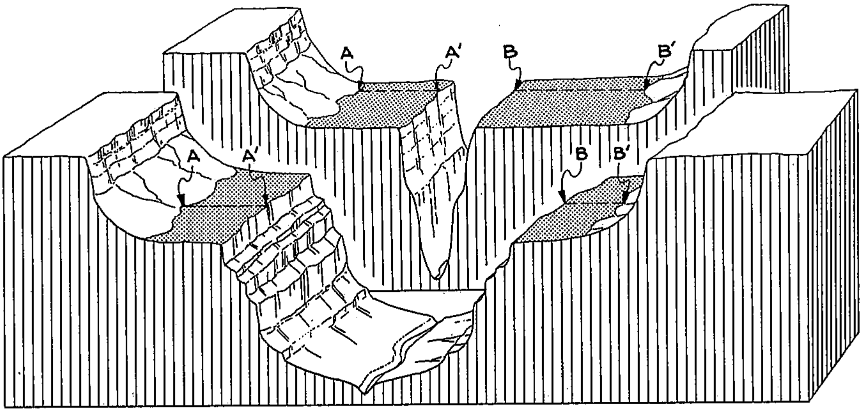
The IBM 360 computer system in the Brigham Young University Computer Research Center was used in the analysis of the data obtained in the course of this study. A computer program identified by the code name MULTR was used to produce a series of regressive correlation matrices in which the information to follow was considered.

The width of the Esplanade, which was programmed as the dependent variable, was determined by the method portrayed in Text-figure 30. The measurement from the toe of the Hermit slope (A) to the edge of the inner rim (A') was added to the distance measured from the canyon rim (B) to the toe of the Hermit slope (B') on the opposite side of the canyon. As one can see in the diagrams, erroneous widths would be obtained for different portions of the canyon if the Esplanade width was considered to be the distance from A to B'. In the western end of the canyon, where the Esplanade is developed on only one side of the river, the A to A' measurment was simply doubled for the sake of comparison.

The remaining factors were considered independent variables:

1. the thickness of the Hermit Shale
2. the thickness of the Supai Formation
3. the thickness of the Esplanade Sandstone Member of the Supai Formation
4. percentages of ledges and slopes in the Hermit Shale

5. percentages of cliffs and slopes in the Supai Formation
6. percentages of sandstone and shale in the Hermit Shale
7. percentages of sandstone, shale, and limestone in the Supai Formation

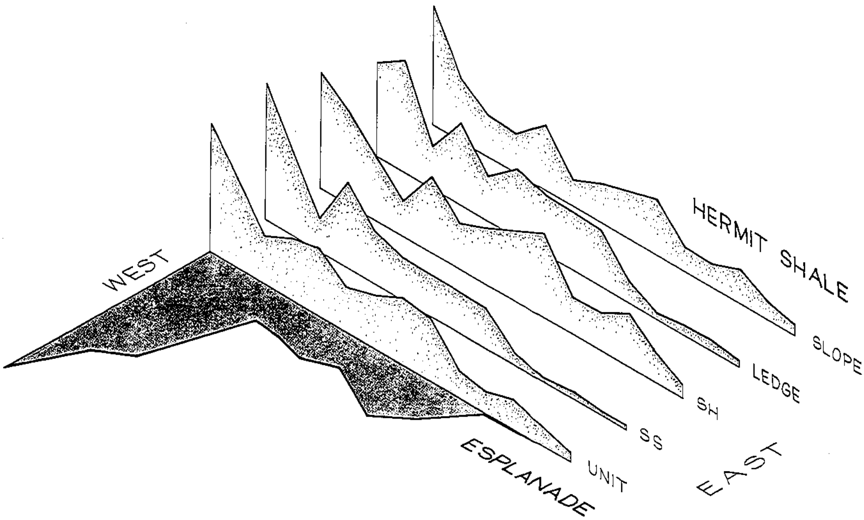


TEXT-FIGURE 30.—Conceptual block diagrams showing methods of measuring width of the Esplanade. (See discussion under Analysis of Data.)

A regressive correlation matrix is based on a comparison of rate-of-change values for the dependent variable and the various values for the independent variables. This rate of change has two components: direction, either positive or negative; and amplitude. In other words, if the values for the width of the Esplanade had a correlation of 100 to the values for an independent variable such as the thickness of the Hermit Shale, then a widening of the Esplanade platform would be reflected by a corresponding rate of change (positive or negative) for the thickness of the Hermit Shale, with an appropriate amplitude value. But because "pure values" are usually found only in theoretical models, it is not expected that one would find an independent variable having a correlation of 100 to the development of the Esplanade. Rather, one would expect to find factors of significantly high correlation which would suggest or strongly indicate a correlating relationship between two or more variables.

An isometric correlation diagram was constructed (Text-fig. 31) which shows the relatively high correlation of components of the Hermit Shale to the width of the Esplanade. In this diagram, the values for the width of the Esplanade and for components of the Hermit Shale are graphically represented in an east-to-west display consisting of the 14 sections utilized in Text-figures 3-6. These sections are spaced with a constant interval and were plotted on varying vertical and horizontal scales to facilitate comparisons. The component values for section 8—Kanab Canyon—were not plotted, since the Hermit Shale was not described in detail there.

The overall unit thickness of the Hermit Shale increases to the west as does the width of the Esplanade platform. The computer analysis indicated an approximate correlation of 86 for these two variables. Also, a correlation of approximately 78 between the buildup of sandstone in the Hermit and the width of the Esplanade was demonstrated. The correlation value for the ledges in the Hermit was slightly less (74) than for the sandstone. This is presumably



TEXT-FIGURE 31.—Isometric correlation diagram. Diagram compares components of the Hermit Shale to the changing width of the Esplanade. Data from 14 columns (Text-figs. 3-6) spaced at constant intervals from east to west. Vertical scales (Hermit Shale components) and horizontal scale (Esplanade width) vary to facilitate comparison.

a reflection of the sandstone values, since the ledges in the Hermit are primarily composed of sandstone. The correlation value for the shale in the Hermit was somewhat lower (67) than that for the sandstone, and its relative value was reflected in the slope correlation value of 75.

The correlations of the Supai Formation and its components to the width of the Esplanade were so low (Table 1) that plotting a correlation diagram for those values was not considered profitable. Although a relatively high correlation (72) of the limestone in the lower Supai to the Esplanade width is indicated by the matrix, it is not considered to be of significance to the development of the Esplanade.

It should be pointed out that since the data for the computer analysis was taken largely from measured sections, there may have been some inherent weaknesses introduced. For example, due to the steep vertical cliffs in the Grand Canyon, accessibility is limited to trails which have been built along zones which were produced primarily by faulting and local changes in cliff morphology. This may or may not account for the fact that the cliff values for the Supai Formation did not show a significant correlation. Since the computer analysis did not strongly support observations made in the field concerning changes in Supai cliff morphology (correlation of 42), other approaches to that problem were undertaken. This problem is discussed elsewhere in the text.

INTERPRETATION AND SUMMARY

The Esplanade is in fact a structural terrace as Davis (1901, 1903) basically proposed, and its significant controlling factors, as determined by this study, are:

1. an increase in the unit thickness of the Hermit Shale to the west (Text-figs. 3, 31; Table 1)
2. a change in the physiographic expression of the cliffs in the Supai Formation from a step-slope topography in the east to a steep-walled cliff with fewer and thinner shale partings in the west (Text-figs. 7, 13)
3. a buildup of sands in the Hermit Shale to the west, which increases its erodibility (Text-figs. 4, 31; Table 1).

Additional studies concerning the thinning of the Upper and Middle slopes (Text-fig. 7) and the nature of the sands of the Hermit Shale would seem to be warranted by the indicated trends of their relationships, as suggested by this study.

The outer rim, which marks the recessional edge of cliff-slope retreat and the marginal extent of the Esplanade, forms cuspate headlands and concave slopes which, according to Penck (1929), represent a waning development in which the denudation rate exceeds the rate of uplift.

APPENDIX

The measured stratigraphic sections utilized in this study, which correspond by number to those illustrated in Text-figures 3-6, are broken into their various component values below. The values listed are those used in the computer analysis and were also used to construct the isometric correlation diagram (Text-fig. 31). The unpublished measured sections by E. D. McKee are listed by name and total thickness. Sections by other authors are available in the sources indicated.

Section / Author Component Description	1. Iceberg Canyon E. D. McKee	2. Twin Springs Canyon E. D. McKee	3. Blue Mountain Canyon E. D. McKee	4. Toroweap Valley E. D. McKee	5. Tuckup Canyon Billingsley (1970)
Esplanade width (feet)	74,500	52,800	46,500	13,500	14,750
Hermit Shale (feet)	1,590	1,121	598	770	813
Supai Formation (feet)	1,176	936	831	949	924
Esplanade SS Mem. (feet)	258	297	221	127	247
Hermit—ledges (feet)	477	536	203	396	211
Hermit—ledges (%)	30	48	34	51	26
Hermit—slopes (feet)	1,113	585	396	374	602
Hermit—slopes (%)	70	52	66	49	74
Supai—cliffs (feet)	912	598	477	552	647
Supai—cliffs (%)	78	64	57	58	70
Supai—slopes (feet)	264	338	354	397	277
Supai—slopes (%)	22	36	43	42	30
Hermit—sandstone (feet)	868	526	203	548	337
Hermit—sandstone (%)	55	47	34	71	41
Hermit—shale (feet)	723	595	396	222	476
Hermit—shale (%)	45	53	66	29	59
Supai—sandstone (feet)	186	445	310	452	345
Supai—sandstone (%)	16	48	37	47	37
Supai—shale (feet)	181	301	329	339	122
Supai—shale (%)	15	32	40	36	13
Supai—limestone (feet)	809	191	193	158	457
Supai—limestone (%)	69	20	23	17	50

Component Description / Section / Author	6. Havasu Canyon E. D. McKee	7. S B Canyon E. D. McKee	8. Kanab Canyon E. D. McKee	9. Thunder River E. D. McKee	10. Bass Trail Noble (1922)
Esplanade width (feet)	17,000	12,500	17,500	22,500	14,500
Hermit Shale (feet)	577	641	807	787	332
Supai Formation (feet)	934	1,060	1,058	830	953
Esplanade SS Mem. (feet)	178	266	410	300	306
Hermit—ledges (feet)	319	279	*	266	99
Hermit—ledges (%)	55	43	*	34	30
Hermit—slopes (feet)	258	362	*	521	233
Hermit—slopes (%)	45	57	*	66	70
Supai—cliffs (feet)	717	701	824	603	589
Supai—cliffs (%)	77	66	78	73	62
Supai—slopes (feet)	217	359	234	228	365
Supai—slopes (%)	23	34	22	27	38
Hermit—sandstone (feet)	286	279	*	266	99
Hermit—sandstone (%)	50	43	*	34	30
Hermit—shale (feet)	291	362	*	521	233
Hermit—shale (%)	50	57	*	66	70
Supai—sandstone (feet)	553	638	677	514	550
Supai—sandstone (%)	59	60	64	62	58
Supai—shale (feet)	179	273	207	226	344
Supai—shale (%)	19	26	20	27	36
Supai—limestone (feet)	203	149	174	91	60
Supai—limestone (%)	22	14	16	11	6

Component Description	Section / Author: 11. Hermit Trail, Chesser (1971)	12. Kaibab Trail, North Rim, E. D. McKee	13. Kaibab Trail, South Rim, Chesser (1971)	14. Blue Springs Trail, E. D. McKee
Esplanade width (feet)	0	0	0	0
Hermit Shale (feet)	264	378	224	125
Supai Formation (feet)	1,076	825	808	715
Esplanade SS Mem. (feet)	218	336	180	312
Hermit—ledges (feet)	30	50	47	31
Hermit—ledges (%)	11	13	21	25
Hermit—slopes (feet)	234	328	177	94
Hermit—slopes (%)	89	87	79	75
Supai—cliffs (feet)	617	639	475	490
Supai—cliffs (%)	57	77	59	68
Supai—slopes (feet)	459	186	333	226
Supai—slopes (%)	43	23	41	32
Hermit—sandstone (feet)	30	50	27	31
Hermit—sandstone (%)	11	13	12	25
Hermit—shale (feet)	234	328	198	94
Hermit—shale (%)	89	87	88	75
Supai—sandstone (feet)	544	573	468	436
Supai—sandstone (%)	51	70	58	61
Supai—shale (feet)	431	151	300	251
Supai—shale (%)	40	18	37	35
Supai—limestone (feet)	101	102	41	29
Supai—limestone (%)	9	12	5	4

*Insufficient information.

REFERENCES CITED

Billingsley, Jr., G. H., 1970, General geology of Tuckup Canyon, central Grand Canyon, Mohave County, Arizona: unpublished M.S. thesis, Northern Arizona Univ., 115 p.

Chesser, W. L., 1969, Classification of morphological features in the Grand Canyon, Arizona (abs.): Geol. Soc. Amer., Rocky Mountain Section, 22nd Ann. Meeting, p. 13.

Darton, N. H., 1910, A reconnaissance of parts of northern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, p. 25.

Davis, W. M., 1901, An excursion to the Grand Canyon of the Colorado: Harvard Coll., Mus. Comp. Zoology Bull. 38, Geol. Ser. 5, p. 107-201.

———., 1903, An excursion to the plateau province of Utah and Arizona: Harvard Coll., Mus. Comp. Zoology Bull. 42, Geol. Ser. 6, p. 1-50.

Dutton, C. E., 1882, Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, 264 p.

Fenneman, N. M., 1931, Physiography of western United States: McGraw-Hill, Inc., New York and London, 534 p.

Fisher, W. L., 1961, Upper Paleozoic and lower Mesozoic stratigraphy of Parashant and Andrus Canyons, Mohave County, northwestern Arizona: unpublished Ph.D. thesis, Univ. of Kansas, 345 p.

Hamblin, W. K., 1965, Origin of "reverse drag" on the downthrown side of normal faults: Geol. Soc. Amer. Bull., v. 76, p. 1145-1164.

———., 1969, Late Cenozoic lava flows in the Grand Canyon of the Colorado River, Arizona: Four Corners Geol. Soc. Guidebook, Fifth Ann. Field Conf., p. 41-60.

———., and Rigby, J. K., 1969, Guidebook to the Colorado River, part 2: Phantom Ranch in Grand Canyon National Park to Lake Mead, Arizona-Nevada: Brigham Young Univ. Geology Studies, v. 16, 126 p.

James, G. W., 1910, The Grand Canyon of Arizona, how to see it: Little, Brown, and Co., Boston, 265 p.

McKee, E. D., 1969, Paleozoic rocks of the Grand Canyon: Four Corners Geol. Soc. Guidebook, Fifth Ann. Field Conf., p. 78-90.

———., and Schenk, E. T., 1942, The lower canyon lavas and related features at Toroweap in Grand Canyon: Jour. Geomorph., v. 5, p. 245-273.

McNair, A. H., 1951, Paleozoic stratigraphy of part of northwestern Arizona: Amer. Assoc. Petroleum Geologists Bull., v. 35, p. 503-541.

Noble, L. F., 1914, The Shinumo Quadrangle, Grand Canyon district, Arizona: U. S. Geol. Survey Bull. 549, 100 p.

———., 1922, A section of the Paleozoic formations of the Grand Canyon at Bass Trail: U. S. Geol. Survey Prof. Paper 131, p. 23-73.

Penck, W., 1929, Die deomorphologische analyse: J. Engelhorn's Nachf., Stuttgart, English translation by H. Ozech and K. C. Boswell, 1953, Macmillan, London.

Powell, J. W., 1875, Exploration of the Colorado River of the west and its tributaries: Smithsonian Inst. Ann. Rept., 291 p.

Sorauf, J. E., 1962, Structural geology and stratigraphy of the Whitmore area, Mohave County, Arizona: unpublished Ph.D. thesis, Univ. of Kansas, 361 p.

White, D., 1929, Flora of the Hermit Shale, Grand Canyon, Arizona: Carnegie Inst. Wash. Pub. 450, 219 p.