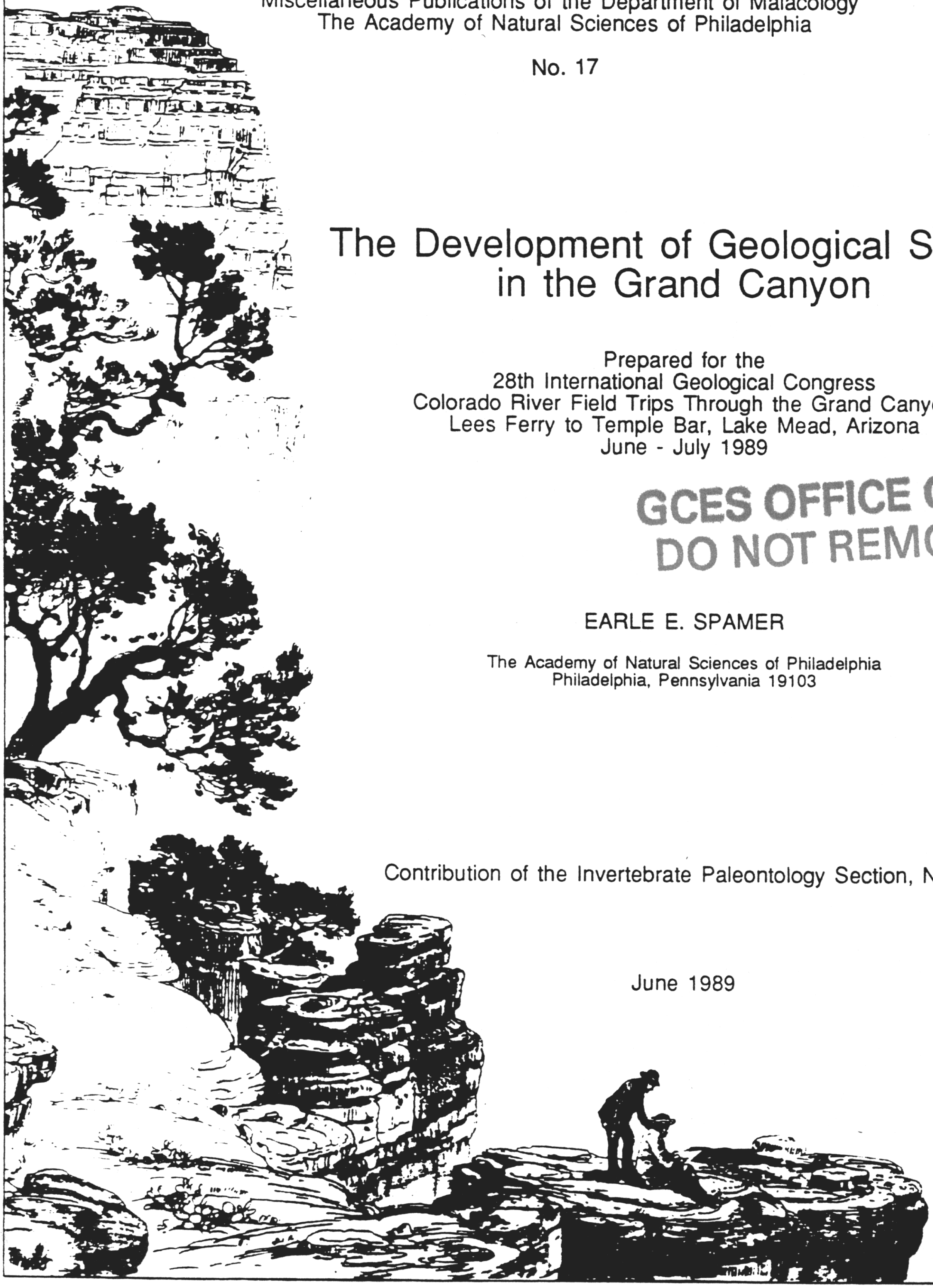
TRYONIA

Miscellaneous Publications of the Department of Malacology
The Academy of Natural Sciences of Philadelphia

No. 17



The Development of Geological Studies in the Grand Canyon

Prepared for the
28th International Geological Congress
Colorado River Field Trips Through the Grand Canyon
Lees Ferry to Temple Bar, Lake Mead, Arizona
June - July 1989

EARLE E. SPAMER

The Academy of Natural Sciences of Philadelphia
Philadelphia, Pennsylvania 19103

Contribution of the Invertebrate Paleontology Section, No. 1.

June 1989

TRYONIA

Department of Malacology
The Academy of Natural Sciences of Philadelphia
Nineteenth and the Parkway
Philadelphia, PA 19103, U.S.A.

All inquiries regarding the production and sale of TRYONIA should be directed to the Business Manager, M. Andria Garback.

COVER: Geologist Clarence E. Dutton and artist William H. Holmes consult at Point Sublime, North Rim of the Grand Canyon, in the summer of 1880. Dutton's (1882) magnificent monograph and accompanying atlas of the Grand Canyon region is the one publication which sparked the world's love for the Grand Canyon. Detail from the illustration by Holmes, "Panorama from Point Sublime (Part I. Looking East)." (Dutton, 1882, Atlas, Sheet 15.)

CONTENTS

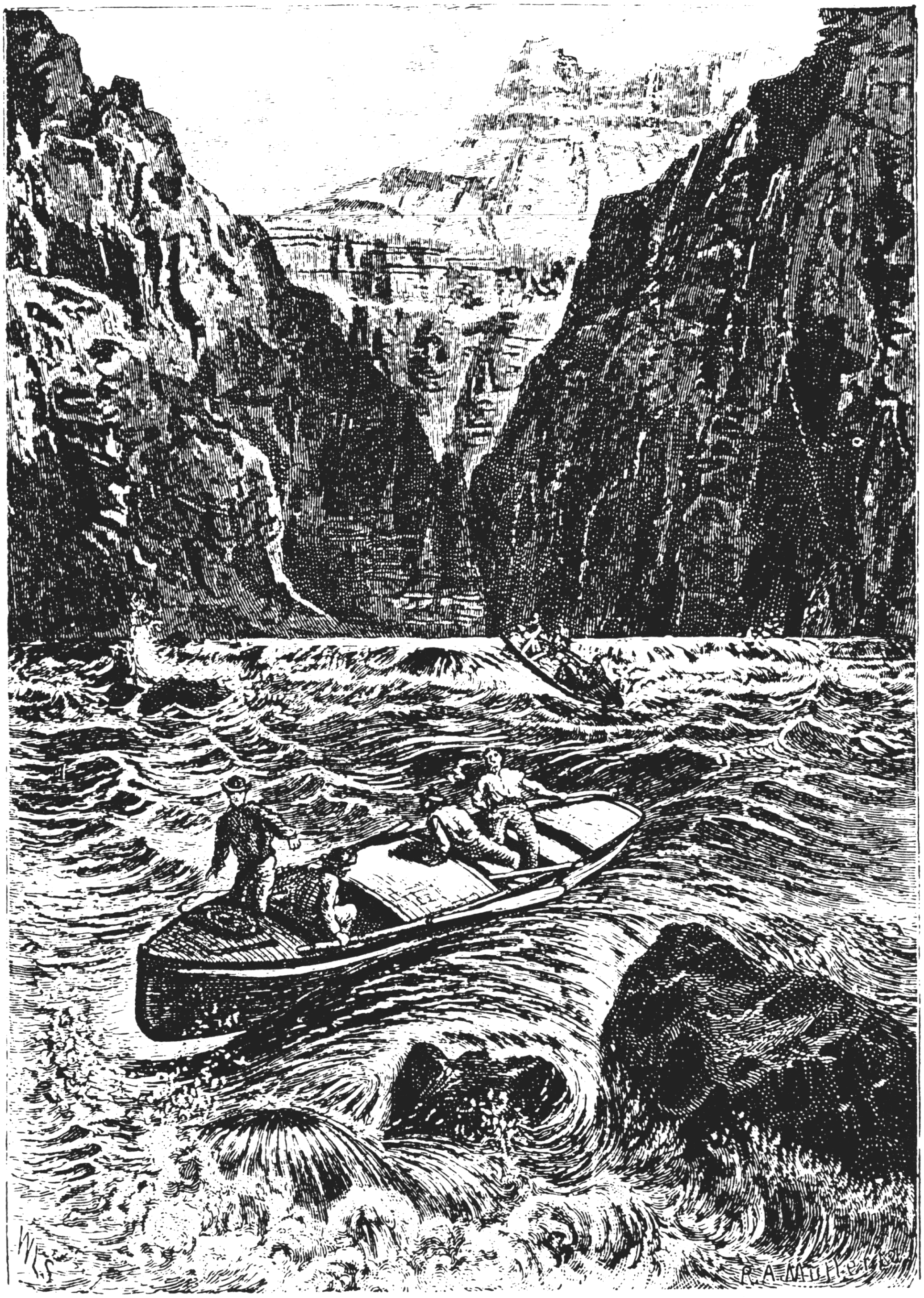


Figure 28.—Running a rapid.

FRONTISPIECE. The Powell expeditions of 1869 and 1871-1872 were the first to navigate the treacherous rapids of the Colorado River through the Grand Canyon. Besides investigating the entire stratigraphic section of the Canyon for the first time, these men learned first-hand to predict how their boats would fare in each rapids. In so doing they were the first to study the hydrodynamics of the Colorado River. The large rafts used by most river travellers today make the journey a little safer, but the exhilaration of riding white water is not diminished. Before the 28th International Geological Congress in 1989, no internationally sponsored group of geologists ever followed Powell's path down the Colorado. (Powell, 1875, fig. 28.)

GENERAL INTRODUCTION

The Grand Canyon has played a prominent role in many aspects of the development of the science of geology. Some principles which today are part of geological textbooks were either developed or practically demonstrated in the Canyon. The late Edwin D. McKee, whom we may argue was the most productive of Grand Canyon geologists, summarized the significance of the Canyon to geology (McKee, 1983a):

> "The Grand Canyon with its rock walls extending nearly 200 miles [320 km] from east to west along the course of the Colorado River is geologically outstanding, primarily because of its record of earth history. This record is displayed in a sequence of rock layers, one upon another, in a simple, orderly fashion--layers that are little disturbed by faulting or folding. The magnitude and the quality of this exhibit establish it as a truly remarkable demonstration of the principles of stratigraphy. Because its nearly continuous rock exposures are little concealed by talus or by vegetation, the Grand Canyon presents an ideal medium for tracing in time and in space changes in fossil life and sediment.
>
> "Doubtless because of the excellent opportunities to observe and to demonstrate, beyond reasonable doubt, various concepts in the field of stratigraphic geology, numerous basic geologic principles have been initially recognized or greatly advanced through Grand Canyon studies. Among the most important are (1) the concept of facies, (2) the establishment of time planes in the form of key beds (marker beds), (3) the criteria for recognizing shoreline transgression and regression, (4) cyclothems of Pennsylvanian and Permian age, (5) unconformities and diastems, and (6) base-level changes controlling sedimentary accumulation. All these concepts and others are represented in strata of the Grand Canyon and our knowledge of them has been greatly enhanced by canyon studies.
>
> "Numerous procedures have been applied and tested during the establishment of various geological concepts in Grand Canyon strata. Approaches include the preparation and analysis of various types of maps such as isopach, lithofacies, paleogeographic, and environmental. Further, the plotting of data on stratigraphic columns and fence diagrams has proven especially useful in recording data in three dimensions. Various types of statistical studies--especially those that determine trends in cross-bedding vectors, ripple orientation, grain size and sorting distribution, insoluble residues and calcium-magnesium ratios--have proven to be useful. Finally, the formulation of classifications of various rock properties, such as fossil assemblages, grain attributes, and cross-strata genesis as found in Grand Canyon strata, has received much attention.
>
> "Second in geological interest only to the Earth's history as recorded in the walls of Grand Canyon is the story of the Canyon's origin. This geomorphic event, especially as it involves the genesis of the Colorado River and uplift of the Colorado Plateau, was the subject of several pioneer treatises on the area, notably those by Powell and Dutton. In a symposium designed to summarize the state of knowledge on this subject, sponsored by the Museum of Northern Arizona in 1967, the conclusion was reached that, at that time, many aspects of the Colorado River history were not known and that although numerous problems requiring future study were indicated, only a foundation had been laid for further investigations. During the century starting with Powell's work in 1875, at least eight hypotheses have been proposed to explain the evolution of the Colorado River in Grand Canyon, and new ideas continue to be proposed and to flourish.
>
> "Additional aspects of geology to have aroused interest in and around Grand Canyon and to have stimulated noteworthy investigations are structure, paleontology, and volcanism. Structural problems are intimately related to those of historical geology already cited, for they determine the time and cause of major events involving erosion and deposition. They are also important to an understanding of the plateau uplift, which was a major factor in the cutting of Grand Canyon."

In the survey provided by the present volume, it is hoped that the reader will appreciate the rich history of geological studies in the Grand Canyon. Overall, the volume in hand means to fill a gap that exists in the literature. It provides a historical view of various geological disciplines as developed in the Grand Canyon. It is not a text on the geology of the Canyon. It is a text on history, a guide to the literature on each aspect of Grand Canyon geology. As such it may be of value to visiting geologists and students alike, who may not be familiar with the Grand Canyon literature, providing an entrance to that very large amount of material. Because each worker will have his or her own area of interest, this volume is organized by general topic.

This review, although written to stand as a separate monograph, is designed to supplement the formal guidebook to Grand Canyon geology first issued to the participants of the 28th International Geological Congress Colorado River trips in June and July, 1989. That guidebook, edited by Elston et al. (1989), is composed of papers that represent current thought and research interests in Grand Canyon geology. None of them, for lack of space, can fully review how each of those subjects has developed to its present level of understanding. In fact, no general review of the history of Grand Canyon geology has ever been published.

To facilitate better use of the present volume and the IGC guidebook together, most chapters herein begin with a list of the pertinent guidebook chapters. They are not cited in the bibliography to this volume unless they are mentioned for particular purposes within the text. The reader can thus quickly refer to the appropriate guidebook chapters to see the current standing in research in each subject. Additionally, most chapters herein begin with a list of locations of the pertinent geological features that appear on the river, as listed in the river guide prepared for the guidebook by Billingsley and Elston (1989). A list of all river locations mentioned in the text appears at the end of the volume.

Each chapter is written to stand alone; hence some very minor redundancies exist between some of the chapters. This volume, though, does not cover in detail everything published about Grand Canyon geology. It does supplement two papers that are already available: McKee's (1969) paper on the development of stratigraphic studies in the Canyon, and Spamer's (1984a) review of the development of Grand Canyon paleontological studies. Therefore, those sections in the present volume are proportionately shortened, in order to concentrate more on studies which have been done since McKee's and Spamer's papers were published.

Workers who are interested in the Canyon's many aspects, geological and otherwise, can find information in several bibliographies: an annotated bibliography of Grand Canyon geology, incorporating an annotated catalogue of Grand Canyon type fossils (Spamer, 1983, 1984b, 1988), and a non-annotated bibliography on all subjects about the Grand Canyon with a bibliography on the lower Colorado River (Spamer et al., 1981; 2nd ed. in prep.).

Acknowledgements

This volume was originally intended to be a brief summary for distribution to those people who were going to travel on the same IGC Colorado River trip for which I had registered. At that time a friend asked if it would be possible to instead produce something for all the IGC members who would sign up for river trips. The present volume is the result. I wish to express my sincere thanks to those who reviewed this paper on short notice, who agreed to do so without knowledge of the length of the manuscript: George H. Billingsley, Edward Daeschler, Donald P. Elston, William B. Gallagher, James E. Sorauf, and Richard A. Young. I thank them for their time and for many thoughtful comments. Any errors which still may have crept into the manuscript are mine alone.

Special thanks are extended to George Billingsley for providing me with a preliminary copy of the IGC Colorado River trip guidebook; without it the cross-referencing would have been impossible. Thanks also go to Robert C. Euler for providing copies of early topographic maps and scarce publications that added to the historical data on early geological trips to the Canyon. Finally, this volume could not have been produced without the support of George M. Davis, Chairman of the Department of Malacology at the Academy of Natural Sciences of Philadelphia (that department incorporates the Invertebrate Paleontology Section of the Academy). The department also generously provided the facilities for part of the production of the manuscript and final camera-ready copy.

Note on Units of Measurement

Throughout this monograph, linear, areal, and volumetric measurements are given in both metric and English units. Distances along the Colorado River, however, by convention are listed in Miles. Mile 0 is at Lees Ferry, Arizona. All available river guides follow this convention, which is adopted herein. To convert river miles to kilometers, multiply the figure by 1.6.

Note on Interjected River Distances

In this volume, distances along the Colorado River, measured in miles according to convention, are interjected into the text. These additions will enable the reader to more quickly locate the geographic or geologic feature that is discussed. For linear features which extend some distance from the river, the interjected mileage is the place where the feature occurs at the Colorado River. A list of all of these interjected mileages appears at the end of this volume; it pertains only to those localities mentioned in the text of the volume.

Note on Names in the Grand Canyon

The U.S. Board on Geographic Names (1988a, b) has recently made some rulings affecting the spellings and usage of some geographic names in the Grand Canyon. The following affected names are used in the present volume.

The community of **Grand Canyon**, on the South Rim, is not "Grand Canyon Village" (USBGN, 1988b). However, it is often preferable to use the descriptive term "village" in some sentence structures to avoid confusion with the Grand Canyon. Therefore, in the present volume, "Grand Canyon Village" is used in reference to the community of Grand Canyon. "Grand Canyon Village" is also a colloquial term.

Indian Gardens, a locality on the Bright Angel Trail, is officially "Indian Garden," as it appears on the 1:62,500-scale Bright Angel topographic sheet (USBGN, 1988a). However, Grand Canyon afficionados will probably always call it by its colloquial plural. Signage on the Bright Angel and North Kaibab Trails, as well as wording on non-government maps, also use the plural form.

Sinyala fault. The word "Sinyella," as it appears in Mount Sinyella, Sinyella Canyon, Sinyella Mesa, and Sinyella Rapids is not spelled "Sinyala" (USBGN, 1988b). The spelling of "**Sinyala fault**," however, probably should be retained because it is widely used in the literature. Since it is not a stratigraphic feature, Sinyala fault does not come under the rules of the North American Stratigraphic Code (as in the case described next).

Watahomigie Point is not spelled "Watahomigi" (USBGN, 1988b). However, this revision should not affect the spelling of the **Watahomigi Formation** (Supai Group; McKee, 1975a), whose type locality is below Watahomgie Point. This formational name is already well-established in the literature, and forcing its conformation with the official, or map, spelling would not be advisable at this time. (This is unlike the situation with the Sixtymile Formation of the Grand Canyon Supergroup, which was originally spelled "Sixty Mile" but shortly thereafter was changed to Sixtymile to conform with the map spelling of the type locality in Sixtymile Canyon, prior to its widespread use in the literature.) The North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983), Article 7(d), mandates the preservation of original spellings of stratigraphic names even if they are misspellings of the geographic feature after which they were named; e.g., Pensauken Formation (Pleistocene of New Jersey), where the geographic locale is Pennsauken.

I. THE GEOLOGISTS AND A SKETCH OF THE DEVELOPMENT OF GRAND CANYON GEOLOGY

FROM THE TIME that the first scientific explorers reached the Grand Canyon in 1858, this chasm has been studied and restudied by generations of geologists. For as grandly simple as this place appears, geologically, we continue to be presented with new facts, new interpretations, and new lessons. Probably nowhere else on this planet can so much be learned about geology, at one location, than at the Grand Canyon. This was recognized from the outset, and still is true today.

It is not difficult to single out those early geologists who had the greatest impact on studies of the geology of the Grand Canyon; there are only a few. But as we progress through the 20th Century, particularly in the years following World War II, it is more difficult to select authors who were most significant in developing the understanding of Grand Canyon geology. Today is a time of specialization, and many workers have reported important findings within their disciplines. Many authors who could have been mentioned may not have been, lest this introduction lengthen disproportionately to the rest of the volume, where their work is noted. This introduction highlights only the trends of geological studies in the Canyon.

The first expedition to reach the Grand Canyon was under the command of Lieutenant Joseph C. Ives, U.S. Army Corps of Topographical Engineers. Travelling upstream on the Colorado River aboard the "Explorer," a specially constructed small steamboat, the expedition ran aground in Black Canyon below present-day Hoover Dam. After an exploratory jaunt further upstream in a small boat, they then set out overland and reached the Grand Canyon near Diamond Creek on 3 April 1858. Lt. Ives wrote (Ives, 1861, Pt. 1, p. 99):

> "The famous 'Big cañon' was before us; and for a long time we paused in wondering delight, surveying this stupendous formation through which the Colorado and its tributaries break its way."

However, Ives was more impressed by the desolation of the region, and the privations of the journey were taking their toll on him. He was later moved to write, on 18 April (Ives, 1861, Pt. 1, p. 110):

> "The region last explored is, of course, altogether valueless. It can be approached only from the south, and after entering it there is nothing to do but to leave. Ours has been the first, and will doubtless be the last, party of whites to visit this profitless locality. It seems intended by nature that the Colorado river, along the greater portion of its lonely and majestic way, shall be forever unvisited and undisturbed."

Exploration of this region might have ended had the Ives Expedition not included John Strong Newberry, Balduin Möllhausen, and the Freiherr F. W. von Egloffstein. Möllhausen and Egloffstein presented the first artistic views of the Grand Canyon (even if moody and imaginary), and Egloffstein compiled the first reasonably accurate maps of the region. Newberry's (1861) geological report of the expedition contains a number of important observations, reliably describing the Canyon for the first time in the literature. Möllhausen (1860?, 1861) may have gotten into print before Newberry with a description of the geology of the route travelled, but that account does not compare in detail with Newberry's report. (Möllhausen's volumes are scarce, apparently not having been widely distributed as was Ives' volume containing Newberry's report, and never have been translated from the German. Möllhausen's stratigraphic columns for the Grand Canyon region have been reprinted by Spamer, 1984b, pp. 41-45.)

Newberry recognized the scientific and aesthetic value of the Grand Canyon region. His geological report offers the usual descriptions of stratigraphic relationships, economic deposits, and paleontology, but it also recognizes the fluvial origin of the Canyon, discrediting a volcanic genesis for the canyon complex. He also postulated the paleogeographic extent of the "Palaeozoic continent." His description of the Grand Canyon generally is quite clinical, lacking embellishment, but his stratigraphic column for the Canyon, the first ever published, is at once historical and quite accurate (Fig. 1).

Newberry also attempted to correlate the Grand Canyon strata with the much more well-known areas of North America. He was, however, confounded by the apparent absence of well-preserved fossils upon which he was depending for time-stratigraphic correlation. Newberry's success at this was feeble only due to the lack of information from wide areas of the American West, but the attempt was laudable. It provided a benchmark for Powell's historic expeditions through the length of the Grand Canyon little more than a decade later.

In 1869, John Wesley Powell led an intrepid group of explorers by boat along the length of the Green and Colorado Rivers. Departing from the town of Green River, Utah, on 24 May 1869, they reached Marble Canyon below Lees Ferry (usually considered to be the head of the Grand Canyon) on 5 August. By that time they already were well into unknown territory, whence many people believed the party would not return. But the group survived together until they reached Separation Canyon Rapids (Mile 240) on 28 August, where three members of the party decided to leave the expedition. The three cited unknown dangers on the remaining questionable length of the voyage, as well as depleted rations. Their fate was not provident. They were killed in a case of mistaken identity by some American Indians north of the Grand Canyon (Anderson, 1982; Belshaw, 1979; Dobyns and Euler, 1980; Stanton, 1932). Ironically, Powell and party were nearly through the long reach of canyons, and near the end of their journey. They reached the Grand Wash Cliffs the next day.

Powell repeated the expedition in 1871-1872, accumulating enough information about the territory to begin writing several important government-sponsored publications on the geology and geography of the arid lands of the American West. He went on to become the second director of the U.S. Geological Survey. He was so taken by the land and its people that he also produced scholarly studies of the ethnography of the American Indians of the region, and he later headed the Smithsonian Institution's Bureau of American Ethnology.

Powell was encouraged to write an account of his explorations of the canyons of the Green and Colorado Rivers. In 1875, his narrative was published by the

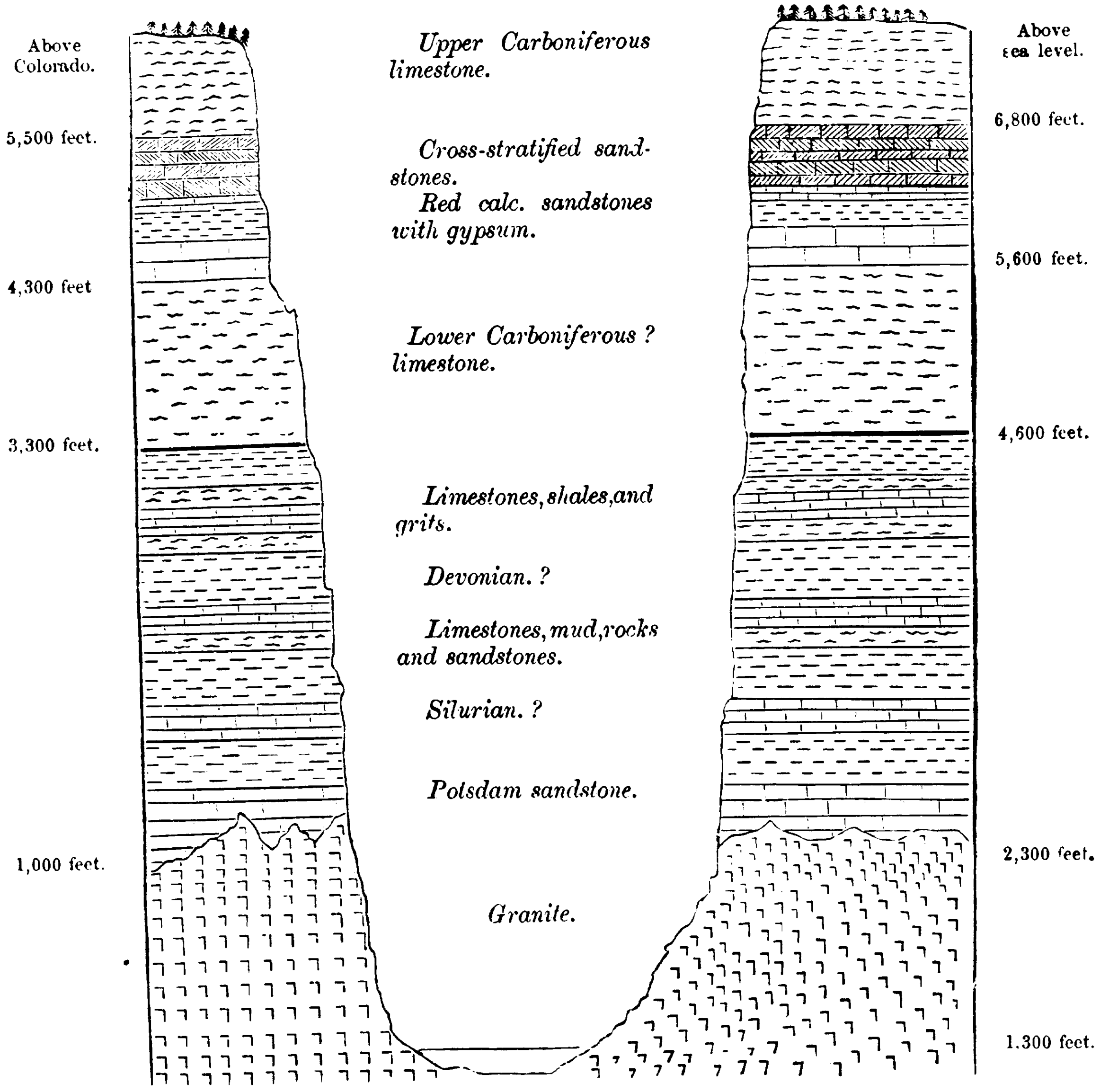


Fig. 12.—SECTION OF THE CAÑON OF THE COLORADO ON HIGH MESA WEST OF THE LITTLE COLORADO.

Figure 1. The first stratigraphic column depicting the Grand Canyon, as published by Newberry (1861, fig. 12). This column represents the stratigraphic section as seen in the eastern part of the Grand Canyon.

Smithsonian Institution. The account is written as though it were a single journey--the one made in 1869--borrowing from the notes of both expeditions. It also apparently draws heavily from memory. The journals kept by several of the expedition members, including Powell, have been edited and published together in chronological order (Cooley, 1988). With parallel comparisons quoted from the later published narratives written by some of the explorers, it is clear that the short, terse field notes were greatly embellished, though not usually exaggerated, for publication.

Regarding the geology of the Grand Canyon, Powell wrote just a few different items. In 1873, he published a paper in which he described structural influences on valley formation in the region north of the Canyon (Powell, 1873a). In 1876, in a report on the geology of part of the Uinta Mountains of Utah, he briefly outlined the Grand Canyon section in three pages (pp. 60-62). That short description, however, is significant to Grand Canyon geologists because he formally described what today we call the Middle and Late Proterozoic Grand Canyon Supergroup. His 1875 volume, though, remains the classic first thorough description of the Canyon. The first generalized stratigraphic column of the entire Grand Canyon section appeared therein (Fig. 2). He also published the first physiographic diagram showing the cross-sectional structure of the Grand Canyon region (Fig. 3).

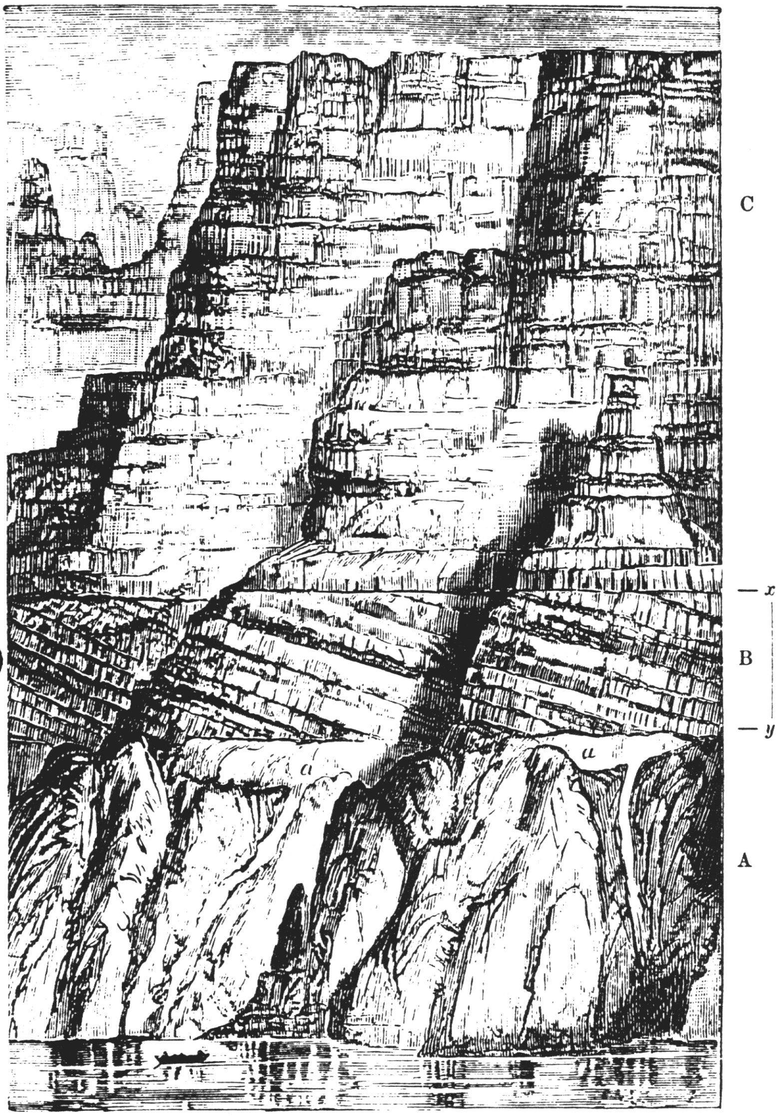


Figure 79.—Section of wall in the Grand Cañon.

Figure 2. John Wesley Powell's (1875, fig. 79) generalized stratigraphic section for the Grand Canyon. "A" is the metamorphic basement complex (Early Proterozoic Vishnu Group),with igneous intrusives labelled "a"; "B" is the Grand Canyon Supergroup (Middle and Late Proterozoic); "C" indicates the Paleozoic strata; "x" and "y" delineate the major unconformable contacts.

In 1871, an expedition led by Captain George M. Wheeler, U.S. Army Corps of Topographical Engineers, travelled overland through the Grand Canyon region. They circumvented the Canyon-proper by travelling southward to the Colorado River along Grand Wash (Mile 285). The Grand Wash Cliffs (Mile 277) delineate the western physiographic boundary between the Colorado Plateau and Basin and Range provinces. Gilbert (1872, 1875), Lyle (1872), and Marvine (1875) published narrations of the journey past the mouth of "Big Cañon."

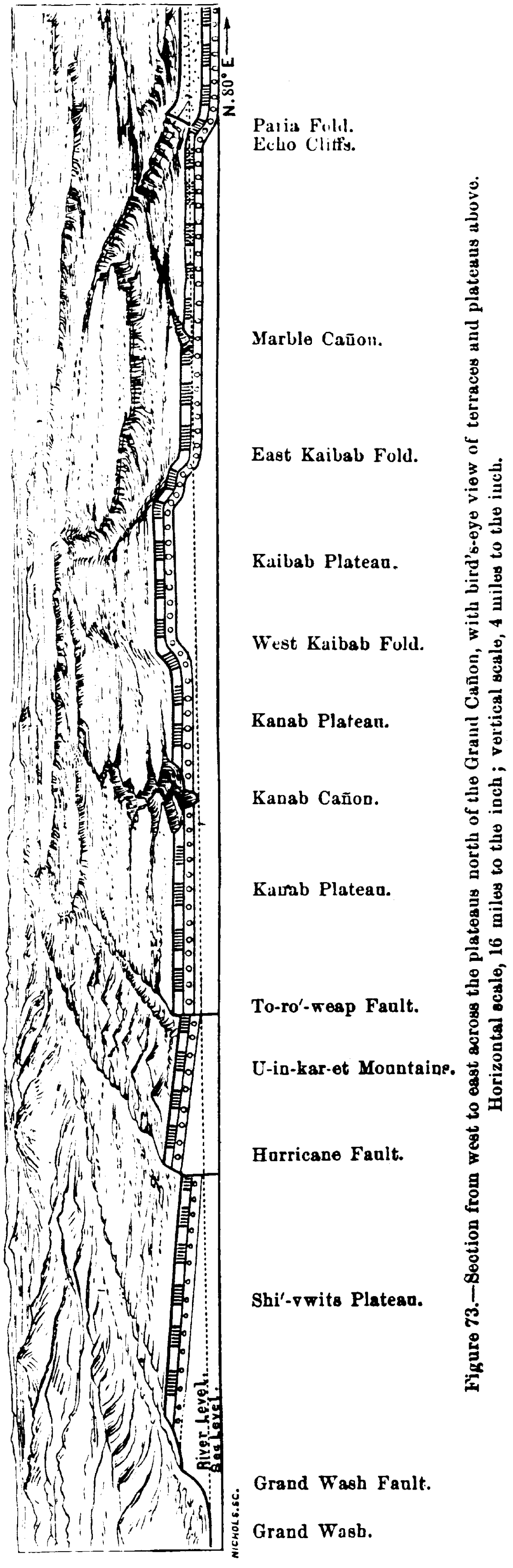
By the time Powell and Wheeler had completed their forays into the Grand Canyon region, it was becoming clear to geologists that the whole Colorado Plateau was a district in which the geologist could formulate and test ideas new to science. Gilbert (1876) was quick to describe the opportunities given to geologists who ventured onto the plateaus and into the canyons. Virtually every discipline then known to the science of geology could be investigated in a new light.

The first monograph to treat the geology of the Grand Canyon region easily answered the promises made by Gilbert. Published in 1882, the Tertiary History of the Grand Cañon District, by Captain Clarence Edward Dutton, U.S. Army Ordnance, was a monumental production, outstanding in its scope and presentation. In this volume was unfolded the definitive geological description of the region. Dutton's prose is timeless; in parts it reads as a travelogue, quite personable in its descriptions of a land completely foreign to its readers in the East. This style, Dutton said, was done purposely to impress upon the reader important facts which might have been overlooked if they had been presented in more formally written language. The attempt was successful and well received.

Accompanying Dutton's text is the Atlas, a folio-sized volume of 23 sheets, most of them double width. It contains the first geological maps of the Canyon, but, more impressively, exquisite panoramas of the Canyon and adjacent plateaus drawn by the preeminent artists William H. Holmes and Thomas Moran. These views, unlike the somber, Dantean, sometimes ghostly views by Möllhausen and Egloffstein (in Ives, 1861), were photographic in precision. More than for any other reason, the artistic portrayals sparked the world's love affair with the Canyon.

Dutton's monograph, including the epic atlas, have been acclaimed by bibliographers and bibliophiles as the quintessential publication about the Grand Canyon--popular or scientific. Its scientific merits aside, it was a monumental publication from a technical viewpoint and for its aesthetic appeal. The atlas is visually imposing, and the maps contained therein are to this day remarkably accurate, even if greatly expanded and embellished by a century of continued work. The stunning panormamic views are to this day without compare. About this work, the bibliographer Francis P. Farquhar (1953, p. 49) commented,

> "One of the greatest, if not the very greatest of all Grand Canyon books, it should be republished in a form worthy of its content. On its technical side it would doubtless need some corrections and explanations, but as a description of the Grand Canyon it stands firm. * * * The atlas, containing the superb panoramic views by William H. Holmes and a drawing by Thomas Moran, is a rich portfolio of art as well as a collection of maps and an exposition of geology."



The prospect of reissuing Dutton's monograph calls for pause when one sees the Atlas. But in 1977, Perigrine Smith, Inc., of Santa Barbara, California, and Salt Lake City, Utah, released a facsimile edition of the monograph and atlas with an introduction by the historian Wallace Stegner. He noted the century of acclaim received by Dutton's Tertiary History, received "perhaps because art ages less swiftly than science." The atlas was reprinted not as a bound volume like the original but as separate sheets held in a slipcase; the sheets folded, though, as were those of the original edition. The Peregrine Smith reprint was released in a limited edition of 1,500 copies with a price of $175.00. (Dutton's original, in contrast, was printed in one edition of 3,000 copies with a price of $10.12.)

Powell's expeditions are said to have been a "second opening" of the American West (see Stegner, 1954), but Dutton's monograph is the one most significant publication that launched American geologists--and southwestern North America--as a field for new geological studies into the world view. In it Dutton presented the data necessary to interpret the Tertiary history of the Grand Canyon region; simply put, how the Grand Canyon got to be grand. Dutton explained how the structure of the Grand Canyon region directly influenced the development of the chasm and its myriad tributaries and sculpted landforms. In interpreting the history of the Colorado River, he considered it to have been present early in Tertiary time, as the outlet of "the great Eocene lake." The Grand Canyon itself was created much later, when the land was uplifted. "Corrasion and weathering" were the recurring tenets through the volume; these forces, above all else, "explain how those abnormal architectural forms so abundantly displayed in the chasm and the region roundabout have been generated" (Dutton, 1882, p. 8). In examining such variables as cliff recession and stratigraphic inhomogeneity, Dutton also developed a picture of variable rates of recession in areas of horizontal stratigraphy, a basic tenet of geomorphology.

While Dutton was preparing his definitive monograph, the young Charles Doolittle Walcott had already published the first of many papers that would deal wholly or partly with the Grand Canyon. On his first assignment for the new U.S. Geological Survey, Walcott went down Kanab Creek from Utah to its confluence with the Colorado River (Mile 143.5), along what McKee (1946) would later call "the trail of scientists." Walcott (1880) described the Paleozoic strata as they occur through Kanab Canyon, redefining several stratigraphic boundaries from the usage of Powell (which Dutton would again redefine).

In the winter of 1883, Walcott, under Powell's direction, blazed a horse trail from the Kaibab Plateau into the Nankoweap Canyon area, in easternmost Grand Canyon (Walcott, 1884). This trail, today called the Nankoweap Trail, is not maintained. He spent several months studying the "pre-Carboniferous" strata in that part of the Canyon and was the first to spend time exploring the interesting strata that comprise the Late Proterozoic Chuar Group. Together, Walcott's papers (1883, 1884) describing most of the Grand Canyon stratigraphic section, are the pioneering works of systematic Grand Canyon stratigraphy. His attention to fossils was more as an aid in stratigraphic correlation

Figure 3. Powell's (1875, fig. 73) physiographic cross-section of the Grand Canyon region (looking north). The principal physiographic features of the region were recognized from the outset of Grand Canyon studies to be related to structural elements of the plateau country.

between the Canyon and other regions, not as a contribution to studies of paleoecology.

Throughout Walcott's working career, in publications through 1925, he repeatedly returned to the information provided by the Grand Canyon (see in Spamer, 1983). He was the first geologist to continually employ the Grand Canyon data in works of global perspective. The Grand Canyon was recognized as an important element in worldwide time-stratigraphic correlation, and so it was a key in Walcott's many works on Precambrian and Cambrian stratigraphy, paleontology, and evolution.

Once Walcott was reporting data from the Grand Canyon, other geologists, one by one, began to take advantage of the Canyon's lessons. William Morris Davis, the father of modern process geomorphology, published several papers about the Canyon and surrounding plateaus. He was the first person to depart from the hypothesis of antecedence for the origin of the Colorado River (although Gilbert had questioned the antecedent hypothesis). Davis (1901) did not fail to interpret in his study of the Grand Canyon his most famous result of erosion, the peneplain. But, departing from Dutton, he favored a single cycle of erosion, with the Colorado River as a superposed stream, consequent upon a peneplain. This departure from the tenets of Powell, Dutton, and Gilbert paved the way for new, more complex interpretations by other workers. The problem of the origin and history of the Colorado River has been researched and revised from Davis' time to the present.

Early in the 20th Century, new geologists were coming into the scene, attracted by the Grand Canyon. The physiographers H. H. Robinson (1907, 1910) and Douglas W. Johnson (1909) followed in Davis' footsteps in interpreting the history of the Grand Canyon landscape. With the opening of a route through Bright Angel Canyon (Mile 87.7), when François E. Matthes was mapping the Canyon in 1902-1903, Frederick L. Ransome was able to study the Unkar Group as it occurs in that part of the Canyon; these strata had before been studied only in the easternmost part of the Canyon. Ransome's report (1908b) was the first to describe the relationship of these strata to the Bright Angel fault. He also (1908a) studied the stratigraphic relationships between the Paleozoic and Precambrian strata in the Canyon, comparing them with other, similar sequences in Arizona. Later, Ransome (1917) would study the Paleozoic section of the Canyon, correlating it with stratigraphic sections elsewhere in Arizona. Stratigraphers Nelson Horatio Darton and Levi F. Noble both began publishing on the Grand Canyon in 1910; Noble concentrated his early labors in the eastern Grand Canyon, while Darton was looking at the Canyon as a critical element in the big picture of regional geology. Darton (1910) finally subdivided the broadly defined and uncertainly delineated "Aubrey group" of Pennsylvanian and Permian strata (see Appendix B herein); Noble (1914) subdivided Gilbert's original Tonto Group (Cambrian) and the Unkar Group (Middle Proterozoic). Both authors continued to publish on the Grand Canyon for a number of years.

Noble and Hunter (1917) wrote a paper that, for the first time, examined the Early Proterozoic metamorphic basement complex of the Grand Canyon, the Vishnu Group. They recognized eight geographically segregated groups of rocks and attempted to correlate them in a relative time frame. The Vishnu Group is difficult to explore because it can be reached only along the river and in deep side canyons incised into the Inner Canyon benches.

By the mid-1920s, the Grand Canyon was well enough known and sufficiently accessible to promote detailed studies by workers who were interested in specific problems. In 1919, the Canyon been incorporated into the National Park system, and its new landlord, the National Park Service, encouraged investigations of its new property. A village had grown up on the South Rim, catering to tourists and transient scientists. The Canyon, for all its intrigue as a remote, rugged part of America, was becoming a relatively accessible place. The village also allowed Park Service employees to "commute" to work in some parts of the Canyon.

This era was also the beginning of the great engineering projects designed to tame the Wild West for the benefit of man. A 1923 expedition was led down the Colorado River by E. C. La Rue. The party was to survey the river for possible dam sites for flood control and power generation; this included the seemingly ideal Inner Gorge of the Grand Canyon. Their comprehensive report (La Rue, 1925) included detailed topographic maps, reservoir capacity calculations, engineering notes, photographs, river profiles, and stratigraphic sections. The appendix to that report, by Raymond C. Moore, examined the geology of the Inner Gorge.

Higher up, in the open spaces of the Grand Canyon, detailed investigations of paleontological interest were beginning. The Carnegie Institution of Washington funded several ongoing projects that, in part, were attempting to derive how various paleocommunities could be fitted into interpretations of evolution. Other studies examined something a little more basic--the history of the earth. Charles W. Gilmore was studying the amazing ichnofauna (footprints and trackways) of the Pennsylvanian and Permian strata mostly in the Hermit Basin, west of Grand Canyon Village. His three major reports (Gilmore, 1926, 1927, 1928) are still the definitive works on the subject, even if outdated by advances made from studies of other world localities. At the same time, David White was investigating the unique paleoflora of the Lower Permian Hermit Shale; his monograph (1929) is still the authority on the subject.

The 1930s and 1940s brought detailed studies of the Permian, Cambrian, and Precambrian rocks of the Grand Canyon. McKee (1933) turned out a work on the Coconino Sandstone, the first of five extremely important monographs on various Paleozoic rock groups of the Canyon. In 1938, he published the monograph on the Kaibab and Toroweap Formations (formally naming the latter; McKee, 1938a), and in 1945, McKee and Resser's work on the Grand Canyon Cambrian was printed, having been delayed since 1942 by the war and based on field work done mostly in the latter half of the 1930s. The works by McKee were also supported by the Carnegie Institution. Before then Wheeler and Kerr (1936) had published the only examination of the Grand Canyon Cambrian through the length of the Canyon. Stoyanow (1936) correlated the Arizona Paleozoic formations between the Grand Canyon and exposures in central and southern Arizona.

Throughout the mid-1930s Ian Campbell and John H. Maxson surveyed the Early Proterozoic metamorphic basement in eastern Grand Canyon. Their brief yearly reports to the Carnegie Institution served as the definitive reference on the subject until reinvestigations of the basement complex were made in the 1970s by several workers. Norman E. A. Hinds, also working with the help of the Carnegie Institution in the 1930s, completed a several-year study of the basement and Middle and Late Proterozoic strata of the Canyon, correlating those units with other units in western North America (Hinds, 1936a,b).

The structural and geomorphological work by Arthur N. Strahler (1944a,b, 1945, 1947, 1948) on the Kaibab Plateau and eastern Grand Canyon concluded the first period of geological specialization. During the 1950s, fewer workers did original work in the Canyon or referred to knowledge already derived from Grand Canyon studies. But the work by Charles B. Hunt (1956) marked a transition into an era of broad reinvestigations of Grand Canyon geology. It is in Hunt's works that new discussions began on a controversial subject--the origin of the Colorado River and its Grand Canyon.

In the 1960s, dramatic changes came about in the study of Grand Canyon geology. The work of old masters--Noble, Darton, Davis, Dutton, and Powell--appeared to be outdated, and yet our perspectives of the Canyon were still derived from their vantage points, using their data. Only the ongoing work by McKee was surviving as the unchallenged authority on many aspects of Grand Canyon geology. In the 1960s, McKee substantiated his position as the most productive of Grand Canyon geologists in his investigations of the Redwall Limestone (McKee, 1960, 1963) which resulted in McKee and Gutschick's (1969) monograph on that formation. McKee's contributions to paleotectonic investigations in the Permian System (McKee, 1967) and Pennsylvanian System (McKee, 1975b) drew from studies made in the Canyon. But, as the 1960s progressed, many new students came to the forefront; it was a period of diversification. Very specialized topics were examined, some of them the subject of short papers, but many more were printed only as abstracts of research projects and unpublished theses and dissertations. Still, this period is notable for revitalized investigations of the Grand Canyon's rocks, from the Permian strata of the rim and plateaus to the basement complex of the Inner Gorge.

The approaching centennial of the Powell expeditions through the Grand Canyon served as an impetus for reflection and reinvestigation of Grand Canyon geology. The 5th Field Conference of the Four Corners Geological Society devoted its proceedings and its guidebook to the 1969 centennial. Ford and Breed (1969, 1972a,b, 1973a,b, 1974a,b) published new studies of the Grand Canyon Supergroup, concentrating on the Chuar Group of easternmost Grand Canyon. In 1973, the Museum of Northern Arizona and the Grand Canyon Natural History Association joined to produce Geology of the Grand Canyon (edited by Breed and Roat, 1973), the first book of solicited papers devoted exclusively to Grand Canyon geology. It is now out of print, but is brought up to date by the IGC guidebook edited by Elston et al. (1989). In 1974, the Rocky Mountain Section of the Geological Society of America concentrated its proceedings on the geology of Northern Arizona (Karlstrom et al., 1974).

The 1970s continued the diversification of Grand Canyon studies. Probably the most significant of works to come from that decade was McKee's (1975a) subdivision of the Supai formation of Darton (1910) into four formations, elevating the Supai to the status of stratigraphic Group. In that short paper McKee formalized what had been long suspected--that the Supai could be subdivided. No one else had been able to gather the widely-spaced field evidence to complete such an undertaking. That work culminated with McKee's (1982) monograph on the Supai Group of Grand Canyon, the product of more than 50 years of work. Thus McKee rounded out a life-long task of monographic treatment of the Canyon's Paleozoic strata. Only the Permian Hermit Shale and Devonian Temple Butte Limestone escaped detailed treatment by McKee. The Hermit was investigated in part by White (1929) and by McKee (1982), but no separate stratigraphic monograph exists. The Temple Butte received light treatment in a paper by Poole et al. (1967). Although McKee had been working on the Grand Canyon Devonian at the time of his death in 1984, no monographic treatment of that formation exists. However, Beus (1973) produced a volume on the Devonian stratigraphy and paleogeography of the western Mogollon Rim, south of the Grand Canyon.

In 1976, the Geologic Map of the Grand Canyon National Park (Huntoon et al., 1976) was published by the Grand Canyon Natural History Association and the Museum of Northern Arizona. It greatly improved upon the less adequate maps that had been prepared by Maxson (1961b, 1967, 1969). It was certainly a far cry from Dutton's (1882, pl. 4) map which, in the area covered by the 1976 map, showed only three colors--for "Carboniferous," "Silurian," and "Archean."

The 1980s in Grand Canyon geological studies have not been too greatly different from the 1970s. Diversified papers and abstracts have been the main source of new information about the Canyon. McKee's (1982) Supai monograph, as noted above, has been the only major Grand Canyon publication to have been printed so far [1988] in this decade. However, the many special-interest papers and several meeting guidebooks produced in this time have brought current research on the Canyon to the attention of other investigators. The 1986 meeting of the Rocky Mountain Section of the Geological Society of America was held in Flagstaff, Arizona, as it had been 12 years before. Many of the presentations and field trips dealt with the Grand Canyon area. For the first time there was a field trip to examine the mineralized breccia pipes of northern Arizona, one of the newest subjects of investigation.

Further research promises to be invigorating, but the prospect of definitive monographs seems to be faint at this time. We approach another period of transition, like that of the 1960s which marked the resurgence of interest in Grand Canyon geology. Interest in all aspects of the Canyon is increasing--the guidebook prepared for the 28th IGC river trip (Elston et al., 1989) substantiates this observation. The diversity of ongoing research covers all disciplines of geology. This new period is taking the appearance of one which is drawing more upon the work of teams of investigators more than individuals. Large-scale funding is also required for some investigations (such as breccia pipe exploration and development). In biostratigraphic studies, interesting new applications to sedimentological and correlative investigations are being pursued. Studies of the Pleistocene-Holocene paleoenvironments, hampered by the destruction of Rampart Cave (Mile 274.9) (Blair, 1980), but greatly assisted by studies made in Stanton's Cave (Euler, 1984) and from data gleaned from geographically dispersed packrat (Neotoma spp.) middens, may help in the continuing attempts to interpret the physiographic history of the Canyon itself.

The series of Colorado River trips sponsored by the 28th International Geological Congress, in June and July 1989, are historic in that they are the first internationally sponsored field trips down the Colorado. The guidebook is a look at current research interests, presenting views of current understandings and hypotheses on Grand Canyon geology. It is not the final chapter, but just the next chapter in the history of the development of geological studies in the Grand Canyon.

II. INTERNATIONALLY SPONSORED TRIPS TO THE GRAND CANYON

As an outstanding geological laboratory and educational tool, the Grand Canyon is continually visited by professionals and students. Geological meetings frequently sponsor field trips throughout the Grand Canyon region. But meetings that are internationally sponsored are held less often, and much less frequently are held in the United States. Thus the opportunity to register for Grand Canyon field trips, accompanied by delegates from around the world, is a rare opportunity. Of various internationally organized congresses meeting in the United States, only four, including the current 28th International Geological Congress (convening in Washington, D.C., in July 1989), have offered Grand Canyon trips; the 28th IGC trips are the first to travel on the Colorado River. The others were the 5th IGC (Washington, D.C., 1891), the Transcontinental Excursion of 1912 (sponsored by the American Geographical Society), and the 16th IGC (Washington, D.C., 1933).

The first international excursion to the Grand Canyon, technically, was that made by Pedro de Castañeda and a small party of Spaniards guided by native Americans. In 1540 they arrived at the South Rim of the Canyon probably west of Desert View, but, finding little of the glory of gold or God, left in three days (Winship, 1896; Bartlett, 1940). The Canyon was not visited again by an international group until the Ives Expedition reached it in 1858 (Ives, 1861), including two German artists (one of them a cartographer). The first organized group of international geologists did not arrive at the Canyon until 1891, 22 years after Powell and party travelled down the river through the length of the Canyon. The first internationally sponsored group of geologists to follow Powell's route would not do so until 1989, 120 years after Powell.

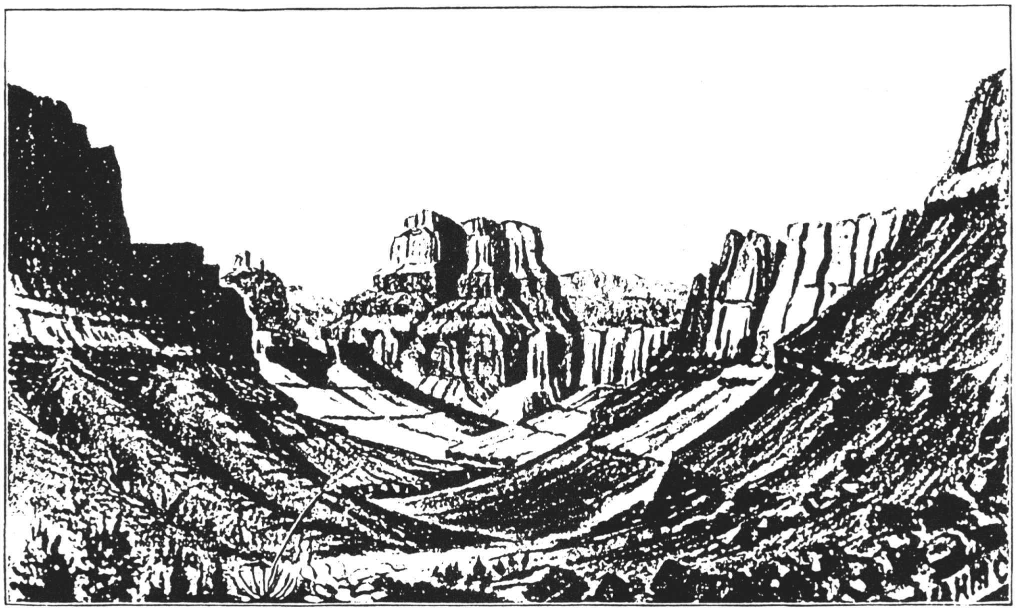
The 5th IGC was attended by 251 members (of 546 registering), of whom 78 were able to travel from countries as far away as Russia and Chile. (Accommodations in Washington cost from $1 to $10.50 per day.) The president of the Organization Committee was John Strong Newberry, the first geologist to reach the Grand Canyon. His itinerary for the Rocky Mountain Excursion noted the use of a special train for 75 attendees, traveling for 25 days through the eastern states, the Mississippi Valley, Yellowstone National Park, and the Rocky Mountains--with a special 1,180-km side-trip to the Grand Canyon guided in part by John Wesley Powell. The cost of the basic excursion was $265 per person. The cost of the supplementary Grand Canyon trip had not been fixed when the 3rd Circular was printed, but $100 was anticipated.

In 1891, the railroad from Williams, Arizona, to Grand Canyon was still just an idea, so visitors had to leave Flagstaff on wagons or saddle horses for a one- or two-day trip to the South Rim. The 5th IGC members had to endure an unforeseen event--"storms of rain, snow, and wind"--which forced the party to bivouac during the journey to the Canyon (Gilbert, 1893, p. 472, footnote). (For accounts of typical journeys to the Canyon from Flagstaff, see Martin, 1894, 1982; James, 1900. But Woods, 1899, p. 163, painted the most pleasant picture; he was General Manager of the Grand Cañon Stage Line.)

At the Canyon, the IGC members were introduced to the Canyon's geology "at a point nearly opposite Point Sublime" (Fig. 4), as noted by Gilbert (1893) and Frech (1893, 1895). However, the locale is a misnomer, identified as such because the most well-known vantage point in the Canyon in those days was at Point Sublime on the North Rim, so grandly illustrated by William H. Holmes in Dutton's (1882) monograph and atlas. The IGC vantage point was further identified as "Congress Canyon," no doubt spontaneously renamed to honor the expedition. Noble (1914, p. 14) was the first to note the error in location: "The supposition that Congress Canyon is opposite Point Sublime is erroneous. Point Sublime is 25 miles [40 km] west of a point opposite Congress Canyon." Ransome (1917, p. 163) added, "Congress Canyon is apparently what is known as Red Canyon, through which runs the old Hance Trail...." (Red Canyon meets the Colorado River at Mile 76.7.) In 1891, the difficult Old Hance Trail was still in use (replaced by the New Hance, or Red Canyon, Trail in 1894 when part of the Old Hance was obliterated by rockslides; neither trail is maintained today, and the Old Hance is barely more than a route).

The IGC party stayed at the rustic tourist accommodations that John Hance had built on the South Rim east of present-day Grand Canyon Village when he discovered that tourists were more profitable than his asbestos mine. Hance was quite a character; he admitted to having dug out the Canyon by himself. His guest register, now held at the Research Library at Grand Canyon National Park and as reprinted in part by Woods (1899), takes note of the IGC visitors; this is the only known list of 5th IGC members who visited the Canyon, and has not been printed elsewhere than in Woods' privately printed volume (Woods, 1899, pp. 39-40, sic):

September 26, 1891.
  Mary Caroline Hughes,
    Cambridge, Eng.
  Dr. Fritz Frech,
    Berlin, Germany.
  Dr. Wrifinz,
    Tubingen, Germany.
  Dr. D. Marchand,
    Photo Artist London 'Graphic.'
  Dr. Baron Sibney Wohrmann Holhen,
    Livonia, Germany.
  Dr. A. Botpletz,
    Municha, Germany.
  Dr. H. Credner,
    Leipzig, Germany.
  Dr. Johannes Walthur,
    Feria, Germany.
  Dr. Rudolf Cridner,
    Germany.
  Dr. A. Ulrich,
    Strasburg, Deutchland.
  H. M. Cadell,
    Grange Boness, Scotland.
  Willard D. Johnson,
    Washington, D.C.
  Alfred Harker,
  Wm. Kerney Hughes,
    Cambridge, England.



CONGRESS CANYON BELOW HANCE'S CABIN.

Figure 4. "Congress Canyon" as figured by Frech (1893, pl. 12), when visited by members of the 5th International Geological Congress in late September 1891. Congress Canyon is actually known as Red Canyon and was probably spontaneously renamed by the members of the field trip.

Dr. Aug. Streng,
  Professor from Giessen, Ger.
Dr. D. J. Brannen,
  Flagstaff, Arizona.
Dr. John R. Haynes,
  Los Angeles, Cal.
Dr. Geo. V. J. Berine,
  Halle A. L., Germany.
F. Plieninger,
----Kayser,
  Marburg, Germany.
I. Romburg,
  Berlin, Germany.
Dr. Carl Diermer,
  Vienna, Austria.
H. Tolliez,
  Professor University Lausanne,
  Switzerland.
Ernest Vanden Broek,
  Buinelles, Belgieque.
Morz Lohertsiege,
  Belgieque.
Dr. V. Zittel,
  Municha, Germany.
E. De Margerie,
  Paris, France.
Dr. Burgeart,
  "Mente et Malleo,"
    Munchen, Bayern.

In addition, the first visitor of the 1892 season, Horace C. Hovey of Middletown, Connecticut, wrote into Hance's register on 9 April, "Intended to come last fall with Geological Congress, but am contented to open the ball for 1892, 'Mente et Malleo,' as special correspondent of Scientific American" (Woods, 1899, p. 43).

The Compte Rendu of the 5th IGC, published in 1893, included a brief description of the stratigraphic section at "Congress Canyon," written by Frech, which he reprinted in German in 1895. Van Hise (1893, p. 136) briefly remarked on the Precambrian rocks of the Grand Canyon, correlating what we today call the Grand Canyon Supergroup with strata of "Algonkian" age elsewhere in North America, and the Vishnu Group with "Huronian"-age rocks of the Lake Superior region. No new information on the Grand Canyon strata was reported by the attendees of the IGC trip.

In 1904, the 8th International Geographic Congress was held in Washington, D.C. Although no trip was made to the Grand Canyon, of special note is the publication of an abstract by Matthes (1905a) published in full elsewhere (1905b). In it he outlined the monumental efforts taken in surveying 1:48,000-scale maps of 500 mi^2 (1,300 km^2) at contour intervals of 50 ft (15.2 m). The Bright Angel quadrangle, although replaced by more modern maps, remains a classic of cartographic art (see also herein the section, Cartography).

Physiographer and geomorphologist William Morris Davis confidentially approached a few correspondents in 1910 about the possibility for an international excursion across the United States. After some difficulty obtaining financial patronage, letters of invitation were sent out in June 1911 to leading geographical societies in Europe, who were invited to send delegates to the Transcontinental Excursion of 1912. The expedition, sponsored by the American Geographical Society, was finally organized, and the group of 43 foreign members left New York City on 22 August 1912 aboard a special train. Ninety American members participated in some parts of the excursion; six travelled the whole route, returning to New York on 18 October. The only problem faced by the travellers during the trip was, again, at the Grand Canyon. Unbeknownst to the party at the moment it happened, the train's locomotive and baggage car derailed just short of the station at Grand Canyon Village.

The 1912 excursion reached the Grand Canyon in the early morning of 2 October; one party descended to the Colorado River on Bright Angel Trail (Mile 88.9), while another party traversed the rim that day; they exchanged routes the next day. The one evening was apparently spent at El Tovar Hotel, and the group was also entertained by a show presented by one of the Kolb brothers. Ellsworth and Emery Kolb were Grand Canyon pioneers and photographers who were the first to make motion pictures along the Colorado. Ellsworth wrote a book about their trip (1914) and lived on the rim of the Canyon the rest of his life, until 1974. The Kolb Studio is now one of the historical buildings of Grand Canyon Village, administered by the National Park Service.

In addition to the foreign members, 13 American members of the excursion travelled to the Canyon. One paper, that by Drygalski (1915), described the observations made of the Canyon during the excursion. But it was said better by Brigham (1915, p. 25):

> "Two days were spent at the Canyon,...in hours of vision and wonder, pondering the physical history, reveling in changes of light and color, and in trying to describe the indescribable--all in all, a place which it is better to say only--go and see!"

(Sources for this section were Brigham, 1915, and Davis, 1915b.)

An outstanding early guidebook to the geology of the Grand Canyon region was prepared by Darton et al. (1915) as part of the U.S. Geological Survey's series of geological guides to major railroad routes of the United States. Although these guides were prepared independently of any organized meetings, they easily could have been used as fieldtrip guides for a national or international meeting in this country. Geological strip maps of the railroad routes accompanied detailed illustrated texts pertaining to segments of the total route. The guide by Darton et al. (1915) included a side trip to the Grand Canyon. This rail route to the Canyon was followed by members of the 16th International Geological Congress.

The last internationally sponsored geological trips to the Grand Canyon were offered by the 16th International Geological Congress, which convened in Washington, D.C., in 1933. One trip each visited the North and South Rims of the Canyon. Brief itineraries were included in the Colorado Plateau fieldtrip guidebook by Gregory (1932).

In 1989, field trips sponsored by the 28th International Geological Congress will visit the Canyon. For the first time, trips will be conducted on the Colorado River. The South Rim at Grand Canyon Village will be visited during the Colorado Plateau flyover trips that are planned by the IGC.

III. MESOZOIC STRATA

28th IGC Guidebook Chapter:

16. Mesozoic strata at Lees Ferry, Arizona. (George H. Billingsley)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	First appearances of Mesozoic strata
Lees Ferry	Chinle Fm.
0.1	Moenkopi Fm.

ALL OF the textbooks and guidebooks on the Grand Canyon region note the absence of Mesozoic strata at the Canyon. These strata have been eroded away from the uplifted area into which the Canyon is cut. The strata belonging to that era are expressed physiographically by the receding erosional edges of the Echo Cliffs and Vermilion Cliffs to the northeast and north, yet still within sight of the Grand Canyon. The nearest unquestioned occurrences of Mesozoic strata are at Red Butte, south of Grand Canyon Village, and Cedar Mountain, east of Desert View.

It is little noted, however, that two small outcrops of Triassic strata may occur very near the Canyon's rim: one about five miles along the Grand Canyon Railroad, on the east side of the Bright Angel fault, the other east of the axis of the Grandview-Phantom monocline between Grand Canyon Village and Desert View. Both outcrops show lithology like that of the Moenkopi Formation and the unconformable contact between it and the underlying Permian Kaibab Formation. But, although these rocks may be the Moenkopi Formation, they more probably are redbeds of the Harrisburg Member of the Kaibab Formation (G. H. Billingsley, written communication). These outcrops were discovered and reported by McKee in 1934, and more widely distributed in 1935. The localities are shown on the geologic map of eastern Grand Canyon National Park (Huntoon et al., 1976) and are unfossiliferous at both places. The Shinarump Conglomerate Member of the Chinle Formation, overlying the Moenkopi, occurs nearest to the Canyon atop Cedar Mountain and yields petrified wood there (Noble, 1922). Red

Butte also shows these strata. A synopsis of the Mesozoic strata was written by Colbert (1974).

A study of the Mesozoic strata at Lees Ferry, the starting point for Colorado River trips, was made by Phoenix (1963). Stratigraphic studies of the Moenkopi and Chinle Formations, in northeastern Arizona and surrounding areas, have been presented by Repenning et al. (1969).

IV. PALEOZOIC STRATA

28th IGC Guidebook Chapters:

12. Preliminary polar path from Proterozoic and Paleozoic rocks of the Grand Canyon region, Arizona. (Donald P. Elston)
13. Paleozoic strata of the Grand Canyon, Arizona. (Stanley S. Beus and George H. Billingsley)
14. Cambrian stratigraphic nomenclature, Grand Canyon, Arizona--mapper's nightmare. (Peter W. Huntoon)
15. Correlations and facies changes in Lower and Middle Cambrian Tonto Group, Grand Canyon, Arizona. (Donald P. Elston)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	First and Repeat Appearances of Paleozoic Strata
0.8	Kaibab Formation
2.1	Toroweap Formation
4.5	Coconino Sandstone
8.5	Hermit Shale
11.4	Esplanade Sandstone
17.0	Wescogame Formation
18.0?	Manakacha Formation
20.2	Watahomigi Formation
23.0	Redwall Limestone
23.3	Surprise Canyon Formation
24.5	Surprise Canyon Formation
35.1	unclassified dolostones
35.3	Muav Limestone
37.8	Temple Butte Limestone noted
46.9	Bright Angel Shale (gradational contact)
58.2	Tapeats Sandstone (gradational contact)
118.8	Tapeats Sandstone/Vishnu Schist contact
120.2	Tapeats Sandstone/Vishnu Schist contact
123.2	Bright Angel Sh./Tapeats Ss. (gradational)
126.6	Tapeats Sandstone/Vishnu Schist contact
137.7	Tapeats Sandstone/Bass Limestone contact
140.4	Tapeats Sandstone
168.0	Surprise Canyon Formation (high up)
178.8	Tapeats Sandstone
179.8	dated tuff in Muav Limestone
189.5	Tapeats Sandstone/Vishnu Schist contact
190.0	Tapeats Sandstone/granite contact
205.7	dated tuff in Muav Limestone
207.6	Tapeats Sandstone/Vishnu Schist contact
209.0	Bright Angel Shale/Vishnu Schist contact

Tapeats Sea Islands

102.9, 108.6, 138.0, 212.0

CONSIDERING the Grand Canyon's outstanding continuous exposures of essentially horizontal strata, it should come as no surprise that the Canyon's Paleozoic strata comprise the majority of Grand Canyon geological investigations. So much has been written about them that even a general description of those works would occupy more space than is available for the present volume. Furthermore, McKee (1969) has already presented a concise history of the studies of the "Stratified Rocks of the Grand Canyon." The sections of that paper are: "Pioneer stratigraphic work--pre-Powell era," "John Wesley Powell's Colorado River trips of 1869 and 1871-72," "Stratigraphic work during the early days of the U.S. Geological Survey," "Expanded stratigraphic studies, 1900-1935," "Recent studies and their interpretation," and "Conclusions." The "Recent Studies" section is divided into several subsections: "Rock classification--revisions and additions," "Refinements in age determination," "Paleogeography and paleotectonics," "Significance of unconformities," "Advances in sedimentology," and "Paleontology and paleocology." Therefore, this section of the present volume by necessity includes only a representative view. More attention is given to the major works and publications that have appeared since McKee's review. To present additional information graphically, Appendix A lists data for the entire Grand Canyon stratigraphic column. There the reader will find information on interpreted depositional environments and paleogeography, and citations of first publication of various names. Appendix B lists the Paleozoic stratigraphic nomenclature as used in selected major publications.

Much information about the Paleozoic strata pertains to paleontological studies, and a voluminous amount of material can be collected about that aspect of Grand Canyon geology. This has been presented by Spamer (1984a), to whom the reader is directed for a review of paleontological studies. For a few remarks on publications appearing after that review, see herein the section on Paleozoic-Mesozoic Paleontology.

To briefly summarize the progress in stratigraphic studies over nearly a century and a half, we must appreciate first how the Grand Canyon region was opened to exploration. When Marcou (1856, 1858) first made notes on the rocks of the region south of the Grand Canyon, no one had explored the territory beyond the thin routes travelled by early military reconnaissance parties. At best, the only knowledge of those farther areas came from itinerant travellers like trappers, traders, and missionaries. The Sitgreaves Expedition of 1851-1852 (Sitgreaves, 1853) had travelled across northern Arizona, abandoned an attempt to reach the Big Canyon, and continued to the Colorado River along a route south of the Canyon. That expedition did not have a geologist travel with it, although the naturalist Samuel W. Woodhouse went along as a physician. Woodhouse did collect a few specimens of petrified wood from Late Triassic strata of northern Arizona (Chinle Formation), but little else geologically (Spamer, 1989b).

The Ives Expedition of 1858 (Ives, 1861) was successful in reaching the Canyon; they were fortunate to have a trained geologist with them, John Strong Newberry. In 1869, John Wesley Powell led his first expedition down the Colorado River through the length of the Canyon, repeating the heroic effort in 1871-1872. His report (Powell, 1875) captured the imagination of westward-expanding America. Clarence E. Dutton was commissioned to explore the Grand Canyon country north of the river, and this report (Dutton, 1882) captured the glory and splendor of the Canyon (Fig. 5). By that time, geologists were being attracted to the Canyon from far afield; more and more references to it were appearing in the literature. And by the time Walcott's first papers were published (Walcott, 1880, 1883, 1886, 1890), all of the major rock groups of the Grand Canyon had been identified and given names--a far cry from Marcou's Paleozoic triumvirate (borrowed from the English) composed of the Magnesian Limestone, the Mountain Limestone, and the venerable Old Red Sandstone.

Once the major Grand Canyon stratigraphic units had been established in the literature, future studies dealt with reexamination and revision in the light of more intense surveys and improved knowledge of the science of geology. Today we identify 24 formations above the crystalline basement complex, 15 of them in the Paleozoic. We might imagine, "What more can be done?" But who among us just 20 years ago would have imagined the presence of the Surprise Canyon Formation (Billingsley and Beus, 1985)?

The early 20th Century in Grand Canyon geological stuides was a period which saw much work in the Paleozoic strata. Lithologic boundaries were defined, stratigraphic correlation contributed to the refinement of age assignments, and some work was done on subdividing the recognized formations. By the 1930s, the understanding of Grand Canyon stratigraphy had progressed to the point that monographic treatment of selected formations was possible.

In 1933, McKee's study of the Coconino Sandstone became the first of the major Grand Canyon works that is still regarded as an authoritative reference. In it he described the formation of the great sand dunes and the relationship between the various types of dune structures. It was the seminal paper in a life-long interest in the origin and structure of sand bodies--eolian, fluvial, and marine. McKee followed the Coconino paper shortly with another study of the Grand Canyon Permian strata, wherein he took the "Kaibab limestone" of Darton (1910) and divided it into the Kaibab Limestone and Toroweap Formation (McKee, 1938a). In that paper was the first demonstrated use, over a large area, of the correlation of key beds and the paleoenvironmental implications of facies within a formation.

The studies of the Upper Permian strata by McKee were a proving ground for applying the same methods of observation and interpretation to the great sequence of Cambrian strata of the Grand Canyon. McKee and Resser (1945) produced the definitive monograph on those formations, for the first time demonstrating that the formational boundaries cross time planes, due to transgressions and regressions of the sea, but that members within these formations do not. McKee and Resser's figure 1 is a diagrammatic section of the Grand Canyon Cambrian strata, showing the relationships of transgressions and regressions to facies; it is probably the most reproduced figure in the Grand Canyon geological literature.

In 1969, McKee and Gutschick culminated a period of investigations of the history of the Mississippian Redwall Limestone. The four well-defined lithologic members of the Redwall were interpreted to represent two cycles of transgression and regression. The study is a classic one of cyclical carbonate deposits. The time zones delineated by faunal elements were seen to be independent of the lithologic units. (See Peirce, 1979, for a summary of the Mississippian System in Arizona.)

In the same year, McKee (1969) remarked that continued work was necessary in order to interpret the history of the "Supai Formation" (then undivided) and the overlying Hermit Shale; but, he lamented, the task was made difficult by the absence of marker fossil zones in those rocks. Indeed, the only fossils which appear with any regularity in these strata are plants (particularly in the Hermit) and the ichnofauna of vertebrate animals. The Hermit plants are for the most part unique to the Grand Canyon, creating difficulties in correlation, and the ichnofauna of the Hermit and "Supai" (Wescogame Formation) are unreliable for correlation and very much in need of taxonomic revision (Spamer, 1984a). Subsequently, McKee pointed out that intertonguing carbonate units in the western and southern part of the Supai permitted relative dating of various parts of the Supai. McKee (1969, p. 35) concluded, "Thus, although no formal names are as yet proposed and boundaries are not recognized in many areas, available evidence suggests that at least four definite subdivisions (members) occur with in [sic] the Supai-Hermit sequence."

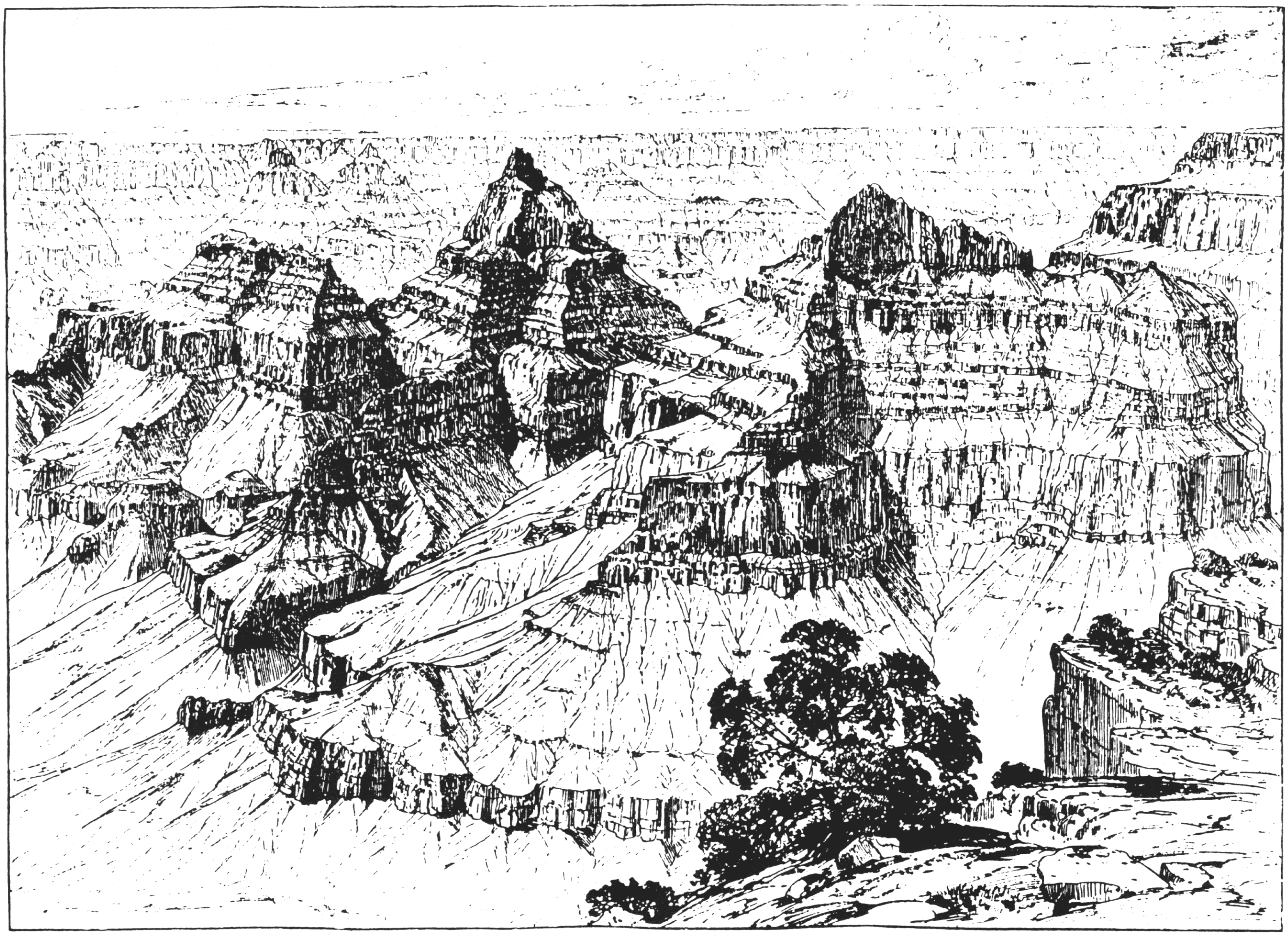


Figure 5. The entire Paleozoic section of the Grand Canyon stratigraphic column is exposed in Vishnu Temple. Dutton (1882, p. 148) called this feature "the finest butte in the chasm." (Dutton, 1882, pl. 34.)

Six years later, McKee (1975a) subdivided Darton's (1910) Supai into four formations, elevating the Supai in rank to a stratigraphic Group, and in the process retaining the Hermit Shale as a separate formation. The Hermit Shale was described earlier, by Noble (1922) who named it, and by White (1929) whose monograph was restricted more to paleobotany. These remain the standard references on the Hermit. McKee's Supai revision was followed by his last monographic treatment of the Grand Canyon Paleozoic formations, The Supai Group of Grand Canyon (1982). That volume, the product of 50 years of work in the Canyon, transcended the "hammer and compass" geology that was the trademark of all of McKee's earlier work in the Canyon. It included detailed technological investigations into the makeup of many strata within the group (for example, X-ray studies and stable isotope analyses), mostly by other workers, but which nonetheless were incorporated as part of the "big picture" of the Supai Group.

Included in McKee's Supai volume is a chapter by Billingsley and McKee (1982) on the "pre-Supai buried valleys." Already mentioned in the literature (e.g., U.S. Geological Survey, 1979), but then still under preliminary investigation by Billingsley and other workers, the buried valleys were described as having been filled by sediments of a formation previously unrecognized in the Grand Canyon section. The valleys were cut into the top of the Redwall erosional surface and filled in both by fluvial deposits and by sediments of an advancing Chesterian sea. Another unconformity separates these sediments from those deposited as the Watahomigi Formation. The new formation was named the Surprise Canyon Formation and formally described by Billingsley and Beus (1985).

Recent years have also been a time of new perspectives on the standard interpretations of sedimentology and paleogeography for some Grand Canyon Paleozoic formations. Wanless (1973) presented in his doctoral dissertation a critical re-evaluation of the depositional environments of the

Grand Canyon Cambrian strata. Based on lithologic and paleontologic evidence, he argued a case for a "Bahama-type, storm-dominated tidal flat" in one western facies of the Muav Limestone, an area traditionally treated as an off-shore environment. He also interpreted part of the Bright Angel Shale in central to eastern Grand Canyon as a tidal-flat environment, as well as other shoal water conditions throughout these formations.

Other recent doctoral dissertations have taken a new look at the stratigraphy of the Kaibab and Toroweap Formations. Clark (1981) re-examined these formations in the Grand Canyon region, whereas Nielson (1981) worked where these formations occur in southwestern Utah.

Lastly, it should be noted here that the stratigraphic members of the Kaibab and Toroweap Formations informally named in Sorauf's (1962) doctoral dissertation are about to be formalized. Long adopted by workers in the Grand Canyon region, these names will be applied to formal descriptions of these members, in a U.S. Geological Survey Bulletin by Sorauf and Billingsley, in 1989 (Sorauf, written communication, 1988). The type sections and descriptions will not differ greatly from those that appeared in Sorauf's dissertation.

V. MIDDLE AND LATE PROTEROZOIC GRAND CANYON SUPERGROUP

28th IGC Guidebook Chapters:

9. Middle and Late Proterozoic Grand Canyon Supergroup, Arizona. (Donald P. Elston)
10. Petrology and chemistry of igneous rocks of the Middle Proterozoic Unkar Group, Grand Canyon Supergroup, northern Arizona. (John D. Hendricks)
11. Potential petroleum source rocks in the Late Proterozoic Chuar Group, Grand Canyon, Arizona. (Mitchell W. Reynolds, James G. Palacas, and Donald P. Elston)
12. Preliminary polar path from Proterozoic and Paleozoic rocks of the Grand Canyon region, Arizona. (Donald P. Elston)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

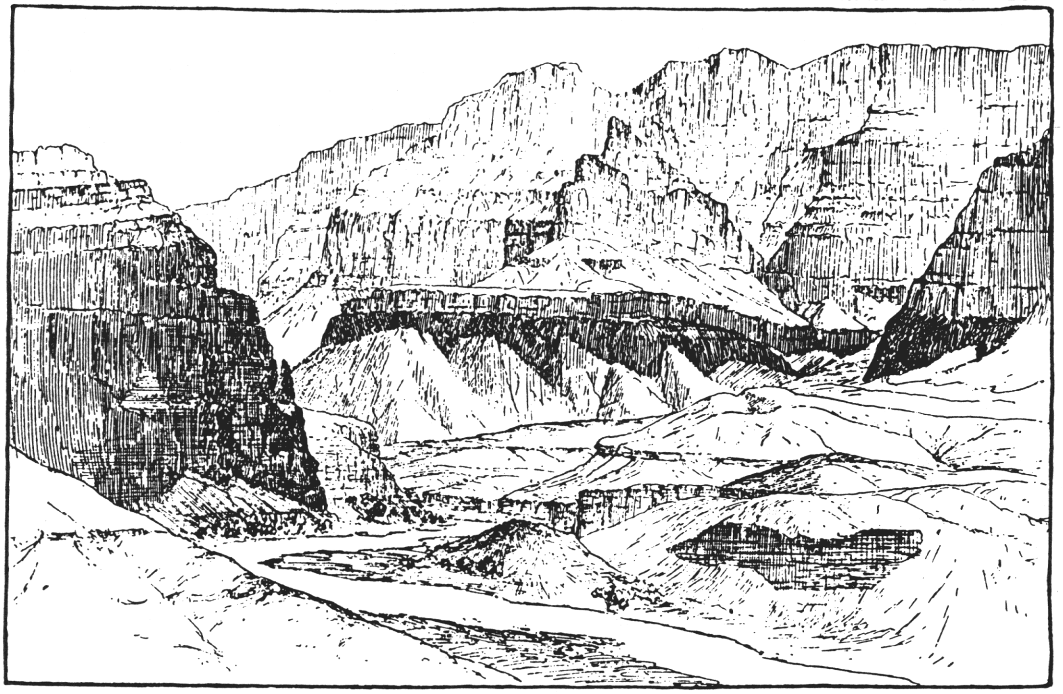
Mile	First and Repeat Appearances of Middle and Late Proterozoic Strata
63.0	Great Unconformity/Dox Formation
67.0	Great Unconformity/Cardenas Basalt
68.5	Cardenas Basalt
74.8	Shinumo Quartzite
76.2	Hakatai Shale
77.0	Bass Limestone
77.5	Hotauta Conglomerate Member/Vishnu Schist
130.6	Bass Limestone/Vishnu Schist contact
134.6	Bass Limestone
138.0	last outcrop of Grand Canyon Supergroup

THE NORTHEASTWARD-DIPPING sediments that lie unconformably between the Paleozoic strata and metamorphic basement rocks of the Grand Canyon have attracted the interest of geologists ever since John Wesley Powell first saw them in 1869. In outcrop they are known only from the Grand Canyon, but they also have been noted in the subsurface of southern Utah (Hintze, 1988). Their correlation is most recently discussed by Elston (1989). A key to the nomenclature of these strata appears herein in Appendix C.

Powell (1875) was the first to elaborate on the rocks that unconformably underlie the Paleozoic strata of the Grand Canyon. He called them the "non-conformable rocks," which included the metamorphic basement and the inclined series of sediments that we know as the Grand Canyon Supergroup (see Fig. 2). In 1876, however, he formally divided these rocks into the "Grand Cañon Schists" and the "Grand Cañon Group." Since these rocks had no bearing on the Tertiary history of the Grand Canyon region, Dutton (1882) simply noted the presence of "Lower Silurian and Archean unconformable" rocks ("Lower Silurian" being the usage of Gilbert, 1875, for strata below the "Carboniferous"). But the strata of what we now know as the Grand Canyon Supergroup went unstudied until Charles D. Walcott went to the Canyon with the express purpose of investigating that series.

Walcott spent the winter of 1883 in the northeastern section of the Grand Canyon, below what is now called the Nankoweap Trail (an unmaintained trail), where he studied the Early Paleozoic and Late and Middle Proterozoic rocks and structure of the area (Walcott, 1884). In 1883, he published the results of this field work, wherein he recognized two groups of strata lying unconformably below the Paleozoic sequence. The upper group he named the Chuar Group; the lower group he called the Grand Cañon Group, retaining the name that Powell (1876) had given to the whole section of Middle and Late Proterozoic sediments. He attributed the name "Chuar" to Powell, but since Powell had never published it himself, Walcott is the author of that group. Furthermore, Walcott attempted to correlate the Grand Cañon and Chuar Groups with similarly ordered stratigraphic groups elsewhere in North America. He observed that the stratigraphic relationships of these units, between metamorphic basement and Paleozoic strata, were

U. S. GEOLOGICAL SURVEY FOURTEENTH ANNUAL REPORT PL. LXI



CLIFFS FORMED BY LAVA BEDS ON THE COLORADO RIVER ABOUT TWO MILES SOUTH OF CHUAR LAVA HILL.
From a sketch by B. L. Young.

Figure 6. Part of the Unkar Group of the Grand Canyon Supergroup as exposed at about Mile 68-69. The "lava beds" noted in the original legend are outcrops of the Middle Proterozoic Cardenas Basalt. (Walcott, 1894, pl. 61.)

like sections seen in the "Huronian"-age strata of the Keweenewan series in Wisconsin, and probably also correlated with strata seen at St. Johns, New Brunswick (Canada), and at Braintree, Massachusetts (northeastern United States).

Walcott retained his Precambrian terminology in papers published in 1886 and 1890, but in 1894 he gave the name "Unkar terrane," or Unkar Group, to the Grand Canyon Group, combining the Chuar and Unkar Groups as the "Grand Canyon Series," of "Proterozoic (Algonkian)" age. That same paper also included the first petrographic study of the Cardenas Basalt, unnamed at that time, by Iddings (1894). In 1895, Walcott noted that the Chuar Group could be divided into an "upper division" and a "lower division." At that time he was uncertain whether these strata could in fact be correlated with either the "Keweenawan series" of the Lake Superior region or to the "Llano series" of Texas. (See Wilmarth, 1925, for a key to older usages of chronologic units in geology.) Walcott's correlations were based on paleontological evidence, some of it erroneous but which nonetheless was consistent between regions (see the section herein, Proterozoic Paleontology, as well as in Spamer, 1984a).

Van Hise (1892) attempted a correlation of all Precambrian rocks of North America. He noted that the rocks of the Grand Canyon Supergroup are the thickest known sequence of such strata outside of the Lake Superior region, to which he correlated the Grand Canyon strata of "Keweenawan" age. Van Hise and Leith (1909) sustained this view.

The terminology and subdivisions of Walcott remained in place when Darton (1910) published his stratigraphic reconnaissance of northwestern New Mexico and northern Arizona. However, that same year, Noble (1910) examined the Unkar Group, dividing it into five unnamed subunits which in 1914 he named the Dox Formation, Shinumo Quartzite, Hakatai Shale, and the Bass Formation (containing the basal Hotauta Conglomerate Member). Ransome (1908b) had already noted for the first time that the Unkar strata could be seen in some measure in Bright Angel Canyon (Mile 87.7), but he did not make any attempt to formally subdivide that group. Neither Ransome nor Noble described the Chuar Group.

No one studied the Grand Canyon Supergroup for years after Noble's 1914 paper. Wilmarth's (1932) correlation chart for Arizona rock units shows the undivided Chuar Group and the Unkar Group of Noble still unchanged from earlier usage. However, change came in 1934 when Van Gundy presented "Some Observations of the Unkar Group of the Grand Canyon Algonkian" in a small publication called Grand Canyon Nature Notes. He proposed a new stratigraphic unit, which he called the Nankoweap Group (= Nankoweap Formation), lying unconformably between the volcanic rocks (Cardenas Basalt) of the Unkar Group below and the Chuar Group above.

Van Gundy went more public with the "Nankoweap Group" at a 1936 meeting of the Geological Society of America (Van Gundy, 1937a), but the paper which he presented there was not published until 1951. He continued his work on the Nankoweap Formation, reporting that in 1934 he had found a large jellyfish fossil in the formation (Van

Gundy, 1937b; Hinds, 1938c). This fossil was named Brooksella canyonensis by Bassler (1941), and Seilacher (1956) felt that it could be a trace fossil; but Cloud (1960, 1968) dismissed it as a gas-evasion or compaction feature. Glaessner (1969) resurrected the fossil, placing it questionably in the ichnogenus Asterosoma. The trace-fossil interpretation of this object, whatever it is called, was sustained by Kauffman and Steidtmann (1983) and Kauffman and Fursich (1983). However, the problem of "B. canyonensis" really remains unresolved (Spamer, 1984a). The existence of organisms as complex as the jellyfishes during the Middle Proterozoic is dubious, so reports of their existence in these strata are at this time not helpful in biostratigraphic studies.

In the 1930s, the Carnegie Institution of Washington supported various geological investigations in the Grand Canyon. The "Algonkian"-age rocks of the Grand Canyon Supergroup were examined by Hinds, who published several reports on his ongoing research there (Hinds, 1933, 1934, 1935, 1936a-c, 1937a-c, 1938a-c, 1939, 1940). His emphasis was more on correlation and paleogeography than on sedimentology and local stratigraphy.

The lava flows that occur stratigraphically above the Dox Formation were long incorporated into the Unkar Group. Once the Dox had been named they often were orphaned as a descriptively defined unit, like "basalt and diabase." In 1938, Keyes gave the name "Cardenesan Series" to these rocks; and as they are recognized as a separate, mappable lithostratigraphic unit the name Cardenas Basalt is the name which remains in formal use. (However, all of Keyes' Grand Canyon stratigraphic work has been justifiably ignored by geologists, as outlined by Spamer, 1983, pp. 315-326.) The Cardenas Basalt was later mapped erroneously as Maxson's (1961a,b, 1967, 1969) "Rama formation," into which Maxson mistakenly mapped apparently unrelated sills in the Bass and Hakatai Formations (Ford et al., 1972).

After the activity of the 1930s, there followed a hiatus of three decades in studies of the Grand Canyon Supergroup. Then there began a period of vigorous restudy, inspired in part by the centennial of the Powell expeditions. These studies also included investigations of paleomagnetism and polar wandering paths, which are noted herein in the section on Paleomagnetism.

In 1969, Ford and Breed published a preliminary geological report on the Chuar Group which paved the way to their presentation at the 24th International Geological Congress in Montreal, Canada, in 1972. There they described three new formations and seven members within the Chuar Group (Ford and Breed, 1972a). This was published in a more extended format in 1973 (Ford and Breed, 1973a) and was reviewed in two papers in a 1974 paper. They singled out the new Sixtymile Formation for discussion in a separate paper (Breed and Ford, 1973). They also published several papers on a problematical macroscopic algal fossil that had been described first from the Chuar Group, Chuaria circularis Walcott, 1899 (Ford and Breed, 1972b, 1973b, 1974b, 1977; Spamer, 1989a; and for an annotated bibliography of world occurrences see Spamer, 1988).

At the same time that Ford and Breed were working on the geology of the Chuar Group, various other workers were beginning to reexamine the Unkar Group. Beus et al. (1974) presented a preliminary overview of the group, while Dalton and Rawson (1974) took a look at the Bass Limestone and Stevenson (1974) examined the Dox Sandstone. Stevenson's abstract was the beginning of work that eventually led to Stevenson and Beus' (1982) restudy of the Dox, which they formally subdivided into four stratigraphic members. Daneker (1974) published an abstract in which he recognized five mappable lithologic units within the Shinumo Quartzite; however, this formation still is not formally subdivided.

But by far the most interest in the Unkar Group at that time was in the Cardenas Basalt and the sills and dikes of the group. Hendricks (1972) published an abstract of work on the diabase dikes and sills, and Lucchitta and Hendricks (1972) likewise reported work on the Unkar lavas. Together, this research was elaborated upon by Hendricks and Lucchitta (1974). Elston and Scott (1973) reported on paleomagnetic studies of the Cardenas Basalt and the Nankoweap Formation; they also formally segregated the Nankoweap from the Unkar Group, placing it as a separate formation between the Unkar and Chuar Groups, and redesignated the "Grand Canyon Series" as the Grand Canyon Supergroup. These authors also published another paper describing the pre-Nankoweap unconformity (Elston and Scott, 1976).

McKee and Noble (1976) published a Rb-Sr isochron age for the Cardenas Basalt of 1.09 ± 0.7 Ga. They noted that K-Ar ages previously reported by Ford et al. (1972; 845 ± 15 Ma) and new K-Ar dates of 810, 790, and 781 Ma, may differ because of the diffusive loss of ^{40}Ar during a heating event ca. 800 Ma.

Larson et al. (1978) reported on field and petrographic evidence indicating that the Cardenas Basalt was erupted subaerially, contrasting earlier interpretations which called for some of the lavas to have been erupted into seawater. They also stated that the dikes and sills of the "Rama formation" (an erroneous unit abandoned by Ford et al., 1972) are chemically and petrographically equivalent to alkali-olivine basalts in the lower Cardenas Basalt. Lucchitta and Hendricks (1983) were the last to elaborate on the Cardenas Basalt. They stated that the 1.1 Ga lavas were erupted probably onto tidal flats and that the upper Cardenas may have been erupted at least partly in the subaerial environment. A single vent or a cluster of vents near Ochoa Point was indicated as the source of the lavas. Stratigraphic evidence in the Nankoweap Formation also suggested that the unconformity at the top of the Cardenas Basalt might represent a lengthy hiatus.

From the end of the 1970s, paleotectonic studies have been the main thrust of investigations in the Grand Canyon Supergroup. G. M. Young (1978) identified a three-fold subdivision of stratigraphic sequences in post-Aphebian time (<1.7 Ga): 1.7-1.2 Ga, 1.2-0.8(?) Ga, and 0.8(?)-0.6 Ga. Sediments of the first two sequences appear to have had source areas on the eastern side of the continent. The sediments of the Chuar Group correspond in age to the second sequence and correlate approximately with the time of the Grenvillian orogeny of eastern North America.

Elston (1979) wrote a monograph on the Sixtymile Formation, describing in detail for the first time the type section of that formation. He also interpreted the landslide deposits that constitute this formation as evidence of a "Grand Canyon orogeny" 810-845 Ma. The formation was seen as analogous to stratigraphically and lithologically similar deposits of the Windermere Supergroup of the western Cordillera. Elston and McKee (1982), however, concluded that the Sixtymile Formation was not the product of a full-fledged orogeny and preferred to call the event the "Grand Canyon disturbance," the presently preferred term. They also removed the formation from the Chuar Group, retaining it as a separate unit at the top of the Grand Canyon Supergroup.

Babcock (1980) incorporated the Grand Canyon Proterozoic rocks into a review of the Proterozoic evolution of continental crust in the Grand Canyon region, concluding that that time appears to have been one when the crust was maturing gradually toward a stable state and that "Large-scale plate convergence...probably was not a controlling factor in the evolution of this region." Lucchitta and Hendricks (1980) used data interpreted from the eruptions of the Cardenas Basalt to indicate the paleoenvironment of the Dox sea. Related sedimentologic and stratigraphic information suggest a shallow, hypersaline, epicontinental environment of deposition. Minor tectonic activity, in the form of gentle tilting to the northeast, took place prior to deposition of the Nankoweap Formation.

In 1986, Reynolds and Elston had reported that stratigraphic and sedimentologic evidence in the Chuar Group called for a reinterpretation of the overall depositional environment. The Chuar depositional basin, traditionally interpreted as "marine in a floundering embayment on the passive edge of the continent," may have been "a lacustrine setting in a subsiding region within the continent." This is becoming the preferred interpretation (e.g., Elston, 1989).

Winston (1988) has proposed two hypotheses for an intracratonic setting of Middle Proterozoic basins of the western United States. Evidence taken in part from the Grand Canyon Supergroup may indicate Middle Proterozoic rifting and marine invasion followed by orogensis and more rifting, or Late Proterozoic rifting of Middle Proterozoic intracratonic basins. The strata of the Unkar Group may represent intracratonic deposits, while the Chuar Group may represent lacustrine deposits. Winston favored the hypothesis "that the Belt [in Montana and Idaho], Grand Canyon, Apache [Arizona] and Uinta [Utah] basins formed within a large continent that rifted and drifted late in the Proterozoic" [the rock units are the Belt Supergroup, Grand Canyon Supergroup, Apache Group, and Uinta Group, respectively].

VI. EARLY PROTEROZOIC BASEMENT COMPLEX (VISHNU GROUP)

28th IGC Guidebook Chapters:

6. Setting of Precambrian basement complex, Grand Canyon, Arizona. (Peter W. Huntoon)
8. Early Proterozoic rocks of Grand Canyon, Arizona. (Charles W. Barnes)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	First and Repeat Appearances of Early Proterozoic Rocks of the Basement Complex
77.5	Hotauta Conglomerate Member/Vishnu Schist
84.7	Vishnu Schist/Zoroaster Pluton contact
86.1	Vishnu Schist/Zoroaster Pluton contact
89.1	Vishnu Schist/Zoroaster Pluton contact
89.8	Vishnu Schist/Zoroaster Pluton contact
91.3	Vishnu Schist/Trinity Gneiss contact
92.5	Vishnu Schist/Trinity Gneiss contact
96.2-96.5	granitic pluton
97.7-98.0	Zoroaster Pluton
98.7-99.1	granitic pluton
102.8	Vishnu Schist/Zoroaster Pluton
115.6	Tapeats Sandstone/Vishnu Schist contact
118.8	Tapeats Sandstone/Vishnu Schist contact
215.0	Zoroaster Pluton
215.8	Zoroaster Pluton
223.5-227.0	Diamond Creek Pluton
227.0-230.0	229-Mile Gneiss
230.0-230.9	Travertine Falls Pluton
232.3-236.7	longest exposure of migmatite
236.7-237.0	237-Mile Pluton
238.5-240.0	Separation granite pluton
242.3-243.2	Spencer granitic pluton
246.1	last exposure of Vishnu Schist
246.1-261.0	Surprise-Quartermaster Pluton

Basement also appears later in Iceberg and Virgin Canyons.

THE DEEPEST parts of the Grand Canyon are at first look a dark, forbidding place. John Wesley Powell wrote with great trepidation on the first trip through the Canyon (Powell, 1875, p. 81):

> "At daybreak we walk down the bank of the river, on a little sandy beach, to take a view of a new feature in the cañon. Heretofore, hard rocks have given us bad river; soft rocks, smooth water; and a series of rocks harder than any we have experienced sets in. The river enters the granite!
>
> "We can see but a little way into the granite gorge, but it looks threatening."

Of course, Powell knew that these rocks were schists, but for his generalized public report he preferred to use the rock type better-known to the layman, "granite." He and his fellow explorers had no idea what to expect in that reach of the Canyon; geology, somehow, was not foremost in Powell's thoughts at that moment. The Inner Gorge, where it is made up of the Vishnu Schist and related basement rocks, presents quite a different view of the Grand Canyon (Fig. 7). These rocks are accessible for the most part only from the river and deep side canyons, so detailed studies of them have been long in coming. A key to the development of nomenclature of these rocks is included herein in Appendix D.

All of the early Grand Canyon geologists--Newberry, Powell, Dutton--glossed over the schists and granites of the basement. Walcott (1890) named the Vishnu Schist, which we recognize as the primary unit of the basement complex, but restricted his examinations more to the stratigraphic relationship between the Vishnu and later strata. Ransome (1908a) was the first to treat the basement rocks in a separate study, correlating them with similar rocks elsewhere in Arizona. He was the first to formally examine the gneissic banding and foliation that constitute the Vishnu Group.

Noble and Hunter (1917) provided the first reconnaissance study of the "Archean complex" of the Grand Canyon. They studied the Vishnu Group mostly in tributary canyons cutting the Tonto Plateau, on the south side of the Colorado River, from Red Canyon to Garnet Canyon (Mile 76.7 to 114.5). They recognized eight geographically segregated groups, composed of mixes of gneisses, amphibolites, granite, mica schist, massive basic intrusive rocks, metabasite, and metadiorite. They recognized that some similar rock types, appearing at different places, were genetically related. They also conclusively showed that the mica schists--the classic Vishnu--are of regional metamorphic origin, and they were the first to suggest that the term "Vishnu" would probably be best restricted to the mica schists.

Virtually no studies were made again of the Grand Canyon's basement complex until the 1930s, when the Carnegie Institution of Washington supported a number of geological investigations in the Canyon. Ian Campbell and John H. Maxson spent several field seasons analyzing the basement rocks, producing a series of short reports which stood for decades as the definitive references on the subject (Campbell, 1936, 1937; Campbell and Maxson, 1933a-d, 1934, 1935a,b, 1936, 1937, 1938a,b, 1939a); in 1937 they also reported their conclusions to the 17th International Geological Congress in Moscow (Campbell and Maxson, 1939b). Generally speaking, these reports were field descriptions and laboratory analyses of selected rocks; they also addressed problems of apparent metasediments incorporated into the strongly metamorphosed rocks (Maxson and Campbell, 1934, 1939). They named the Zoroaster Granite (Campbell and Maxson, 1936), mappable granitic bodies in the Vishnu Group. Their work on the pegmatites of the Grand Canyon basement was also cited in Fersman's (1940) monograph on pegmatites.

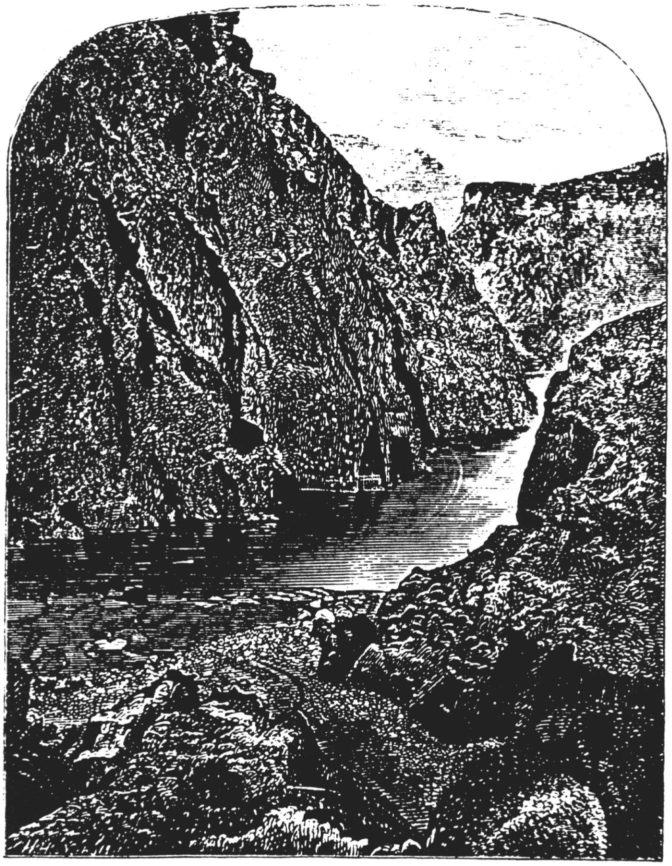


Figure 7. The Colorado River cutting through the Early Proterozoic Vishnu Group. In the background, the Cambrian Tapeats Sandstone unconformably overlies the Vishnu. (Powell, 1875, fig. 29.)

Hinds (1936a,b) presented a bold monograph in two parts, correlating the Precambrian formations of western North America. The Grand Canyon rocks of course figured importantly in that synthesis, but no new data were provided concerning those rocks.

The first radiometric-age dates for the Grand Canyon basement were determined by Aldrich et al. (1957, 1958). They reported K-Ar and Rb-Sr ages for gneiss and granite samples ranging from 1,340 Ma to 1,390 Ma. They used this evidence to determine that basement rocks throughout the western United States underwent widespread recrystallization about 1,350 Ma. Damon and Giletti (1961) and Giletti and Damon (1961) reported new radiometric age dates of 1,530 Ma and 1,550 Ma for a pegmatite in the Vishnu Schist. These authors noted that their results were in agreement with those reported by Aldrich et al. Lanphere and Wasser burg (1963) reported in an abstract that they had determined Rb-Sr ages of about 1,800 Ma for minerals in pegmatites of the Grand Wash Cliffs area. In 1965, Wasserburg and Lanphere reported K-Ar and Rb-Sr ages of 1,650 Ma for granite and pegmatite from the same area.

In 1961, Maxson published his geological map of the Bright Angel quadrangle (Maxson, 1961b) and its accompanying guide to Grand Canyon geology (Maxson, 1961a). Therein he named the Brahma schist, a metamorphic unit which he believed to be distinct from the Vishnu Schist. He retained this distinction in the 1967 and 1969 geological maps of the Grand Canyon. But Ragan and Sheridan (1970), reflecting the general feeling of Grand Canyon geologists, noted that the Brahma schist was not truly distinct from the Vishnu, not accurately mappable, and thus should not be a treated as a separate lithologic unit. They did suggest, though, that the large gneissic masses of the basement complex might be treated as separately mappable units; this was determined to be the case in later years.

In 1973, the first indication of renewed investigations of the Grand Canyon basement rocks was announced by an abstract by Lingley et al. They recognized several metamorphic facies in these rocks and described microscopic- to 0.5-km-amplitude folds. They observed that the Zoroaster granite of Campbell and Maxson (1936) is foliated, and proposed that it should be renamed the Zoroaster gneiss. In 1974, Livingston et al. published an abstract reporting geochemical studies in the Vishnu Group, recognizing a low-Rb and a high-Rb group of rocks. They interpreted the low-Rb group to be pre- to syn-tectonic in metamorphic genesis; the high-Rb group late- to post-tectonic.

In 1974, Brown et al. and Babcock et al. presented overviews of the reinvestigations then underway in the Grand Canyon basement complex. Babcock et al. divided these rocks into four groups: the Vishnu Group (a new term), felsic gneisses (including the Zoroaster, Trinity Creek, and Elves Chasm Gneisses [the latter two being new terms]), weakly foliated to directionless plutons, and pegmatite/aplite dikes and sills. They also presented a scenario for the creation of the basement complex, including a 100-million-year period of metamorphism at about 1,700 Ma. The intensity of metamorphism ranged from greenschist to upper amphibolite facies. Later, Clark (1978) supplemented some of the data by describing the mineral chemistry and phase petrology of the amphibolitic rocks. But these preliminary studies only set the stage for several papers which remain the definitive studies of the Grand Canyon basement complex.

Three papers published in Precambrian Research in 1979 are the most exhaustive studies to date of the Vishnu Group. Part I, by Brown et al., examined the petrology and structure of the "Vishnu Complex" (a new term). They reported that the Vishnu Complex is a metamorphosed complex of sandstones, shales, impure carbonate sediments, and basic volcanic rocks, but is composed predominantly of the first two types. Three episodes of metamorphism and two episodes each of schistose foliation and folding were recognized. The highest metamorphic grade attained was in the second episode of metamorphism, as indicated by mid-to upper-amphibolite facies, with maximum temperatures of 650° C at 3 to 4 kb pressure. The overall first metamorphic episode took place 1,730-1,770 Ma and is thought to be correlative with the metamorphic event of the Yavapai Series of central Arizona. Other radiometric age determinations ranged from 1,635 ± 34 Ma to 1,725 ± 15 Ma.

Part II of the basement trilogy, by Babcock et al. (1979), examined the intrusive rocks of the basement complex. These authors described the petrologic relationships of the igneous and meta-igneous rocks and defined several types: mafic to ultramafic intrusives, granitic plutons, and pegmatite/aplite dikes and sills, and granitic ortho-gneisses. They suggested a common source for all of these rocks.

Part III, by Clark (1979), described the petrology of mafic schists and amphibolites. Five major groups were identified: anthophyllite- and cordierite-anthophyllite-bearing rocks, early (plagioclase-hornblende) amphibolites, the Granite Park Mafic Complex (new term), hornblende-bearing dikes, and tremolite-bearing dikes. Volcanically-derived metasediments were interpreted to be represented by the cordierite-anthophyllite rocks. The early amphibolites might have been created in an island arc environment. Most of the mafic schists and amphibolites are of basic igneous origin, thought to have been deposited in an area of active sedimentation.

In 1982, Condie presented a plate-tectonics model for Proterozoic continental accretion in the Southwest, defining three major crustal provinces ranging in age from 1,720 ± 1,800 Ma to 1,100-1,200 Ma. The Grand Canyon Proterozoic supracrustal rocks were noted to be in the former age group, which also includes similar rocks of Colorado and northern New Mexico, and the Yavapai Series of central Arizona. Condie inferred from the data that the orogenies and marginal basin enclosures interpreted from the rocks can be attributed to southward-migrating arcs.

Active studies continue to supplement the data published in the 1979 papers. Babcock (1988) described in an abstract at least three "lithotectonic superunits" are identifiable in the plutons of the Zoroaster Plutonic Complex. But all three units are not spatially segregated through the east-west Grand Canyon transect. They are interpreted to show the crustal evolution of the Grand Canyon region from about 1,800 Ma to about 1,300-1,400 Ma, as an immature ocean arc developing into a stable craton with incipient rifting. On a broader scale, Chamberlain and Bowring (1988) have reported in an abstract that two Proterozoic crustal provinces are recognized in northwestern Arizona. The boundary, which runs north-south approximately from the Grand Wash Cliffs to the Aquarius Mountains, is interpreted as "juxtaposition of a continental fragment containing remnants of 2.0 to 2.2 Ga crust to the west with largely juvenile, circa 1.7 Ga crust to the east between 1665 and 1690 Ma."

VII. MINERALOGY

STUDIES OF Grand Canyon rocks that are strictly mineralogical in scope are few. Most investigations of the basement complex are, by definition, largely mineralogical because they rely on petrologic work; so, too, are most papers that deal with economically significant deposits. This section will focus only on those papers which have reported mineralogical problems and discuss minerals specifically. Most of these deal with occurrences in the Paleozoic strata.

Salt is of special significance in the human history of the Grand Canyon. A necessary part of the human diet, it was sought by the Native Americans of the region for as long as they have lived in this land. The salt leaches out of groundwater seeps in many locations in the Canyon where the Tapeats Sandstone is exposed. The salt is largely protected from dissolution by groundwater by the nearly impermeable Bright Angel Shale above the Tapeats. But, spiritually, the salt is important because it occurs at the Sipapu of the Hopi Indians--the exit from the underworld from which they came to live on the earth. This place is near the confluence of the Little Colorado and Colorado Rivers (Mile 61.5). The salt seeps at the Sipapu used to be routinely visited, the salt being used in special ceremonies. But changing social values of the Hopi have greatly reduced the frequency of their visits to the Sipapu; many of the Hopi do not rely on ceremony as much as did earlier generations. It may seem as desecration of a site sacred in Hopi beliefs, but an analysis of the salt from the probable site of the Sipapu was published by Taylor (1954); only a quarter of the deposit is in fact common table salt (NaCl), with 15 percent sulphates and chlorides, and the remaining insoluble part largely calcite. Sturdevant (1926a) also briefly described the Tapeats salt occurrences.

Other groundwater-related minerals, in the form of cave deposits, have been described by Mowat (1960a,b) from Silent River Cave. He has described hydromagnesite(?) and gypsum. An early generalized description of deposits in a cave in the Redwall Limestone on Horseshoe Mesa was written by Wasson (1899).

Short notes on mineral occurrences in Grand Canyon strata have been published by Blair (1981; calcite and other minerals near Havasu Falls, Havasu Canyon [Mile 156.8]), Bryan (1936; barite in the Redwall Limestone), McKee (1930a; vanadinite in the Redwall), and Sturdevant (1926b; calcite in the Kaibab Formation).

Waesche (1931, 1932) discussed the occurrence and significance of many economically important mineral deposits in the Grand Canyon. Occurrences of prize-winning mineral specimens were reported from all major stratigraphic units of the Canyon, from the metamorphic basement to the Kaibab Formation, including chrysotile asbestos, satin spar gypsum, garnet (almandite?), white quartz, banded gray and white flint, orthoclase, grayish-green muscovite, calcite, calcite on limestone, galena, hematite, chalcopyrite, and malachite.

In 1922, Rogers reported having found bisbeeite, a hydrous copper silicate, in samples from the Grandview Mine, then said to be the second known occurrence of that mineral. However, Gordon (1923) determined that the mineral is in fact the copper aluminum sulfate cyanotrichite. Another specimen of this mineral, collected in 1906 from the Grandview Mine and placed in the Harvard Mineralogical Museum, was discussed by Palache and Vassar (1926).

From the metamorphic basement complex, the mineralogical studies have been mostly related to analyses of the feldspars. The common pink mineral orthoclase has always been identified in the granitic rocks and pegmatites of the basement complex, based on external features. In 1932, Moomaw tested the mineral's refraction and specific gravity, confirming its identity. Thin-section analysis of Moomaw's sample was performed by Waesche (1933b), reconfirming its identity. However, Waesche also concluded that orthoclase is only a minor mineral in the granites; instead, the pink feldspar is more often microcline or plagioclase.

Campbell (1936) discussed occurrences of sillimanite and staurolite along the Colorado River about 0.8 km downstream from the mouth of Monument Creek at about Mile 94.0, below the (pre-dam) high-water level. In Lone Tree Canyon (Mile 83.9), staurolite was seen in occurrence with garnet.

VIII. GEOCHEMISTRY

As with the purely mineralogical studies, those of geochemistry are few in the Grand Canyon literature except where incorporated into petrologic work on economically significant deposits or in investigations of the metamorphic and igneous rocks. Publications cited here deal with general applications, using Grand Canyon examples only. (See also herein the sections which deal with the Early Proterozoic metamorphic basement complex, igneous strata of the Middle Proterozoic Unkar Group, and the Cenozoic igneous rocks of the western Grand Canyon.)

Giegengack et al. (1979) and Giegengack and Pardi (1982) have approached Havasu Creek (Mile 156.8) as "a natural geochemical laboratory." They have analyzed the waters of the creek and its calcium carbonate tufa to understand to what degree equilibration is taking place between atmospheric CO_2 and the C-isotope spectrum of HCO_3^- ions in solution in creek waters. Radiocarbon dating of the calcareous tufa has helped date periods of geomorphic effects caused by the creek. The basic conclusion is that equilibrium exists at least as far as the mouth of Havasu Creek, that alluviation took place between <3,000 yr B.P. to 900 yr B.P., and that active incision and reconfiguration of the creek had begun 700 yr B.P.

Measured $\delta^{18}O$ values in cherts have been reported in geochemical studies of Paleozoic and Proterozoic sediments. Knauth and Epstein (1976) reported values determined from cherts in the Paleozoic Kaibab, Supai (undivided), and Redwall Formations and in the Middle Proterozoic Bass Limestone. However, except for the Bass Limestone chert samples, the samples could have been obtained from localities not in the Grand Canyon; the authors did not list the sources of those samples. The data indicated age-related domains for $\delta^{18}O$ values, from which Knauth and Epstein interpreted paleoclimatic temperatures of about 52° C 1.3 Ga, decreasing through the Paleozoic from about 34° C to 24° C. Knauth (1982) reported that a 10-15° C warming trend can be observed at the end of the Proterozoic, corresponding with the Phanerozoic explosion of life. Feng et al. (1986) also briefly reported on the sulfur isotope composition of the Galeros Formation (Chuar Group), comparing its value with the higher value in the Altyn Formation (Belt Supergroup of Montana and Idaho).

Summons et al. (1988) described geochemical studies which showed hydrocarbon biomarkers in fossiliferous sediments of the Walcott Member of the Kwagunt Formation (Chuar Group). They noted that this stratum is the oldest yet found to contain gammacerane, indicating an organic contribution from the protozoa living in the Kwagunt waters.

McKee (1982, Chapter Q) reported on stable oxygen and carbon isotope analyses in limestones of the lower three formations of the Supai Group. The data were used to supplement information on the depositional environments of these formations.

In the Late Cenozoic volcanic rocks of western Grand Canyon, Matson et al. (1984) have examined the volatile components of amphiboles and xenoliths at Vulcan's Throne. The primary finding is that reduced carbon species found in the amphiboles support the hypothesis that oxygen fugacity in parts of the upper mantle is less than the quartz-fayalite-magnetite buffer. Total volatiles range from 1.27 to 1.75 wt. %, with H_2O as the principal volatile species.

In 1986, the first specialized geochemical studies relating to collapse-breccia pipes of the Grand Canyon region were published in abstracts. Landais (1986) examined organic matter associated with many pipes, suggesting that there may be a genetic relationship between the migratory products found in the pipes and the kerogens of the Brady Canyon member (beta member) of the Toroweap Formation. Rasmussen et al. (1986) examined authigenic sphalerite crystals in the breccia pipe deposits of the Hack 1 and 2 mines; they concluded that organic material was present in low-temperature (less than boiling) hydrothermal fluids during and after the deposition of sphalerite.

Active investigations continue toward understanding the genesis of breccia pipe mineral deposits. Ludwig and Simmons (1988) reported on the progress of Pb/U isotope studies. Wenrich et al. (1988) noted that the geochemical components of breccia pipes are "remarkably similar" between all pipes, although minor differences may be present between pipes north and south of the Grand Canyon.

IX. PALEOMAGNETISM

28th IGC Guidebook Chapters:

12. Preliminary polar path from Proterozoic and Paleozoic rocks of the Grand Canyon region, Arizona. (Donald P. Elston)
19. Paleontology, clast ages, and paleomagnetism of Upper Paleocene and Eocene gravel and limestone deposits, Colorado Plateau and Transition Zone, northern and central Arizona. (Donald P. Elston, Richard A. Young, Edwin H. McKee, and Michael L. Dennis)

THE GRAND CANYON offers a unique opportunity to those who study paleomagnetism, in that a major segment of the earth's history is exposed in one place. In addition, the relatively simple tectonic and thermal history of the region adds to the value of the Grand Canyon in these studies. Paleomagnetic investigations of the Grand Canyon strata were first published in 1955, and studies continue actively today.

Day and Runcorn (1955) reported on paleopole positions determined from the Middle Proterozoic Hakatai Shale and the Cambrian Tapeats Sandstone, but the data for the Tapeats pole position were disqualified by Creer et al. (1957). Runcorn (1955, 1956) and Doell (1955) reported the Hakatai pole position and calculations determined from shales of the Supai Group. Collinson and Runcorn (1960) calculated pole positions determined from measurements in red sandstones and siltstones of the Unkar Group, Tapeats Sandstone, and Bright Angel Shale, as well as from the Supai Group as exposed elsewhere than the Grand Canyon. Cox and Doell's (1960) important "Review of Paleomagnetism" listed data used in pole determinations from the Bass Limestone, Hakatai Shale, Shinumo Quartzite (all Middle Proterozoic Unkar Group), Tapeats Sandstone (Cambrian), and Permian strata of the Supai Group. The Bass and Hakatai data were again used by Runcorn (1964). All of these early data, though, were obtained through nuclear magnetic resonance and have not been "cleaned" to eliminate spurious data.

After the initial reports of the authors listed above, published information on paleomagnetic studies of the Grand Canyon strata ceased until Elston and Scott (1973) and Elston and Grommé (1974) made preliminary reports of paleopole positions in the Unkar Group and Nankoweap Formation. The significance of these reports is that they are the first studies of sequentially taken samples from a single section of strata in the Grand Canyon--Bass Limestone, Hakatai Shale, Shinumo Quartzite, Dox Sandstone, Cardenas Basalt, and Nankoweap Formation--across most of a 2,000-m-thick sequence. The interpretations of the sequence of Middle Proterozoic paleopole positions showed an apparent polar wandering path describing a complex double loop through the present central and north-central Pacific Ocean. The data supported similar findings from equivalent rocks elsewhere in North America. But one of the loops is the result of overprinting of the current magnetic field; there is only one loop. Elston and Scott's (1973) findings contributed to their decision to segregate the Nankoweap Formation from the Chuar Group, placing it as a single unit between the Unkar and Chuar Groups of the Grand Canyon Supergroup.

In 1979, Elston and Grommé published an abstract in which was indicated for the first time that paleopole data had been obtained from the Chuar Group. The data, together with those determined from the rest of the Grand Canyon Supergroup, were used by Elston and Bressler (1980) to correlate the paleomagnetic measurements taken from the Middle Proterozoic Belt Supergroup of Montana and Idaho. At that time they determined that the end of the apparent pole wander path for the Belt Supergroup overlays the beginning of the path determined for the Grand Canyon Supergroup. (As noted in the section of this volume on the Grand Canyon Supergroup, early workers had placed the Grand Canyon strata within the informal "Beltian" chronostratigraphic unit, ideally correlated with what now is known as the Belt Supergroup. Elston and Bressler effectively demonstrated that the two supergroups are not correlative.)

The paleomagnetic data obtained from the Chuar Group also assisted in Elston and McKee's (1982) decision to remove the Sixtymile Formation from the Chuar Group. They placed that formation separately, at the top of the Grand Canyon Supergroup. Paleopole positions determined from the Galeros, Kwagunt, and Sixtymile Formations were also reported by Elston (1986).

Elston and Bressler (1977) provided paleomagnetic data for Cambrian and Devonian strata of Arizona. Applying the same principles of sampling through continuous sequences of strata, as had been done in the Grand Canyon Supergroup, these authors sampled the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone (Cambrian), and the Temple Butte Formation (Devonian). A low-latitude paleomagnetic pole was indicated for Early and Middle Cambrian times, with a possible large but brief wandering to high latitudes in the Middle Cambrian. However, conclusive evidence for the high-latitude excursion is lacking (Elston, 1988a). By the Middle Devonian, the pole had moved to a "late Paleozoic" position (quotation marks are Elston and Bressler's). However, there is overprinting of the present magnetic field on the strata which contain carbonate cement. Elston and Bressler (1984) presented in an abstract a diagram that refined the Paleozoic polar path for North America.

In 1983, Lucchitta et al. wrote in an abstract that previously-reported anomalous paleomagnetic excursions seen in data from the Grand Canyon Supergroup could be put more into line with data from other time-correlative North American rocks if two units were reassigned in age: the ferruginous weathered zone on the Cardenas Basalt (where it is in association with a sub-Tapeats Sandstone erosion surface), and a small section of non-Nankoweap sediments at the Cardenas-Tapeats contact. However, the present magnetic field appears to have been overprinted on the samples from the weathered zone.

More recently, paleomagnetic studies by Elston (1988a-c) of the Middle and Late Proterozoic and Early to Middle Cambrian sediments of the Grand Canyon, coupled with sedimentological analyses and stratigraphic correlation, have indicated paleolatitudes near the equator and low elevations at times before and after Late Proterozoic glaciation. One hypothesis for the glaciation noted in strata of the North American craton calls for a high-latitude excursion by the craton, but there is an absence of reliable data to support that view. An alternate hypothesis, not generally favored, seeks a cause in the departure of the earth's spin axis from the plane of the ecliptic.

X. SEDIMENTOLOGY

28th IGC Guidebook Chapters:

3. Hydraulics and sediment transport of the Colorado River. (Susan W. Kieffer, Julia B. Graf, and John C. Schmidt)
21. Pre-Pleistocene(?) deposits of aggradation, Lees Ferry to west-central Grand Canyon, Arizona. (Donald P. Elston)
23. Pleistocene volcanic rocks of the western Grand Canyon, Arizona. (W. Kenneth Hamblin)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
4.5	Coconino Sandstone cross-beds
13.2	Esplanade Sandstone cross-beds
14.8	Esplanade Sandstone cross-beds
21.8	Mud cracks in block of Watahomigi Formation

Terrace Deposits and River Gravels and Channels

Lees Ferry, 0.8, 7.7, 52.1, 69.4, 70.7, 72.4, 87.2, 121.5, 122.0, 135.0, 179.0, 192.5, 196.7

OFTEN, SEDIMENTOLOGY is a primary component of stratigraphic work. But studies of the Grand Canyon strata that are purely sedimentological in content--or at least nearly so--are not abundant; however, they cover a wide variety of sedimentary environments, both fossil and modern. Some multidisciplinary monographs also incorporate sedimentology into their texts--McKee's various monographs, for example--but detailed discussions of them are largely ignored in this volume. This section will deal more with those works which are principally applications of sedimentology to certain problems.

Fossil

To workers familiar with the Grand Canyon, perhaps the first formation which comes to mind when sedimentology is mentioned is the Permian Coconino Sandstone, that interesting formation of fossil sand dunes. McKee (1933) made the first detailed study of the Coconino Sandstone. Included in that monograph are sections on composition and texture, and structures. In 1938, Reiche prepared a statistical analysis, using stereographic polar nets, of the structural features of the Coconino dunes. Plotted measurements of the cross-laminae indicated directions of dune sand transport largely to the present south. The immediate source area of the Coconino was presumably "the shore of the early Kaibab (Toroweap) sea, to the [present] west and northwest" (p. 931). In 1944, Decker provided an informal approach to test the origin of the Coconino's ripple marks. In that study, sand was taken from modern dunes near Tuba City, Arizona, and ripples were created on surfaces of the sand. Eolian and subaqueous environments were tested. Decker concluded, empirically, that the Coconino ripple marks were much more like those produced experimentally by eolian processes than those produced subaqueously. McKee (1945) examined small-scale structures in the Coconino, one of which (p. 322) was a specimen first reported by him which Reiche (1938) had interpreted as wetted-sand slump marks. Poole (1957, 1962, 1964) published three papers which analyzed paleowind directions of the late Paleozoic and middle Mesozoic times on the Colorado Plateau; these included the Coconino. Wind directions during deposition of the Coconino were largely from the northwest, north, and northeast, and were laid down on the arid coastal plain on the western margin of North America. McKee, in a 1979 paper contributed to by J. J. Bigarella, described the eolian sand structures of the Coconino, comparing the characteristics to other sandstones considered to be eolian in origin. In 1988, Blakey described "superscoops"--very large-scale eolian structures--in the Coconino.

In 1978 and 1979, Brand challenged the tenet of eolian deposition for all of the Coconino Sandstone. He published experimental evidence for subaqueous environments of deposition wherein he induced amphibians and reptiles to produce trackways on dry, damp, wet, and underwater sands. He observed that the tracks made on the underwater sands most resembled the Coconino tracks. (For a discussion of work on the origin of the Coconino tracks, see Spamer, 1984a, pp. 90-92.) In 1986, Blakey reported in an abstract that the cross-stratified sands of the Coconino are "<u>all</u>" (emphasis his) of eolian origin. Stratification types and depositional <u>processes</u> must be examined to determine the depositional environment; single morphologic characters are useless as definitive indicators (transcribed by Spamer at the meeting).

Of the formations overlying the Coconino Sandstone--the Kaibab and Toroweap Formations--McKee and Breed (1968, 1969) pointed out that studies of sedimentology in these formations had advanced little since McKee's (1938a) monograph on the formations. Unfortunately, this is still pretty much the case 20 more years after McKee's monograph. About the only significant works to include sedimentological analyses in this time have been in the work reported by Rawson and Turner (1974) and Rawson and Turner-Peterson (1979, 1980), Nielson's (1981) doctoral dissertation on the Kaibab and Toroweap Formations of southwestern Utah, and Clark's (1981) dissertation on these strata in the Grand Canyon region.

In the formations lower than the Coconino Sandstone, by far the most thorough studies have been in the strata of the Supai Group. The sedimentology of clay minerals has been discussed in the literature by Hauff and McKee (1979, 1981, 1982), who described seven types of these minerals in the Supai rocks. McKee (1982) analyzed many aspects of sedimentology in the Supai Group, in separate chapters entitled, "Conglomerates," "Sandstones," "Environment of deposition of sandstone bodies," "Minor sedimentary features, contorted structures, and homogeneous sedimentary rocks," "Aphanitic silica rock [jasper]," and "Evaporite deposits and magnesian carbonate rocks." McKee (1983b, 1984) also studied the sand deposits of the Rio Oronoco, Venezuela, as a modern analog of the sandstone body in the Pennsylvanian Wescogame Formation.

The newest recognized Grand Canyon formation, the Surprise Canyon Formation, has not yet been the subject of much sedimentological study, except in Billingsley and Beus' (1985) formal description of the formation. Grover (1986) and Shirley and Parnell (1986) published abstracts which briefly examined, respectively, the overall sedimentologic framework and the clay component of the formation, as used in paleoenvironmental analysis. Grover considered deposits in the Ord River estuary of North West Australia to be a modern analog to the Surprise Canyon Formation (transcribed by Spamer at the meeting).

For the Redwall Limestone, sedimentological studies have been reported in several chapters in the monograph by McKee and Gutschick (1969), "Sequence of sediments and unconformities," "Analysis of lithology," and "Interpretation of environments." Rawson and Kent (1979) also provided some data relating to this formation.

The Cambrian strata of the Grand Canyon have been studied most thoroughly by McKee and Resser (1945). In the first part of that monograph, on stratigraphy and ecology, by McKee, the pertinent sections are "Description of facies" and "Description of members and tongues." Wanless (1973), in his doctoral dissertation, prepared a significant re-evaluation of the depositional environment of the Grand Canyon Cambrian. His premise was that the Cambrian strata of the Canyon were laid down on a broad cratonic platform east of the Cordilleran miogeosyncline, rather than in a deepening offshore environment as traditionally interpreted. The depositional environment was probably a Bahama-type storm-dominated shelf. Wanless' critical evidence in this hypothesis was the presence of a 20-m-thick dololaminite sequence in the Muav Limestone of western Grand Canyon; this stratum and locale had been previously interpreted as the most-offshore and deepest marine sedimentary environment of the Grand Canyon Cambrian. Therefore, the classic sequence of transgressive-regressive cycles in the environment of a deepening continental margin, as interpreted by McKee and Resser (1945), was challenged by the well-documented new interpretations by Wanless. Unfortunately, this reinterpretation has not been well cited in the literature, probably due to the relative lack of study of the sedimentary history of the Grand Canyon Cambrian in more recent years. In 1981, Wanless published an abstract which reiterated the premise of his dissertation.

Merifield and Lamar (1970) had noted the presence of high-tidal-current sedimentary features in the Tapeats Sandstone of the Grand Canyon. This was used as partial evidence to suggest a closer distance between the earth and the moon during Late Proterozoic and Early Cambrian times; but the authors also admitted that some such features may have been only locally produced.

In 1983, Marsaglia and Klein reviewed "the paleogeography of Paleozoic and Mesozoic storm depositional systems." They noted that the Cambrian Bright Angel Shale, whose location they placed near the paleoequator, contains deposits debatably the result of storm action. Martin et al. (1986) described the depositional environment of the Bright Angel Shale as subtidal, affected by normal and storm-generated tidal currents.

The sediments of the Middle and Late Proterozoic Grand Canyon Supergroup also have been studied. Merifield and Lamar (1970) had examined evidence from the Grand Canyon Supergroup while studying paleotidal influences of a less widely separate earth-moon system; but they concluded that the Supergroup was probably deposited in several different environments. Furthermore, if some strata of the Supergroup are treated as non-marine in origin, no paleotidal information would be present.

The Chuar Group of the Grand Canyon Supergroup has been looked at in a quite different light in recent years. Traditionally, the interpretation of the Chuar depositional environment has been as a marine sequence laid down in a subsiding embayment on a passive continental edge. There is some evidence to suggest that the "depositional environment" was a complex of environments related to hypersaline lacustrine settings in a subsiding continental region, as summarized by Reynolds and Elston (1986; additional information transcribed by Spamer at the meeting). The evidence is based on centimeter-resolution measured sections and interpretation of depositional cycles and microfossils. Throughout the Chuar Group are found lacustrine, paludal, floodplain, mud flat, fluvial, playa, windblown, and related sediments.

In the Unkar Group, relatively little work has been done. Stevenson and Beus (1982), concluding work first reported by Stevenson (1974) and in Beus et al. (1974), divided the Dox Formation into four formal members and interpreted depositional environments as lagoonal to possible deltaic-plain, tidal flat, and fluvial.

Nitecki (1971) interpreted many supposed organic features of the Bass Limestone (basal Grand Canyon Supergroup) as inorganic. He was responding to Alf's (1959) and Glaessner's (1969) interpretations of organic remains in that formation. Nitecki had examined the basal white limestone member of the Bass 0.1 mile (0.16 km) east of Shinumo Creek on the Colorado River.

Modern

Sedimentary features of the modern Grand Canyon have also been examined. They fall into two general categories: sedimentary deposits of the Colorado River and Lake Mead, and travertine deposits of groundwater.

THE RIVER AND LAKE. McKee (1938b) was the first to publish on Colorado River flood deposits in the Grand Canyon. He described distinctive original depositional structures, post-flood reworking of sediments by wind, and contemporaneous deformational features. Many studies have been made along the Colorado River in the regime that exists after the 1963 closing of Glen Canyon Dam; these are described in the present volume in the section on Geomorphology. (See also the section, Hydrodynamics of the Colorado River.)

The creation of Lake Mead behind Hoover Dam has created a natural laboratory of the effects of impoundment in a variety of canyon reaches. The Colorado River in westernmost Grand Canyon has been flooded by the lake. Smith et al. (1960) published the Comprehensive Survey of Sedimentation in Lake Mead, 1948-49 which is the authoritative early report on the subject, researched just 10 years after the filling of Lake Mead. In sections of that report, Thomas (1960) studied the effects of the dam on the drainage basin tributary to Lake Mead, and Pampel (1960) surveyed the Lower Granite Gorge of the Grand Canyon between Bridge Canyon and Pierce Ferry.

TRAVERTINE. Evaporating groundwater, particularly from misty sprays at springs and creek falls, leaves mineral deposits in many places in the Grand Canyon. The most well-known deposits are the travertine accumulations along Havasu Creek (Mile 156.8) (e.g., Black, 1955), especially where it plunges over Havasu and Mooney Falls near the village of Supai, in the Havasupai Indian Reservation. Reilly (1961) has also briefly described other localities along the Colorado River, at Royal Arch Creek (Mile 116.5), Deer Creek (Mile 136.5), Stone Creek (Mile 138.8), Mile 147.5, Fern Glen (Mile 168.), Prospect Wash (Mile 179.4), Mile 213, Travertine Falls (Mile 230.5), and Mile 267.6.

Some travertine deposits are "fossil" accumulations. Szabo et al. (1986) reported on U-series dating of Grand Canyon travertine deposits. The ^{230}Th/^{234}U disequilibrium method was used to date deposits in the Kwagunt, Comanche, Cardenas, Elves Chasm, and Havasupai areas. Results showed age clusters at about 170 Ka, 110 Ka, 80 Ka, and 10 Ka, indicating paleospring sites. These data suggested wetter climates that at present, climates more conducive to carbonate deposition.

REGIONAL. In the Grand Canyon region, one form of sedimentation is that produced by faulting. Along a fault scarp, the accumulated eroded material at its base can be used to study what, if any, movement has taken place along the fault line. The first paper to take this view of sedimentation in the Grand Canyon region, and to compare it to observations made elsewhere, was by Longwell (1937). The Grand Canyon field area was the scarp of the Grand Wash Cliffs. (For later studies, see herein the section on Cenozoic Tectonics and Volcanism.)

XI. PROTEROZOIC PALEONTOLOGY

FOSSILS IN THE Middle and Late Proterozoic Grand Canyon Supergroup have been known at least since 1883, when Walcott reported a peculiar "Discinoid" fossil in the Chuar Group. Walcott did not elaborate on the nature of this fossil, but was more interested in its significance as a Precambrian life form; he did believe it was the remains of a shelled animal. In 1899, Walcott formally placed these "circular disc-like bodies" in the new genus and species Chuaria circularis (Fig. 8). This species has been the subject of interest for well over a century in world-wide literature (Spamer, 1988). It appears to be marginally useful as a Late Proterozoic index fossil, but as a macroscopic index fossil of this age its usefulness is amplified by being one of the few such fossils visible to the eye in the field (Spamer, 1989a).

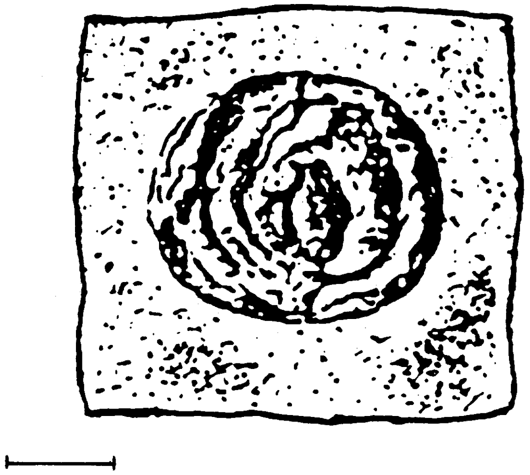


Figure 8. Lectotype of the Late Proterozoic algal fossil Chuaria circularis Walcott, 1899 (after Walcott, 1899, pl. 27, fig. 12). First collected by Charles D. Walcott in 1882 about 30 feet (9 m) below the top of the Awatubi Member of the Kwagunt Formation (Chuar Group, Grand Canyon Supergroup), on the east(?) side of Nankoweap Butte in easternmost Grand Canyon. Wrinkled disc-like form is the result of compaction of the originally spherical alga. Scale bar measures 1 mm. (Lectotype selected from type lot in the National Museum of Natural History, no. 33800, by Ford and Breed, 1972, 1973.)

Walcott also reported several other peculiar fossil-like remains from the Chuar Group; but he had some difficulty in explaining the presence of Paleozoic-like megafossils in demonstrably Precambrian formations. He nonetheless used their presence as a tool in correlating Precambrian strata across North America. Even though his reports were based on incomplete and sometimes erroneous data, they were sustained by his contemporaries and were cited without question into the 1930s. By that time doubts were arising about the existence of such complex animals in Precambrian time, but continued references to Walcott's fossils perpetuated the belief that these biotas did exist. This even led Hinds (1940) to provisionally regard the Grand Canyon Supergroup as earliest Paleozoic in age. Today, after reexamination, these fossils are regarded as pseudofossils (e.g., Ford and Breed, 1977).

Accepted Middle and Late Proterozoic fossils of the Grand Canyon Supergroup are today restricted to the macroscopic Chuaria, various microfossils, and stromatolites of several forms. Chuaria and the microfossils are known from the Chuar Group, while stromatolites are found throughout the Supergroup. Research on the significance of the Grand Canyon Middle and Late Proterozoic fossil communities (including the inferences made of the pseudofossils) is enabling workers to better fit the Grand Canyon strata into the world picture of early life. (For a review of investigations of the fossils in the Grand Canyon Supergroup, see Spamer, 1984a, pp. 60-68, 114-116.)

Research continues on the paleontology of the Grand Canyon Supergroup. Vidal and Ford (1985) presented an important comparison between the Late Proterozoic microbiotas found in the Chuar Group of the Grand Canyon and the Uinta Mountain Group of Utah. Comparisons were also made with the acritarch assemblages found in Late Proterozoic rocks of the southern Urals, U.S.S.R., the Russian Platform, and in Scandinavia, Svalbard, and Greenland. This constitutes the first precise comparison between all of these areas. Many taxa new to the Grand Canyon strata were also reported, including one new species (Vidalosphaeridium walcottii, from the Walcott Member of the Kwagunt Formation). Later, Vidal (1986) reported that acritarch-based biostratigraphic correlations in upper Proterozoic rocks of Scandinavia, Greenland, and North America indicate a Late Proterozoic pre-Varangerian age for the North American units, including the Chuar Group.

Horodyski (1986) reported that in the Chuar Group Chuaria circularis is stratigraphically more widely distributed than previously thought, and that the polyspecific genus of algal microfossil Melanocyrillium Bloeser, 1985 ("Melanospherillia" [nom. van.] of Elston, 1989), is found throughout most of the Chuar Group in mudstone, chert, and carbonate rocks. A new fossil horizon was reported in a "non-stromatolitic carbonate," a setting different from most other microfossil-bearing cherts in the Late Proterozoic strata. The diversity of lithologies which are now being discovered to contain microfossils also is allowing analysis of diagenic processes in the preservation of these organisms. However, Horodyski remarked, if the Chuar Group is thought to have been deposited in a hypersaline lacustrine(?) environment (see herein the section on Sedimentology), "The preserved biotas may not be representative of the late Precambrian oceans."

Applied research on the Grand Canyon Chuar Group microfossils has recently begun to appear in the literature. Halpern (1988) discussed the taphonomic effects of depositional and post-depositional processes on the surface sculpture and ultrastructure of the acritarchs. Since morphometric parameters are used in the identification of these biotas, it is necessary to distinguish between actual biologic features and taphonomic alterations to them. Horodyski (1988) has announced the first sighting of meiofaunal traces in the Chuar Group--elongate U-shaped structures less than 1 mm long seen in thin-sections of mudstone (cut parallel to bedding) from the Walcott Member of the Kwagunt Formation at Nankoweap Butte.

XII. PALEOZOIC-MESOZOIC PALEONTOLOGY

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
14.8	burrows and reptilian footprints in Esplanade Sandstone
34.8	Nautiloid Canyon
205.7	Ollenelus zone in Tapeats Sandstone

THE VERY FACT that most of the Grand Canyon's rock exposures are Paleozoic in age should suggest the likelihood of abundant fossils--and the assumption is correct. Hundreds of species are found, comprising invertebrates, vertebrates, and plants. Trace fossils occur throughout most of the sequence, too, including at certain localities abundant vertebrate and invertebrate trackways in the Pennsylvanian and Permian rocks. Every Paleozoic formation in the Grand Canyon is fossiliferous, representing Cambrian, Devonian, Mississippian, Pennsylvanian, and Permian Periods. It should suffice to say about the scant remains of Mesozoic strata very near the Canyon that only petrified wood has been found, in the Shinarump Conglomerate Member of the Chinle Formation that caps Cedar Mountain, just to the east of the Canyon (Noble, 1922). (For a synopsis on the Mesozoic strata of the Colorado Plateau, see Colbert, 1974.)

So much has been written about the Paleozoic fossils of the Grand Canyon, beginning with Newberry (1861; Fig. 9), and so much stratigraphic work in the Canyon depends upon the faunal evidence, that even a review of the development of paleontological studies in the Canyon can easily double the length of the present volume. The history of development of paleontological studies in the Grand Canyon has already been published (Spamer, 1984a), and the reader is directed to that paper for a review of Grand Canyon paleontology.

Two items of more recent special interest to the Cambrian paleontology of the Grand Canyon have been reported by Elliott and Martin (1987a,b). They described the occurrence of a new trace fossil, Angulichnus alternipes (1987a), and Chancelloria sp. (1987b; class Coeloscleritophora, phylum uncertain) below the middle of the Bright Angel Shale at Horn Creek (Mile 90.2). The authors suggested that the trace fossil might have been made by an arthropod perhaps like Habelia optata Walcott, 1912, of the Middle Cambrian Burgess Shale of British Columbia, Canada (1987a). (H. optata is an animal "not placed in any phylum or class of Arthropoda" according to Whittington, 1985, p. 138.) The report of calcareous spicules, identified as Chancelloria sp. (1987b), also corroborates the premise of there having been a Burgess Shale-like component to the Bright Angel paleofauna. Both occurrences are in lenticular heterolithic units which comprise most of the Bright Angel Shale. These units are composed of well-sorted very fine-grained feldspathic sandstone lenses and green fissile muds which represent post-storm deposition of suspended matter.

As a final note to this abbreviated section, the reader should be aware of the principle references on the Paleozoic paleontology of the Grand Canyon. McKee (1938a) is an important source on the faunal studies of the Permian Kaibab and Toroweap Formations, particularly with reference to their

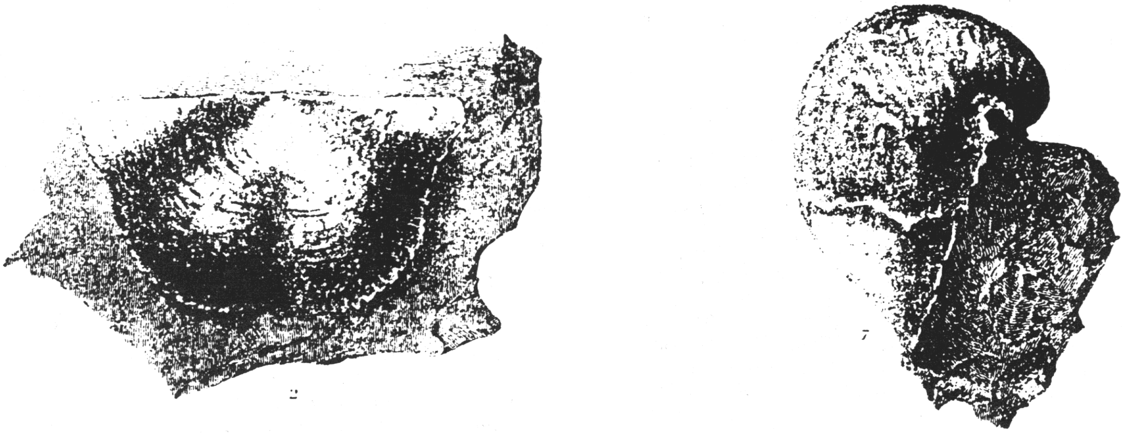


Figure 9. Squamaria ivesi (Newberry, 1861) (Brachiopoda); type specimens from the beta member of the Toroweap Formation near Diamond Creek, Grand Canyon. (Ives, 1861, pl. 2, figs. 2, 7.)

distribution in facies of these formations. McKee (1982) and several papers by other authors, are the best sources for data from faunal studies of the Pennsylvanian-Permian Supai Group. The ichnofauna of the Coconino Sandstone, Hermit Shale, and Supai formation (i.e., Wescogame Formation of the Supai Group) was described by Gilmore (1926, 1927, 1928); but his work is now taxonomically quite outdated (see Spamer, 1984a, for remarks). The remarkable paleoflora of the Permian Hermit Shale was described by White (1929), still the sole comprehensive reference on the subject. Billingsley and McKee (1982) included data on the fauna of the Late Mississippian Surprise Canyon Formation. The Devonian Temple Butte Formation is sparsely fossiliferous in the Grand Canyon, and information on the subject is scattered through the literature.

XIII. CENOZOIC PALEONTOLOGY

28th IGC Guidebook Chapter:

19. Paleontology, clast ages, and paleomagnetism of Upper Paleocene and Eocene gravel and limestone deposits, Colordo Plateau and Transition Zone, northern and central Arizona. (Donald P. Elston, Richard A. Young, Edwin H. McKee, and Michael L. Dennis)

TWENTY MILES (32 km) south of Grand Canyon Village, along the old Grand Canyon Railway, fissure deposits near the Anita Mine have yielded a late Blancan(?) (Late Pliocene?) local fauna (Hay, 1921; Kurtén and Anderson, 1980). A review of work on this fauna has been compiled by Spamer (1984a, pp. 99-104). The Cenozoic paleontology of the Grand Canyon-proper is restricted to Late Pleistocene-Holocene deposits of caves and other cloistered sites. Most of the material is preserved in dung deposits and packrat (Neotoma spp.) middens. Faunal and floral elements are preserved and have been well studied.

Investigations of the Late Pleistocene-Holocene fauna and flora, and of the paleoenvironments of those times in the Canyon, are virtually inseparable. The present warm, dry climate of the Inner Canyon has permitted the preservation of more than 40,000 years of deposits, particularly in caves. The inhabitants and transient users of those caves have left their remains in remarkably condition for study; the twigs, branches, and pollen left there provide a continuous climatic record for various elevations within the Canyon. Indeed, the Canyon has played an important role in the study of altitudinally-controlled zonation of biologic communities, ever since Merriam (1890) first developed the concept of Life Zones in the Grand Canyon region.

The Late Pleistocene environment of the Grand Canyon was first studied when Rampart Cave (Mile 274.9) was discovered in western Grand Canyon (Harrington, 1936; Schenk, 1937; Wilson, 1942; Baldwin, 1946; see also Harington, 1972, for a review of studies to that date). The cave contains thick deposits of dung left mostly by the extinct Shasta ground sloth, Nothrotheriops shastense (Sinclair, 1905), containing plant remains from Late Pleistocene time. Tragically, Rampart Cave is no longer a useful scientific site. The fossiliferous deposits were set afire by vandals in 1976 (Priehs, 1976; Anonymous, 1977; Blair, 1980). The development of studies of the Grand Canyon Pleistocene-Holocene has been outlined by Spamer (1984a, pp. 104-109), along with a discussion of the Grand Canyon as a corridor and barrier to species dispersal (pp. 109-114). Important references are scattered through the literature, with the more recent principal investigators being Kenneth L. Cole, Paul Martin, Jim I. Mead, Arthur M. Phillips III, and Thomas R. Van Devender.

With the loss of Rampart Cave as a source of reliable Late Pleistocene climatic, faunal, and floral data, investigators must now rely upon other locales to supply that information. Rampart Cave was the only known locality in the Canyon to contain the remains of Nothrotheriops shastense. The only other known major cave deposits in the Canyon are in Stanton's Cave (Mile 31.7), in the Marble Canyon section of the Grand Canyon. An exhaustively detailed study of this cave and its paleoecology has been edited by Euler (1984); it contains 13 chapters, by Euler and other authors, on archaeology, geology, zooarchaeology, and paleoecology. This work expanded on the earlier results of research conducted under a grant from the National Geographic Society (Euler, 1978).

Rampart Cave is not known to have been occupied by man, so the data retrieved there are certain to have been unaffected by anthropomorphic disturbance. The fact that Stanton's Cave had been occupied by man at various times, however, does add the anthropological dimension to paleoecological studies. Human bones are not known from that cave; only cultural artifacts exist. The unfortunate aspect of the human use of Stanton's Cave is that the stratified deposits within it, containing bones and plant remains of many Late Pleistocene-Holocene species, have been disturbed to some extent. Incidentally, this site derives its name from another time of human use. Robert B. Stanton's survey for a railroad along the Colorado River used the cave to cache their equipment between two field seasons in 1890. That act also no doubt disturbed some of the deposits.

O'Rourke and Mead (1985) discussed the Late Pleistocene-Holocene pollen record from two caves in the eastern part of the Grand Canyon. The data supplemented ongoing research into the paleoecology of the Canyon during those times, when life zones were depressed in altitude into the Canyon, reflecting a generally cooler, wetter period than that of today. The actual picture is much more complicated, and the reader is referred to the various references noted above and by Spamer (1984a).

XIV. STRUCTURAL GEOLOGY

28th IGC Guidebook Chapters:

5. Modern tectonic setting of the Grand Canyon region, Arizona. (Peter W. Huntoon)
7. Phanerozoic tectonism, Grand Canyon, Arizona. (Peter W. Huntoon)
17. Fission-track dating: Ages for Cambrian strata, and Laramide and post-middle Eocene cooling events from the Grand Canyon, Arizona. (Charles W. Naeser, I. R. Duddy, Donald P. Elston, T. A. Dumitru, and P. F. Green)
26. Gravity tectonics, Grand Canyon, Arizona. (Peter W. Huntoon)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
0.5	Echo Cliffs monocline
3.4	graben
35.7	36-Mile joint system
39.8	36-Mile joint system
40.5	36-Mile joint system
43.3, 43.7	Emminence Break graben
49.7	Emminence Break fault
64.5	thrust fault in Dox Sandstone
65.4	Palisades fault and monocline
68.5	Butte fault
69.0	Basalt Canyon fault
81.1	Vishnu fault
87.5	Cremation fault (associated with Grandview monocline)
88.0	Tipoff fault
88.3	Bright Angel fault
98.0	Slate Creek fault
99.0	fault associated with Crazy Jug monocline
115.5	Monument fault
123.2	Butchart fault
138.7	Sinyala fault
148.0	Matkatamiba syncline
156.6	Supai monocline
171.2	Mohawk-Stairway fault
179.0	Toroweap fault
190.7	first appearance of Hurricane fault zone
196.3	Lone Mountain monocline
198.0	Parashant graben
252.2-255.4	Meriwitica fault
275.5	Rampart Cave fault
278.0-278.5	Grand Wash fault
285.	Wheeler fault

THE FAULTS and monoclines of the Grand Canyon region are often dramatic in appearance; they were recognized even on the first expeditions into the area. The diversity of structural types is not great and, together with the easily visualized simple stratigraphy, it would seem that the structural history of the Canyon should be rather easily determinable. As the reader by now suspects, this is not so. Reactivation and reverse movement along some faults complicates the structural history of many areas. Reactivation of Precambrian faults during Phanerozoic time has created monoclinal flexures, faulted at depth. The Cenozoic structural history is sometimes directly related to much earlier effects along some structural zones. In this section is examined the development of studies of the pre-Cenozoic structural features; the Cenozoic tectonic and volcanic history of the Canyon is covered in a later section.

The earliest examinations of the structure of the Grand Canyon region were made by the first scientific explorers. Newberry (1861) and Powell (1875) both discussed the great physiographic features that are the result of structural influences--most notably the boundaries of the Kaibab and Coconino Plateaus. Dutton (1882) discussed at length the influence that the regional structure has had on the development of the Canyon itself.

The first detailed look at structures in the Grand Canyon was not published until Walcott (1890) described the Butte fault of eastern Grand Canyon (Mile 68.5) (although he first took note of it in 1884). He observed that the Precambrian fault was related to what we call the East Kaibab monocline, and also observed that reverse movement took place along the fault during the Tertiary. Walcott was able to determine that the great buttes of easternmost Grand Canyon are the result of differential erosion of the strata to the west of the fault. He compared the fault type and its history to others and said that the only analogous fault was a portion of the Hurricane fault north of Toquerville, Utah. This was the seminal paper in the systematic study of Grand Canyon structural geology.

Detailed analyses of Grand Canyon structural features did not really begin to appear until well into the 20th Century. Ransome (1908b) had briefly described the offset of strata along the Bright Angel fault (Mile 88.2), and observed that post-Paleozoic movement had taken place along the fault; but that paper was more a description of the strata of the Grand Canyon Supergroup. Strahler (1944) described the structure and geomorphology of the East Kaibab monocline, following up his studies with a similar paper (1948) on the West Kaibab fault zone. Babenroth and Strahler (1945) described the East Kaibab monocline in much more detail than did Strahler in 1944; this study examined the 150-mile (240 km) length of the monocline from the San Francisco Peaks volcanic field in northern Arizona to Bryce Canyon, Utah. Van Gundy (1946) described the faulting seen in the eastern Grand Canyon.

In two papers in 1955, Kelley examined the placement and tectonic relationships of the monoclines of the Colorado Plateau. He delineated a "tectonic Colorado Plateau," differing in areal extent from the physiographic Colorado Plateau. In its western portion, at the Grand Canyon, he placed the tectonic boundary somewhat east of the physiographic boundary (the Grand Wash Cliffs, Mile 277), delineating the western tectonic boundary just west of Grand Canyon Village (1955b). Several monocline types were depicted by Kelley (1955a), one of them being the "broad (Kaibab) type."

In the 1960s, workers began to turn their attention to subject-specific and problematical areas of structural geology in the Grand Canyon. The Canyon here, at it has in other disciplines of geology, lent itself to the development of basic principles in the study of structural features. Probably the greatest contribution that the Canyon has made in this discipline is in the understanding of deep structure of monoclines, which began to be studied in the late 1960s and 1970s.

Hodgson (1961) studied for the first time the jointing that is seen in the Bright Angel area of the Grand Canyon. He took note of the predominance of northeast- and northwest-trending joint systems in the Paleozoic strata (mostly the former). He deduced that they partially reflect major structure directions in the metamorphic basement rocks, and that the Precambrian structural patterns overall probably determined the patterns of folding and faulting of all later sedimentary strata.

Hamblin (1963b) published in an abstract the first modern attempt to describe the origin of the "reverse drag" seen on the downthrown side of some normal faults in the western Colorado Plateau. He elaborated on his work in a paper published in 1965. These seemingly anomalous features are an alternate response to the tectonic forces that otherwise produce antithetic faulting. If a fault plane is curved at depth, faulting creates lateral tension, potentially allowing a void to appear opposite the upthrown side of the fault. Flexible infilling of strata on the downthrown block creates the "reverse drag" phenomenon. These features are well illustrated in the western Grand Canyon region.

The structural history of the West Kaibab fault zone was reexamined for the first time since Strahler's (1948) work, by Huntoon (1969). Huntoon was beginning the first studies of the hydro-mechanics of the groundwater system of the Kaibab Plateau, and this paper was a product of that work. Since structure and groundwater hydrology are intimately related in the Grand Canyon region, all subsequent work on structural geology in this area had direct bearing on groundwater research there (see the section herein, Groundwater Hydrology). Huntoon later went on to publish important papers concerning the structure of Grand Canyon monocline and fault systems: the deep structure of monoclines (1971), high-angle gravity faulting in eastern Grand Canyon (1973), studies of the Bright Angel and Eminence faults (Huntoon and Sears, 1975), and the genesis of Grand Canyon monoclines (1981a). In addition, he worked on post-Paleozoic structural features (as noted in the section herein, Cenozoic Tectonics). He also delineated the structural features of the Grand Canyon region (as noted in the section on Cartography).

In the 1970s, special interests developed in studies of the great fault systems in the Grand Canyon. Huntoon and Sears (1975) examined the Bright Angel (Mile 88.2) and Eminence (Mile 49.7) faults, while Shoemaker et al. (1974, 1978) looked at the Bright Angel and Mesa Butte (north of the San Francsico Peaks) fault systems, and Pierce (1977) offered an abstract of Early Permian movement of the Hurricane (Mile 190.7) and Grand Wash (Mile 278.0) faults of western Grand Canyon. Warner (1978) identified the Sinyala (Mile 138.7), Bright Angel, and Mesa Butte fault systems as part of the great Colorado Lineament, a >1,100-km-long, 160-km-wide complex of northeast-trending Precambrian faults extending from the Colorado Plateau of Arizona to the Rocky Mountains of Colorado and into the subsurface of the mid-continental region.

Investigations into the deep structure of monoclines, made possible by the Colorado River's deep incision through the Kaibab upwarp, began with Huntoon's (1971) initial look at the monoclines of eastern Grand Canyon, and with Reches' (1976, 1977, 1978) development of a general theory of monoclines based in part on studies of the relatively small Palisades monocline, a branch of the East Kaibab monocline in easternmost Grand Canyon. (The Palisades monocline does not cross the Colorado River.) Reches explained that the exposure of the Palisades monocline in three dimensions, and its small geographic extent, were principal reasons for selecting that monocline for study. He also noted that any general theory of monoclines must be able to explain the features of the Palisades monocline, which is a double flexure whose slope varies according to structural level and lithology, and which is affected by a high-angle basement fault. The general theory of monoclines was elaborated upon by Reches and Johnson (1978). The overall monoclinal fold pattern of the Colorado Plateau was examined by Davis (1978). The Palisades monocline was also discussed by Freund (1979), who noted that stratigraphic draping above reverse faults can account for all observed phenomena in monoclines.

XV. GROUNDWATER HYDROLOGY

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
31.9	Vasey's Paradise
274.3	Columbine Falls

Springs

30.3, 30.5, 34.1, 48.0, 51.0, 133.6, 137.9, 147.8, 155.4, 181.3, 259.5, 272.9, 274.0

Travertine

56.3, 61.3, 95.3, 114.4, 116.6, 124.2, 135.0, 151.0, 173.2, 175.4, 176.5, 179.5, 229.2, 259.0, 259.5, 274.2

Salt Springs

61.0, 63.0, 127.4

THERE ARE NOT many springs in the Grand Canyon. Where they do occur they usually are associated with structural features. In the science of groundwater hydrology, the Kaibab Plateau has been the most intensively studied area in the Canyon, but the history of such studies is relatively short. Except for a brief note by Van Hise (1904, p. 411), there is virtually no early work on the significance of the occurrence--stratigraphically or geographically--of the Grand Canyon springs. Van Hise cited the Canyon in respect to hydrology and spring flow in arid plateau lands cut by deep canyons, where groundwater can in places be more than 1,000 m below the surface. He also recognized (pp. 412-413) the karstic sink effect of the "open limestone area" of the Grand Canyon region--the Kaibab Limestone cover of the plateaus that surround the Grand Canyon.

Only one general survey of springs through the Grand Canyon exists, that of Johnson and Sanderson (1968). The streamflow data reported by these authors cover the years 1923 to 1967, although not consistently for all tributaries. The data report only basic statistics of flow measurements.

In the Grand Canyon, springs are affected by structure and lithology. There is virtually no surface runoff except during storms, the result of percolation of water directly into the karst surface of the surrounding plateaus. In the Kaibab Plateau area of the Grand Canyon, the strata dip generally southward. Gravity percolation in permeable strata thus allows water to readily move toward the north wall of the Canyon along dip, while water in the South Rim area generally travels away from the Canyon; hence the paucity of South Rim springs compared to those of the North Rim. Strata that are most permeable to the movement of groundwater act as aquicludes, and water movement is forced to follow those surfaces until an outlet is reached. The outlet may be an incised side canyon, where seeps form at the aquiclude. More often, the outlet from the aquiclude will be a structural feature that allows channeling of the water toward deeper strata. Such channeling also directs water movement toward the canyon walls, where springs gush at the outlet of the channel. Caves often develop along such features, and most of those which exit to open air have been explored.

Roaring Springs Cave, the source of water for Bright Angel Creek (Mile 87.7), was explored as early as 1935 (Seagle, 1935). It is one of three caves at that site. This is a significant spring in the Grand Canyon because it is the sole source of water for visitors and employees at the Grand Canyon. Its waters are treated and piped to Grand Canyon Village (see herein the section on Engineering Geology). The position of Roaring Springs is along the Bright Angel fault and at the Muav aquifer, at the base of the permeable Muav Limestone above the impermeable Bright Angel Shale. The Muav aquifer is the most productive aquifer in the Grand Canyon.

The problem of water supply for Grand Canyon Village, the most heavily visited locale of the Grand Canyon, reached a critical point by 1961. The anticipated expansion of services at the village was going to require more water than could be supplied from the current source, the spring at Indian Gardens along the Bright Angel Trail. The Indian Gardens spring, one of the few South Rim water sources, is also controlled by the Bright Angel fault. Metzger (1961) published a study of spring quality and productivity in the eastern Grand Canyon and determined that additional development at Indian Gardens, and at Hermit Creek (Mile 95.0) to the west, was possible but potentially cost-prohibitive. He noted that North Rim sources might have to be investigated, a suggestion which was adopted when the Roaring Springs source in Bright Angel Canyon was developed.

Beck (1965, 1967) and Beck and Dunn (1967) studied the hydrodynamics of the Muav aquifer; they concentrated mostly on the hydrology and structure of the Crazy Jug area of the Kaibab Plateau but used that area as a model for the hydrologic characteristics of the Kaibab Plateau generally.

Studies of regional groundwater dynamics and supplies also began at about this time. Cooley et al. (1969) published on the regional hydrogeology of the Navajo and Hopi Indian Reservations to the east of the Grand Canyon, where water sources are largely from wells. They noted that in the Grand Canyon area wells and springs yield water in the Kaibab Limestone, Coconino Sandstone, Supai Group, Redwall

Limestone, Muav Limestone, and Tapeats Sandstone. Formations not bearing water are the Toroweap Formation, Hermit Shale, and Bright Angel Shale. This study was supplemented by Cooley (1976), who reported on spring flow from pre-Pennsylvanian rocks in the southwestern Navajo Indian Reservation, near the Grand Canyon. The Marble Canyon and Little Colorado River gorges were part of the study area. Also, in Marble Canyon Reilly (1967) reported a 1963 sighting of a clear-water spring beneath the middle of the Colorado River (muddied by recent local storm runoff) where the Stanton's Cave fissure crosses the river (Mile 31.7). The Stanton's Cave spring is dry.

In 1967, Huntoon published an abstract on the springs of the Tapeats Amphitheater of Grand Canyon. This was the first result of a growing research interest that would lead him to investigate the groundwater hydrology and structural geology of the Grand Canyon region. His doctoral dissertation (Huntoon, 1970) described the hydromechanics of the southern Kaibab Plateau, wherein he noted that about 70 percent of the measurable water leaving the plateau discharges from three springs in the Tapeats Amphitheater, controlled by the West Kaibab fault zone. Later hydrological studies by Huntoon looked at karstic groundwater basins of the Kaibab Plateau (1974c), stratigraphically-affected groundwater prospecting failures on the Hualapai Plateau (1977b), tectonics and hydromechanics in the western Grand Canyon (1977c), and fault controls of groundwater circulation under the Colorado River in Marble Canyon (1981b). R. Young (1978) also made remarks on the groundwater prospecting failures on the Hualapai Plateau. He believed that small structures have played a greater role than previously thought in the movement of groundwater in the Grand Canyon region. Huntoon (1978) replied to each of Young's remarks, providing both clarified and new data to substantiate the conclusions he published in the 1977 paper.

For the Kanab area of Coconino and Mohave Counties, Arizona, two maps showing groundwater conditions in 1976 have been prepared (Levings and Farrar, 1979).

XVI. GEOMORPHOLOGY

28th IGC Guidebook Chapters:

4. Physiographic fetures of northwestern Arizona. (George H. Billingsley and John D. Hendricks)
29. Small meteorite impact in western Grand Canyon, Arizona. (Peter W. Huntoon)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
33.0	Redwall Cavern
46.6	Triple Alcoves
135.2	narrowest point of river; 76 ft (23 m)
142.0	begin river anticlines

Rockfalls

7.2, 18.5, 26.8, 44.4

Landslides

10.0, 175.0, 189.6, 205.5, 205.8, 209.5, 266.5
266.5 (reactivated)
135.0 (Surprise Valley landslide)

The Grand Canyon is, by the very nature of the term, a grand geomorphic feature. Two papers (Lucchitta, 1984, 1988) outline the overall development of the canyons and plateaus of northern Arizona. But descriptions of the form--and interpretations of the origin--of the Canyon date back to Ives' (1861) and Newberry's (1861) reports, and even earlier. In fact, the first notice of the Grand Canyon in scientific literature appeared in print at about the same time that the Ives Expedition was traversing the Canyon region. The description is sketchy at best, but it does constitute the first mention of the Canyon in a scientific context.

In a paper published in 1857 (but already accepted for publication in January 1856, a year before the Ives Expedition set out from Yuma, Arizona), Hitchcock discussed various forms of earth sculpture. In Part II of that paper, entitled, "On the Erosions of the Earth's Surface, Especially by Rivers," he described a variety of different river valleys, organized mostly by the lithology of the strata into which they were incised. In a subsection, "In Limestone chiefly," he listed (Hitchcock, 1857, p. 116):

> "22. Big Cañon on the Rio Colorado of the West. -- This occurs in W. long 115° and N. lat. 36°; but I have not been able to find any detailed account of its extent. Where Capt. Sitgreaves struck a cañon on the Zuni, or Little Colorado, which he was assured extended to the Rio Colorado, its depth was 120 feet, less probably than that of the Big cañon. -- Sitgreaves' Report to Government, p. 8."

This constitutes the entire note on the Grand Canyon. His observation that the Canyon is at longitude 115° W. is about 100 miles (160 km) too far west; the Canyon more or less lies between the 113th and 114th meridians. He may have extrapolated from the positions reported by Sitgreaves along the lower Colorado River, where it flows southward a little to the east of the 115th meridian.

Hitchcock's reference to Sitgreaves' report referred to the volume published in 1853 by Captain Lorenzo Sitgreaves, U.S. Army Corps of Topographical Engineers, but which is largely composed of scientific reports by members of the expedition. That expedition was undertaken in 1851-1852 and was the first organized exploration of northern Arizona. The Sitgreaves party had attempted to reach the Grand Canyon but turned away near the San Francisco Peaks because of dwindling supplies and ailing pack animals. They had reached the Grand Falls of the Little Colorado River, northeast of present-day Flagstaff, whose drop they had erroneously estimated at 120 feet (36.6 m) (which actually fall 185 feet [48.4 m]).

Hitchcock (1857) attempted to determine relative ages of the various stream valleys he described in his paper. He began (p. 125):

> "I have referred to some examples of this work [erosion], commencing at the earliest period, or during the first emergence and drainage of land: and also some cases referable to the last upward movement. The following cases seem most probably to have been produced at an intermediate period, but precisely when...I am unable to determine."

He included in that list (p. 125):

> "3. The cañons of the southwest, described in this paper. Very old."

Brown (1869a,b), who has never been cited in the Grand Canyon literature, had read of the Ives Expedition to the Grand Canyon, but in relating the data to his own discourse "On the Formation of Fjords, Cañons, and Benches," became hopelessly overwhelmed by misunderstanding and conjecture. The six-page "abstract" (1869a) includes a brief mention of "the cañon of the Colorado in Sonora [Mexico]" or "the great cañon of the Colorado River." But he confused the overall interpretation by comparing the "gorge" (his quotation marks) of the Columbia River of Oregon, and the canyons of the Fraser River of British Columbia in Canada, with the Colorado River canyons. He attributed these landforms "to have been caused by the force of the rivers which flow through them when these rivers contained...a greater body of water than at present" (p. 146). The source of this greater body of water was said to have been glacial reserves. In his longer text (1869b, p. 124), Brown referred to the possibility of "sunken rocks or high falls" along the Colorado River in the Grand Canyon. The supposition of "sunken rocks" was a foregone conclusion; the existence of "high falls" was a prediction that did not bear out.

The more traditional descriptions of the landform we call the Grand Canyon--those that are full of superlatives--came with the first explorations of the Canyon. Newberry's (1861) formal geologic descriptions of the Canyon were more matter-of-fact than were those of the expedition leader, Ives, despite the fact that Ives thought the whole region worthless (see the General Introduction to the present volume). The descriptions of the landforms were pretty much just descriptive, but Newberry did impress upon the reader the reasons for interpreting the origin of the Canyon as caused by running water, that its genesis was neither glacial nor volcanic. The fact that from the outset there have been no debates over the process of the origin of the Canyon is perhaps remarkable; or, more probably, the evidence is just too overwhelming to reach more than one conclusion.

When John Wesley Powell travelled the Colorado River through the Grand Canyon in 1869 and 1871-1872, he took note of the many landforms of the canyon country of the Colorado Plateau. He described them in detail first in 1873 (Powell, 1873a), classifying two basic orders of valleys--1st order valleys, which are transverse valleys, running across the strike of strata; and 2nd order valleys, longitudinal valleys, those running along strike. Within each order he proposed three forms, the form depending upon how the valleys pass through the folds and axes of the warped strata. Then, he also noted that "intervening depressions caused by erosion, [are] cañon valleys..." (p. 463).

Powell described the physical features of the Colorado River in his formal report of the expeditions (Powell, 1875, Part 2). For the most part, Powell's writings were descriptive, with less emphasis on process geomorphology.

The first detailed examination of Grand Canyon geomorphology was put to words and illustrated in Dutton's (1882) monograph and atlas. It was the first grand survey of the whole of the Canyon with an eye toward the processes of formation; from the scale of individual cliffs and slopes, to the sculpting of alcoves and amphitheaters, to the formation of side canyons, to the creation of the great complex of canyons called the Grand Canyon. The artistry of William H. Holmes and Thomas Moran, whose illustrations are magnificent works of art in their own right, graced the pages of Dutton's publication. They showed the grandeur of the Canyon, and they exhibited in minute detail the evidence that Dutton had had before him when he made his astute observations and drew his clear conclusions.

The general picture described above, regarding early understandings of the geomorphological context of the Grand Canyon, has been discussed in detail by Chorley et al. (1964). This publicatioin elaborated on the geomorphic work of Powell, Dutton, and other western American geologists. Additionally, Gilbert (1890) noted in a lengthy abstract on the strength of the earth's crust that some 350 mi^3 (1,459 km^3) of rock had been eroded from the Grand Canyon. (Lucchitta, 1988, gives an updated figure of 1,000 mi^3 [4,160 km^3].)

When William Morris Davis seized the opportunity to include the Grand Canyon into his hypothesis on the development of landforms, he inaugurated a period of Grand Canyon research that has continued unabated to today. Davis alone published lengthy papers and short articles on the Canyon from 1900 to 1929 (see in Spamer, 1983); and it was he who wrote the National Academy of Science's biographical memoir of John Wesley Powell (Davis, 1915a). The most significant of Davis' Grand Canyon region papers were those published in 1900, 1901, and 1903, wherein he described the region in detail, of course in the light of Davison geomorphology. This produced the first major diversion from hypotheses on the origin of the Colorado River, held by Powell, Dutton, and Gilbert (see the section herein, Origin and History of the Colorado River and Grand Canyon).

The first challenger to Davis in the analysis of landform development was Walther Penck. His hypothesis, published in 1924, was not translated into English until 1953. American geomorphologists did not readily accept Penck's ideas, most probably above all because of Davis' well-established influence upon the American school of geomorphology. Furthermore, Penck's ideas did not apply themselves well to the landforms of the American West, where besides the work by Davis the geomorphic concepts developed by Powell and Gilbert were dominant.

Penck's hypothesis of landform development was not greatly different from that of Davis; it still retained the concept of erosion to base level which, when uninterrupted, created a peneplain--but in Penck's view this was only an exceptional case. What distinguished Penck's approach was his law (1953, p. 138), "flattening of slopes always takes place from below upwards." This supposition discarded the Davisian concept of the lying-back of eroding slopes; it instead promoted a moving-back under unchanging intensities of erosion in the actively eroding portions of hillsides. A change in hillslope form was the result of a change in erosional intensity.

Like Davis, Penck drew upon the Grand Canyon to illustrate his hypothesis, but not to any great extent. He wrote (1953, p. 128), "The development of peneplains on the scarp summits, like that of the broad ledges in the higher parts of the Grand Canyon (Colorado), is related to outcrops of resistant beds of rock at a lower level, and not to the banks of the streams incised deep below. He added (p. 129), "The breaks in slope gradients of the higher, wider part of the Grand Canyon is related to the upper edge of the steep sides of the inner canyon; and these steep slopes to the Colorado River itself." Penck (1953, p. 177) also discussed "ledge-like denudation terraces," about which he noted, "The most famous example is that of the platform of the Colorado River," referring either to the Tonto Plateau or the Esplanade of the Grand Canyon.

Overall, though, geomorphological studies of the Grand Canyon in the era between Davis and the authors of the 1960s and later are sketchy, addressing only specific problems or isolated localities.

In 1913, Keyes published an abstract on the "angular amphitheaters of the Grand Canyon." He noted that the rectangular map view of many of the amphitheaters, points, and buttes are attributable to "the double system of master-joint structure." This pertains to the northeastward- and northwestward-trending systems of structural features seen the Grand Canyon region. In 1927, Matthes discussed in an abstract (1927a) the profound influence that secondary faults have had in the development of Grand Canyon topography. He also observed that many of the solitary buttes of the Inner Canyon are within their own separate structural blocks. McKee (1929), in an informal article, supported Davis' hypothesis of consequent drainage on the Kaibab Plateau, but noted that the hypothesis did not explain the origin of some north/south-trending valleys. McKee pointed out that these valleys were formed along fault traces.

This trilogy began the long period during which only modest inroads were made toward understanding the topographic development of the Grand Canyon. Some reports were singular notes of interest, as was Grater and Hawkins' (1935) article on a new rockfall in the Coconino Sandstone.

McKee and Schenk (1942) wrote a paper on "The Lower Canyon Lavas and Related Features at Toroweap in Grand Canyon." Relying on the stratigraphic relationships between various lava flow remnants adhering to canyon walls, inter-flow sediments, hanging gravels, buried tributary canyons, and structural evidence, the authors inferred a sequence of physiographic events, a view still held today. Maxson (1949) also wrote about the lava flows and paleodams, and took note of a possibly undocumented lava dam downstream from Mile 194.5.

The lava flows in the Toroweap area (about Miles 177.-187.) are certainly among the more intriguing of the Grand Canyon's physiographic features. They are so pronounced as to be unmistakable in their cause and effect: volcanic vents on the rim of the Canyon, most notably Vulcan's Throne, cascaded lavas over the rim and into the river gorge, temporarily damming the river. John Wesley Powell was the first geologist to note these lava flows, the effects of which he described in a most eloquently brief paragraph (Powell, 1875, p. 95):

> "What a conflict of water and fire there must have been here! Just imagine a river of molten rock, running down into a river of melted snow. What a seething and boiling of the waters; what clouds of steam rolled into the heavens!"

The lava dams of Toroweap were also studied by Hamblin (1970b) (but for more on the volcanics of the western Grand Canyon see herein the section, Cenozoic Tectonics and Volcanism).

A number of papers on geomorphology and structural relations on of the Kaibab Plateau was published by Strahler (1944a,b, 1945, 1947, 1948) and Babenroth and Strahler (1945). In studying the landscape features of the plateau surface, and of the form of the land as affected by structural geology, these authors provided the first comprehensive analysis of the landscape since Dutton's (1882) monograph. The most significant findings of these studies were the interpretation of one cycle of erosion, not two as described by earlier workers, and that there was no evidence of a former peneplaned surface. Strahler (1948) concluded that the Colorado River in this area developed in the weak Triassic shales that ringed the southern end of the Kaibab arch, later entrenching into the Paleozoic strata. Removal of the Mesozoic strata from the area gave the appearance of discordant canyon cutting across the Kaibab upwarp, and therefore the river in this region is a subsequent stream.

But the Grand Canyon is grand because of mass wasting. Studies of the erosional processes in the Canyon did not begin until the 1970s, although Bryan (1923) had studied wind erosion in the Lees Ferry area, Koons (1955) described cliff retreat in the Southwest, and Schumm and Chorley (1966) examined talus weathering and scarp recession on the Colorado Plateau. Chesser (1971) described the process of development of the Esplanade, Aldridge (1971) wrote of rockslides and mudflows in the great December 1966 storm in northwestern Arizona (see Rosvedt et al., 1971, for additional information), and Ford et al. (1974) produced a summary paper on mass wasting in the Grand Canyon. Cooley et al. (1977) provided a detailed study of the effects of the 1966 storm, an event which produced dramatic runoff, erosion, and redeposition in several major tributaries of the Colorado River in the Grand Canyon. Sediment that reached the Colorado River produced significant local effects, too, on the hydraulic regime of the river. Another debris flow in 1984 in Monument Creek (Mile 93.5) was studied by Webb et al. (1988). Data from that event were used to examine the effects the flow had on the formation of rapids in the Colorado River.

There also is evidence of mass movement of large segments of the Canyon walls. The Surprise Valley landslide (Mile 135) is a 0.5 mi^3 (2.1 km^3) block of Paleozoic strata that has faulted and slid 1,500 ft (460 m), with backward rotation, along curved slip planes into the Grand Canyon. It was first described by Huntoon (1975). Failure of the Bright Angel Shale after exhumation by the Colorado River is responsible for the block movement. At least two episodes of sliding are relatively dated by the positions of buried Colorado River channels. Huntoon also predicted that similar slides between Surprise Valley and Kanab Canyon will occur geologically soon. Radbruch-Hall et al.'s (1981) landslide map of the United States indicates that areas of the eastern and western Grand Canyon show high levels of landslide incidence (>15 percent of the area involved).

The Carbon Butte landslide (Mile 63) is another example of a gravity slide feature in the Canyon (Ford and Breed, 1970). It has slid about 1 mi (1.6 km), descending with backward rotation some 1,800 ft (550 m). Stratigraphically it is composed of 400 ft (122 m) of Bright Angel and Muav Formations (Cambrian) and Redwall Limestone (Mississippian); it overlies the Chuar Group of Late Proterozoic age. The basal Tapeats Sandstone has been completely planed off and exists as a slope of detached boulders. Movement was along a synclinal axis in the upper Chuar shales. Jointing and instability caused by headward erosion of surrounding canyons seem to have provided suitable conditions for the dislodgement of the block. The event itself may have been caused by an earthquake. Geomorphically, the feature is young.

Despite the evidence of spectacular geomorphic events, the actual processes of mass wasting do not usually reveal themselves even over the period of a century. Stephens and Shoemaker (1987) have relocated many of the original camera stations from which early views of the Colorado River corridor were taken more than a century ago. Aside from river channel and riverside changes, adjacent slopes are often virtually unchanged. To that end, Dolan et al. (1974) presented a report on Colorado River statistics in the pre- and post-Glen Canyon Dam environments through Grand Canyon, to determine the effects that man has had on the river corridor.

Other forms of erosion and landscape development have been examined by several workers. Karst development on the Kaibab and Coconino Plateaus (first discussed by Dutton, 1882) was contrasted with karst terranes of Alabama by Stringfield et al. (1974). Cave development in the Canyon has been examined by Lange (1955, 1956, 1962) and Bostick (1967); and Wasson (1899) described in a generalized article the stalactite caves in the Redwall Limestone of Horseshoe Mesa, off the Grandview Trail. Cole and Mayer (1982) used radiometrically dated packrat (Neotoma spp.) middens from Grand Canyon caves to derive a value for the mean rate of cliff retreat in the eastern Grand Canyon. Reilly (1960) wrote of natural bridges in the Canyon, with special attention to the development of Keyhole Bridge in the Sinyala fault zone.

In the Marble Canyon segment of the Grand Canyon, the so-called "barbed tributaries" have been of interest to some workers. Billingsley and Breed (1973) summarized the processes in developing those tributaries, whose confluences with the Colorado River are at acute angles against the flow of the Colorado. The drainage patterns do not probably indicate drainage reversal, but appear to be the result of early entrenchment of consequent stream channels parallel to the adjacent cliffs and down the local dip of the Kaibab Formation. Jointing also appears to have had a role in determining the channel directions.

The Grand Canyon has also lent itself to the development of models of erosion and landform sculpture. Pollack (1969) presented the first numerical model of the Grand Canyon profile. Cunningham and Griba (1973) created a model of slope development that assumes only two processes contributed to erosion--linear storm incision and adjacent mass wasting of slopes, causing the orderly development of tributaries and downwearing across the landscape in such a way that less-developed features occur upstream along all streams. However, Spamer and Shapiro (1980) could not corroborate the model from statistical measurements of all of the drainage basins of the eastern Grand Canyon. These authors did detect a significant change in measured geomorphic parameters west of the Kaibab uplift, suggesting the presence of a process-geomorphic boundary; but further investigations still have not been made. Aronsson (1982) has been the last to produce a quantitative model of the Grand Canyon.

More recent geomorphological studies of the Grand Canyon have begun to look more at processes than at description and modelling. In the western Grand Canyon, stream gradients have been analyzed in conjunction with the stratigraphic placement of lava flows, the offset of strata along faults, and the styles and rates of sedimentation along fault fronts. Erosional rates in the Virgin River basin were examined by Hamblin et al. (1975), and stream-gradient analyses performed by Hamblin et al. (1981). A wide range of data have been presented by Young (1966, 1970, 1974, 1979a,b, 1980, 1981, 1982a,b, 1985), Young and Brennan (1974), Young and Hartman (1984), Young and McKee (1978), Young et al. (1975, 1987), and Graf et al. (1987). These data led to interpretations of the Cenozoic development of the Grand Canyon region, particularly with regard to the development of drainage systems. Some of the results contradict previously held views of the drainage history of northwestern Arizona and southwestern Utah, but they all are viable working hypotheses that contribute much needed data to this problem.

One remaining item of geomorphological interest is the so-called "river anticline" phenomenon seen along some reaches of the Colorado River. This system of anticlines parallels the river, with the river as an axis, for 60 miles (97 km) in central Grand Canyon (Miles 142.-202.). They are predominantly in canyon-bottom water-saturated shaly beds of the Muav Limestone in northeast-trending reaches of the main canyon. Hamblin and Rigby (1969) described the anticlines as an effect of lithostatic rebound. When the higher strata were removed from these areas, the lithostatic loading of adjacent canyon walls forced the deformation of the plastic shaly beds, arching them into the space of unloading above the river. These anticlines were also studied by Sturgul and Grinshpan (1975) and Huntoon and Elston (1980).

XVII. HYDRODYNAMICS OF THE COLORADO RIVER

28th IGC Guidebook Chapters:

2. Hydraulic log of the Colorado River from Lees Ferry to Diamond Creek, Arizona. (Julia B. Graf, John C. Schmidt, and Susan W. Kieffer)
3. Hydraulics and sediment transport of the Colorado River. (Susan W. Kieffer, Julia B. Graf, and John C. Schmidt)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
18.5	historic river flood deposits
130.4	bedrock rapids

Refer to the hydraulic guide to the Colorado River (Graf et al., IGC Guidebook Chapter 2).

WHEN JOHN WESLEY POWELL and company travelled down the unexplored Colorado River in 1869, they had hydrodynamics first on their mind--as a matter of survival, not as a scientific interest. They learned how to manage their wooden boats through the rapids, and to decide when to try to portage around them. They learned of standing waves and hidden boulders. But the concept of the origin and placement of rapids, and of the sculpting of sedimentary forms, were disciplines beyond their understanding at that time. Dutton (1882) published the first profile of the Colorado River through the Grand Canyon (Fig. 10), but he was not concerned as much with how the river acted more than he was with the results of erosion. Only since the 1960s has the hydrodynamic regime of the Colorado River through the Grand Canyon been studied. We understand today that there is a direct correlation between river hydraulic parameters, structural geology, and process geomorphology.

In 1969, a century after Powell's first expedition, Leopold published the first scientific study of the rapids and pools of the Colorado River in the Grand Canyon. He noted that radiometric measurements of the lava dams at Toroweap (Miles 177-187) indicate that the downcutting power of the Colorado River has not been appreciable during the last million years or so. Because of this, Leopold deduced that for the most part the Colorado is in a state of quasi-equilibrium between its hydraulic carrying capacity and the load input of debris from tributaries upstream. (This, of course, evaluates the canyon in its natural state before the construction of dams.)

Leopold presented the first study of the Grand Canyon's river from the viewpoint of hydrology. However, unlike other aspects of Grand Canyon geology, further studies by others were not immediately forthcoming, no doubt complicated by difficulties in measuring a swift stream contained by canyon walls. In 1976, two papers were published which examined the Colorado River below Glen Canyon Dam. Laursen et al. (1976) reported on the sediment load carried by the Colorado through the Grand Canyon and warned that in the post-dam hydrologic regime all of the beaches and bars in the Canyon would be eroded away within 200 years. Pemberton (1976) did a statistical study of the relationships between sediment load, water flow, and channel morphology in the short run between Glen Canyon Dam and the Paria River; he noted significant stabilization of the river channel.

In 1978, Dolan et al. published a study of the structural control of rapids and pools of the Colorado River in the Grand Canyon. They noted a direct correlation between the occurrence of river rapids and fracture zones, that the tributaries tended to develop along such fracture zones, and that mass-wasted debris in the tributary valleys was removed and deposited in the Colorado River predictably at the intervals indicated by the spacing of structural features.

Graf (1979) presented the results of a more ambitious project, studying 410 rapids in 12 canyon rivers. In the Marble and Grand Canyons, over a length of 385.4 km (239.5 mi) of the Colorado River, 170 rapids are distributed as mean intervals of 2.3 km (1.4 mi), 79 percent of which are located at tributary mouths. The distribution is slightly more regular than random chance would dictate.

At the same time, Graf (1978) had calculated that the spread of tamarisk--Tamarix chinensis (Lour.), a plant introduced to the Southwest in the 1800s--was progressing up the river channels of the Colorado Plateau at an average 20 km (12.4 mi) per year (see also Harris, 1966). This plant effectively contributes to the vegetational and sedimentological stabilization of islands, bars, and beaches. In river stretches "tamed" by the construction of dams upstream, as in the Grand Canyon, the spread of tamarisk affects channel morphometry and the flow regime of the river. Turner and Karpiscak (1980) provided a photographic study of the invasion of tamarisk into the Grand Canyon, comparing historical photographs with photographs taken for the study from the same camera positions.

In 1981, Howard and Dolan presented a definitive statistical study, "Geomorphology of the Colorado River in the Grand Canyon." They recognized four types of structurally controlled channel morphology in the Canyon: wide valleys with a freely meandering channel, valleys of intermediate width, narrow valleys in fractured igneous and metamorphic rocks, and narrow valleys in massive limestones. They also described three dominant sediment sizes: alluvial fan boulders, cobbles and gravel, and fine-grained sands. They observed that sediment transport through the Grand Canyon is affected by complex interactions between the sizes of sediment in transport, rates of supply and removal of each grain size, and transport and depositional effects of particular grain size populations on the other populations.

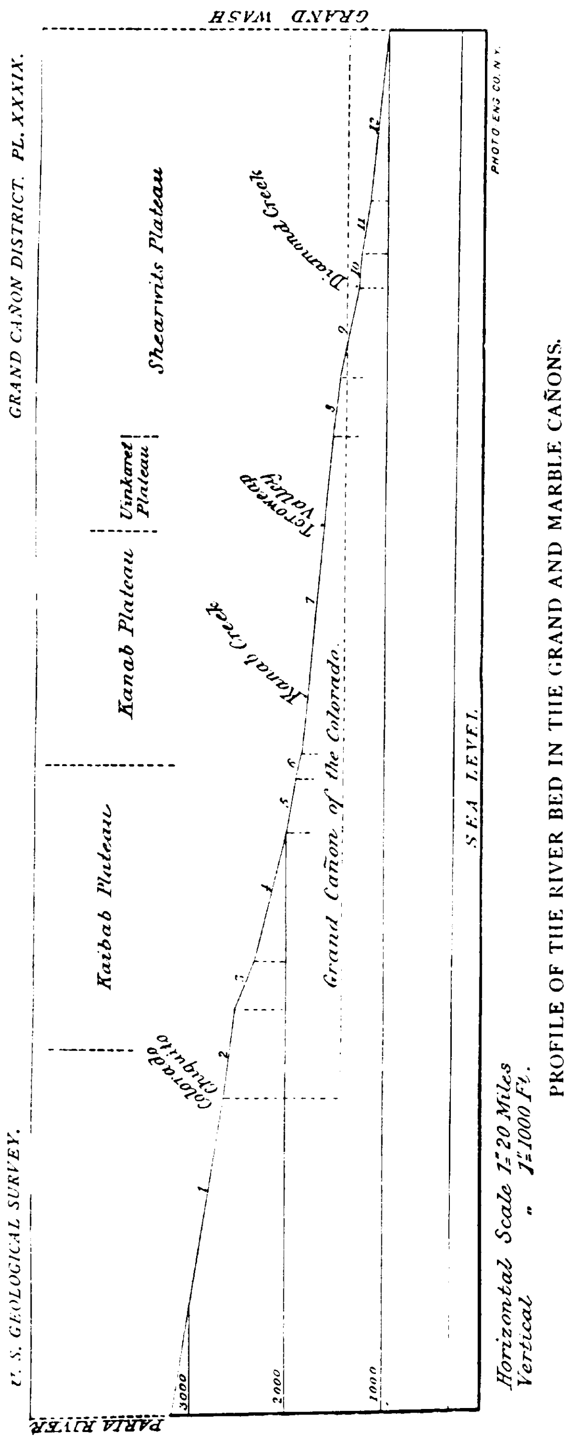


Figure 10. Dutton's (1882, pl. 39) profile of the Colorado River through the Grand Canyon.

Beus (1984, 1985) and Beus et al. (1985) investigated two erosional and depositional processes at work on Grand Canyon beaches in the post-dam environment. They noted a continuous removal of sand from the beaches since dam closure in 1963. But during the 1983-1984 "spill" through the Glen Canyon Dam spillways (caused by extreme runoff from the Rocky Mountains into the Colorado River drainage basin), a net gain in sediment volume was recorded. The authors suggested that periodically planned increases in discharges through the dam would replenish dwindling beach sand deposits. (Downstream from the Grand Canyon, Lake Mead also filled to capacity, and the Hoover Dam spillways were opened, causing significant damage in communities downstream. For both dams, it was the first time that the spillways had ever been used.)

The 1983-1984 Glen Canyon Dam "spill" was used to advantage by Kieffer (1985), who studied the effects of the 96,000 ft^3/sec (2,688 m^3/sec) maximum discharge rate on the debris fan emplaced in the Colorado River at Crystal Creek (Mile 98.2) as the result of runoff from the great 1966 storm on the Kaibab Plateau (see Cooley et al., 1977). She developed a model of debris-fan slopes, from which she concluded that the occurrence of 400,000 ft^3/sec (11,200 m^3/sec) discharges has molded some existing fans (in the pre-dam environment). The effects of new debris flows into the Colorado River have been examined in the example of the 1984 Monument Creek (Mile 93.5) debris flow (Webb et al., 1988).

Schmidt (1986a,b) reported studies of the location and characteristics of alluvial deposits in the Colorado River through the Grand Canyon. Sandy alluvial deposits, commonly associated with flow-separation zones, occur most frequently downstream from channel constrictions; they remain relatively stable when other hydraulic constraints do not substantially vary. (See also Schmidt and Graf, 1988a,b.)

Finally, a new approach to studies of Grand Canyon rapids has appeared at the time this paper is being written. A 1:1,000-scale map of the House Rock Rapids (Mile 17) was published by the U.S. Geological Survey (Kieffer, 1988), the first of ten such maps that also will cover 24.5-Mile Rapids, Hance Rapids (Mile 76.8), Bright Angel Rapids (Mile 87.9), Horn Creek Rapids (Mile 90.2), Granite Rapids (Mile 93.4), Hermit Rapids (Mile 95.0), Crystal Rapids (Mile 98.1), Deubendorff Rapids (Mile 131.7), and Lava Falls Rapids (Mile 179.3) (U.S. Geological Survey Miscellaneous Investigations Maps I-1897-A through J). The House Rock Rapids map, printed on one sheet, includes colored maps of the rapids as they appear at Colorado River discharge rates of 5,000 and 30,000 ft^3/sec (140 and 840 m^3/sec), a map of water-surface contours at the 5,000-ft^3/sec discharge rate, and a map of float velocities through the rapids. These maps are the product of research discussed in part by Keiffer (1987).

XVIII. CENOZOIC TECTONICS AND VOLCANISM

28th IGC Guidebook Chapters:

5. Modern tectonic setting of the Grand Canyon, Arizona. (Peter W. Huntoon)
17. Fission-track dating: Ages for Cambrian strata, and Laramide and post-Middle Eocene cooling events from the Grand Canyon, Arizona. (Charles W. Naeser, I. R. Duddy, Donald P. Elston, T. A. Dumitru, and P. F. Green)
19. Paleontology, clast ages, and paleomagnetism of Upper Paleocene and Eocene gravel and limestone deposits, Colorado Plateau and Transition Zone, northern and central Arizona. (Donald P. Elston, Richard A. Young, Edwin H. McKee, and Michael L. Dennis)
22. Petrology and geochemistry of Late Cenozoic basalt flows, western Grand Canyon, Arizona. (J. Godfrey Fitton)
23. Pleistocene volcanic rocks of the western Grand Canyon, Arizona. (W. Kenneth Hamblin)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
159.1	Pleistocene dikes and cinder cones
177.0	basalt flow remnant; source unknown
178.0	Vulcan's Forge
184.8	Lava Falls cascade
187.7	lava-filled canyon

Basalt Flows

177.2, 178.2, 179.0 (Lava Falls), 225.3, 246.0, 249.0, 254.2

THE GRAND CANYON, usually promoted as nature's great window on the history of the earth, is not all ancient-earth stories. The Cenozoic era is well and dramatically represented in the western Grand Canyon. Faulting and volcanism there have been the subjects of study since Newberry (1861) and Powell (1875) first wrote about the region. But the early reports did little more than describe the features found there, using them to interpret generally the "Tertiary" history of the Canyon.

Huntington and Goldthwait (1903, 1904) studied one of the region's great structural elements, the Hurricane fault, but did those studies in southwestern Utah. That work nonetheless has direct application to later studies of the tectonics of the western Grand Canyon region. Lee (1908) was the first to systematically study the western Grand Canyon district, where he also discussed new observations leading to interpretations of the history of the Colorado River (see the section herein, Origin and History of the Colorado River and the Grand Canyon). For the most part, though, investigations of the Cenozoic history of the western Grand Canyon were not actively pursued until after World War II. Only the wartime publication by McKee and Schenk (1942) preceded other work, studying the lava dams at Toroweap (which have already been noted in the section on Geomorphology). The work published by Koons (1943, 1945, 1948) on the Uinkaret Plateau and the eastern Hualapai Indian Reservation added to the post-war publications on the Cenozoic history of the Grand Canyon region.

In 1956, Hunt's important monograph on the "Cenozoic History of the Colorado Plateau" included discussions of the western Grand Canyon area. He indicated that the pre-Tertiary history of the Colorado Plateau has controlled the Cenozoic history of the area, that in Paleocene-Eocene time the Plateau was a depositional basin, and that in post-Eocene time the region has become more tectonically active as the result of epeirogenic uplift. Such uplift accelerated erosional processes and was marked by increased volcanism and faulting, which continue to the present. (Indeed, investigations into the present-day tectonic activity of the region have been vigorously pursued, as is discussed in upcoming paragraphs.)

Lovejoy (1956, 1959) published two abstracts addressing problems met in studying the Hurricane fault of Utah and Arizona; he incorporated geomorphic and sedimentologic evidence into his conclusions that the fault is a compressional feature, probably with reverse displacement, originating in Laramide time. Lovejoy went on to examine other structural problems of the region, using his findings to develop hypotheses on the origin of the Colorado River in western Grand Canyon (Lovejoy, 1964a,b, 1969, 1973, 1974, 1976, 1977). (More is said about his work in the section herein, Origin and History of the Colorado River and the Grand Canyon.) Lucchitta's work, beginning with his doctoral dissertation in 1967, likewise discussed the Cenozoic history of the western Grand Canyon. Those of his papers which have direct bearing on structural studies were published in 1974 and 1979. His other papers have dealt more with the history of the Colorado River.

Hamblin (1963a) published an abstract which launched a series of publications continuing into the 1980s, on the Cenozoic history of the western Grand Canyon region, with the first full-length paper on the Late Cenozoic lavas appearing in 1969. Hamblin and Best (1970) edited a volume composed mostly of papers by them (individually, jointly, and with other authors) on the geology of the western Grand Canyon district; it remains one of the important references on the subject and includes studies and interpretations of structure, tectonics, and volcanism. Several papers by both of the editors appear in that volume, including Hamblin (1970a,b.). Other pertinent papers by these authors are those of Best and Brimhall (1970, 1974, on basalt types), Best and Hamblin (1970, on tectonics and volcanism of the western Grand Canyon region; 1978, on the geology of the eastern boundary of the Basin and Range Province), Best et al. (1966, on basalts; 1980, on the composition of Late Cenozoic volcanic rocks with respect to their distribution in time and space in southwestern Utah and adjoining areas), Hamblin (1969, on the lava dams and intracanyon lava flows of western Grand Canyon; 1974, on Late Cenozoic volcanism in the western Grand Canyon generally), and Hamblin et al. (1975, on the rates of erosion in the Virgin River drainage basin, determined through K-Ar dating of lavas that overlie former erosional surfaces; 1981, on investigations of vertical crustal strain rates, estimated in part through measurements of structurally offset radiometrically dated lava flows).

Other investigations of the tectonics of the western Grand Canyon include those of Eastwood (1974), Gray (1964), Lucchitta (1987), Lucchitta and Young (1986), and Huntoon (1988, who hypothesized that the Colorado Plateau may be rotating into the space opened by the extending Basin and Range Province). Basaltic compositions also were the subject of a paper by Leeman (1974); and Johnson (1963) studied the effects of contact metamorphism of some basalts with sedimentary rocks. Comparable tectonic studies of the eastern Grand Canyon region have been presented by Huntoon (1974a,b). Smith and Eaton (1978) edited a volume of papers on the Cenozoic tectonics of the western Cordillera, in which the Grand Canyon region is addressed in two papers (Best and Hamblin, 1978; Shoemaker et al., 1978).

One of the long-standing themes of the Cenozoic structural history of the southern Colorado Plateau Province calls for uplift of the Plateau in Pliocene time, an event which led to the development of the present drainage network and hence to the present landscape. This process was discussed by McKee and McKee (1972), but Shakel (1976) replied that this was a persistent myth in Colorado Plateau geology. Shakel cited contrary sedimentologic evidence from various localities in the southern Plateau, stating that drainage reversal in the Mogollon Rim region of central Arizona took place at different times in different places, as early as Miocene time. Peirce et al. (1976) also stated that "'Great' or 'major' uplift, either 'plateau' or 'regional', is not necessary to explaining either drainage reversal or canyon cutting...," that the role of epeirogenic uplift in the region remains elusive.

Young, beginning with his doctoral dissertation in 1966, continues to publish on the Cenozoic tectonics and geomorphology of the western Grand Canyon region, and includes the Grand Canyon in larger studies of the history of the southern Colorado Plateau. With coauthors he has systematically investigated structural, stratigraphic, sedimentologic, and geomorphic evidence for the history of drainage (and landscape) development in the southern Plateau: Young (1970, 1974, 1979a,b, 1980, 1981, 1982a,b, 1985), Young and Brennan (1974), Young and Hartman (1984), Young and McKee (1978), Young et al. (1975, 1987), Lucchitta and Young (1986), and Graf et al. (1987).

Holocene faulting and tectonic activity is implied or briefly discussed in a number of papers, but Huntoon (1977a) addressed the subject specifically. Pearthree et al. (1983) discussed the distribution, recurrence intervals, and estimated magnitudes of Quaternary faulting in Arizona, noting that 6.3- to 7.4-magnitude surface-rupture earthquakes occur at intervals of >15,000 years. Modern seismicity in the Kaibab Plateau has been analyzed by Kruger-Knuepfer et al. (1985) and Brumbaugh (1988); and McHenry (1935) reported first-hand a tremor at the Grand Canyon.

XIX. ORIGIN AND HISTORY OF THE COLORADO RIVER AND THE GRAND CANYON

28th IGC Guidebook Chapters:

18. Development of Cenozoic landscape of central and northern Arizona: Cutting of Grand Canyon. (Donald P. Elston and Richard A. Young)
19. Paleontology, clast ages, and paleomagnetism of Upper Paleocene and Eocene gravel and limestone deposits, Colorado Plateau and Transition Zone, northern and central Arizona. (Donald P. Elston, Richard A. Young, Edwin H. McKee, and Michael L. Dennis)
20. Paleogene-Neogene deposits of western Grand Canyon, Arizona. (Richard A. Young)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile

Outcrops of Muddy Creek Formation

277.6, 285., 291., 300., 301., 307., 312.

THE GREATEST OF the Grand Canyon's enigmas is the problem of how it was made. This is the most volatile aspect of Grand Canyon geological studies. From the time that John Wesley Powell perceived three kinds of historical relationships between rivers and structural features on the Colorado Plateau--consequence, antecedence, and superimposition--the Grand Canyon has held tight to her secrets of origin and age. Every approach to this problem has been cloaked in hypothesis, drawing upon the incomplete empirical evidence of stratigraphy, sedimentology, and radiometric dating.

The history of the whole Colorado River is problematical; different parts have different histories, and some histories have multiple interpretations--especially for the Grand Canyon; "the grand problem" as Hunt (1969) called it. Even a century and a quarter after Powell, there is no consensus on the history of the Colorado River in the Grand Canyon. The drainage history of the whole Grand Canyon region, as interpreted from Cenozoic sediments layering parts of the Colorado Plateau and Transition Zone, must be reconciled to interpret the history of the Canyon itself. Simply and much too abruptly put, the Colorado River beyond the mouth of the Grand Canyon (Grand Wash Cliffs) is too young to reconcile the "older" age of the Colorado River at the head of the Grand Canyon (upstream from and at the Kaibab upwarp). At the western end of the Canyon, beyond the Grand Wash Cliffs, the Late Miocene Muddy Creek Formation must be understood before the creation of the Canyon can be interpreted. This formation was in place before the Colorado River cut through this part of its course; yet upstream from the Canyon the Colordo is believed to have been in place at a much earlier time. With this paradox in mind, we will briefly examine the history of study of the grand problem. For a current perspective of the interpretation of this problem, see Elston and Young (1989).

Newberry (1861) had supposed that the Colorado River below the Grand Canyon was the result of overflowing basins, which technically is a hypothesis of superposition of the river because it incised through younger strata into unconformably older strata without structural influences.

Powell (1875), though, was the first to address the problem of the age of the Colorado River in the Grand Canyon, except that he did not know there was much of a problem. It was clear to him that the river is an antecedent stream in that part of its course. Incised in Mesozoic strata upstream from the Grand Canyon, the river flowed across these same strata as it approached the Grand Canyon region. When the Grand Canyon area was uplifted, in part forming the Kaibab upwarp, the Mesozoic strata were stripped away and the Colorado, not being diverted, incised into the Paleozoic strata of the rising plateau, creating the Grand Canyon. Gilbert (1872, 1875, 1876) concurred for the most part with Powell, but recognized that there also exists evidence for consequence (where streams follow existing structural trends) and superposition. Dutton (1882), upon investigating the Tertiary history of the Grand Canyon region, sustained the hypothesis of antecedence for the river in the Canyon, an interpretation upheld by Walcott (1890) when he worked in the Marble Canyon area. Jefferson (1897) also supported an antecedent origin of the Colorado by studying meander patterns, but he also indicated that the river was originally a consequent stream.

The geomorphologist William Morris Davis was the first to deviate completely from the hypothesis of antecedence of the Colorado River. He called for superposition of a stream which had been a consequent stream on the peneplain of the Colorado Plateau (Davis, 1901).

Robinson (1907) reviewed the geologic history of the Colorado Plateau, as interpreted by Gilbert, Dutton, and Davis, and by Huntington and Goldthwait (1903, 1904). He extended in time the great denudation (of Dutton) through the Pliocene and restricted the erosion of the Grand Canyon to the Quaternary, the first writer to do so. He indicated that the paleodrainage of the Grand Canyon region was to the south or southwest atop what are called today the Moenkopi and Chinle Formations. The Colorado River west of Diamond Creek was interpreted to be a subsequent stream, adjusted to the structure that had underlain the peneplain. Smaller tributary streams were seen as consequent in origin; but the main body of the Colorado, and the Little Colorado River, were to Robinson uncertainly ascribable to unique causes.

In 1910, Robinson restated his views on the Quaternary age of the Grand Canyon and proposed three episodes of faulting with one period of erosion, creating the canyons in a peneplain surface. In 1911, he elaborated on Davis' single-cycle hypothesis, noting that the benches of the Tonto Plateau and the Esplanade are simply stripped surfaces of resistant formations, not older base levels of erosion.

In 1926, Moore published two papers describing and analyzing the pattern of enclosed meanders of the Colorado River as it flows through the Colorado Plateau, from above the confluence of the Grand (now Colorado) and Green Rivers to Lees Ferry (1926a) and to the upper part of Marble Canyon (1926b). He noted that the meander sizes depend upon the size of the river and that the Grand Canyon is older than the canyons upstream from it.

Longwell (1928) supported superposition for the origin of the Colorado below the Grand Canyon, and he gave it a Quaternary age. He upheld the superposed origin for the river in his 1946 paper, but, in 1960, he said that the age of the river in the Lake Mead area is unknown but certainly Cenozoic.

Blackwelder (1934) took the Quaternary age assignment a step further, determining that its age is early Pleistocene. He believed that the long Tertiary history of the river, as given by earlier workers, was improbable. Increased regional precipitation during the Pleistocene, together with overall climatic changes associated with that epoch, might have created a sequence of basin lakes connected by rivers discharging from overflow points. Steep outlet gradients may have caused canyon cutting across the drainage divides. Regrading of the basins by the Colorado and its tributaries eventually led to the present physiography.

Babenroth and Strahler (1945) developed a hypothesis for the Colorado River where it crosses the Kaibab upwarp (ca. Mile 70). The Colorado River is seen as a subsequent feature there, having already established a valley across the arch while cutting through the Mesozoic strata that overlay that area at the time. The valley had been cut into the weak Mesozoic shales that ringed the Kaibab uplift. The river became incised in the Kaibab Formation because it continued to deepen its canyon. Entrapment within that resistant formation made down-dip migration of the river course difficult. Finally, the Mesozoic overburden was stripped off, and the river continued to cut through the Paleozoic strata. This hypothesis was similar to that advanced in an abstract by Maxson (1940).

In 1948, Strahler repeated the hypothesis of Babenroth and Strahler (1945) in his study of the geomorphology and structure of the West Kaibab fault zone and Kaibab Plateau. He further emphasized that although the Colorado River is a subsequent stream there, the streams of the Kaibab Plateau are resequent and subsequent, following stratigraphic dips and structural faults. He indicated that there is no evidence of a former peneplain in the area.

Gregory (1947) reverted to late Tertiary interpretations of the age of the Grand Canyon. He blamed the confusion of analyses and interpretations on the incomplete record of stratigraphy, paleofauna, and tectonics. Overall, he believed, there is a pattern of late Miocene to early post-Miocene uplift, with stream systems generally superposed.

Hunt (1956) effectively concluded the era of pan-Plateau portrayals of Colorado River history. He observed that the pre-Tertiary history of the Colorado Plateau has largely controlled the Plateau's Cenozoic history. Each segment of the river must be treated separately, but always bearing in mind that it is but one link in a dendritic pattern of active streams. According to Hunt, the Colorado River, first thought to be antecedent and later thought to be superposed, has had a history which he hypothesized as a combination of genetic effects: "anteposition" (structural arching and backwater ponding) and (once downcutting resumed) superposition, creating aspects of antecedence. Hunt's 1969 review of the same subject finally formally declared that no whole-river hypothesis can possibly accommodate the history of the river's many segments. However, a daring new hypothesis was presented to circumvent (literally) geomorphic/sedimentologic problems met in analyzing the history of the Colorado in the western Grand Canyon. Hunt invoked large-scale piping of the river through subterranean cavernous limestone, with an outlet at the mouth of the Lower Granite Gorge into a deep lake in which was deposited the Hualapai Limestone Member of the Muddy Creek Formation. Hunt (1974) later referred to this as "an amusing hypothesis."

Over a number of years, Lovejoy addressed the problem of the age of the Colorado River and the Grand Canyon in several published items. His interests were largely restricted to the western Grand Canyon district and the area of the Basin and Range Province immediately adjacent to it. Unfortunately, all of his river history-related items were published as abstracts (Lovejoy, 1964a,b, 1969, 1976, 1977), so little elaboration by him is available to us in the literature; and, sadly, he is no longer alive.

It was at this time, in the late 1960s, that many reinvestigations of all aspects of Grand Canyon geology were beginning. McKee et al. (1967), publishing a hypothesis developed at a symposium in 1964 (and first alluded to by Lovejoy, 1964a), presented the first multi-imaged view of the Colorado River in northern Arizona. The hypothesis was considered to be tentative by the 21 participants of the Symposium on Cenozoic Geology of the Colorado Plateau in Arizona, held in August 1964 at the Museum of Northern Arizona in Flagstaff. Sixteen separate geographic areas were studied, and the Cenozoic history of the region was divided into five stages. The modern Colorado River drainage pattern was thought to have been established during the fifth stage, beginning sometime in the Pliocene. During this stage, according to the hypothesis, an ancestral lower Colorado River eroded into the rising Kaibab uplift, capturing and diverting an ancestral upper Colorado River which previously had drained toward the Rio Grande generally along the course of the present Little Colorado River. The diversion itself took place between 2.6 and 10.6 Ma. Koons (1969) later said that he could corroborate the findings of McKee et al. by examining the present anomalous distribution of certain populations of the tiger beetle (Cicindela spp.) in the drainage basin of the Little Colorado River, data derived without published credit from an article by Rumpp (1961). Spamer and Shapiro (1980), also in an abstract, thought that a geomorphic boundary they detected west of the Kaibab upwarp might have some application to the hypothesis presented by McKee et al. (1967). No further work has yet been done on that subject.

In 1968, McKee et al. reported a significant finding in establishing the age of the Grand Canyon (but first noted in print by the U.S. Geological Survey, 1967). K-Ar radiometric dates were obtained for the basal lava flow of the "Lower Canyon group" of intracanyon lavas at Toroweap: 1.16 ± 0.18 Ma. This flow occurs just 50-100 feet (15-30 m) above the present Colorado River. This means that the Grand Canyon at Toroweap has been deepened by just 15 m in the last 1.16 million years. Until the radiometric evidence was published by McKee et al., dating the Grand Canyon was strictly relative. A stratigraphically-determined minimum depth of the Grand Canyon had been calculated by Childs (1948), who noted that the Canyon was at least 2,000 feet (600 m) deep when the Black Point lava flow (related to the San Francisco volcanic field southeast of the Canyon) reached Black Point which is 680 feet (207 m) above the valley of the Little Colorado River (reported by Childs as 500 feet [150 m]). Lucchitta and McKee (1975), in studying lava flows of the Shivwits Plateau, assumed that the maximum age for the Colorado River in that area is 6.0 ± 0.3 Ma. But evidence reviewed in the 28th IGC guidebook (Elston et al., 1989) makes this young age highly unlikely. The surface of the Shivwits Plateau is a Cretaceous-Paleocene suface whose age; it is not a Miocene-age surface on which the Colorado River flowed. The river log by Billingsley and Elston (1989) points out evidence for a large relict prior to the accumulation of the Muddy Creek Formation.

Also at this time in Grand Canyon studies, in response partly to the increase in investigations inspired by the Powell expedition centennial, several reviews were prepared concerning the history of the Colorado River and its canyons: C. S. Breed (1969), Hunt (1969), Lucchitta (1969), and Cooley et al. (1969). Soon thereafter, Young initiated his series of researches into the Cenozoic history mostly of the western Grand Canyon region (see particularly Young 1970, 1981, 1982a,b, 1984; Young and Brennan, 1974; Young and McKee, 1978). Young and Hartman (1984), Young (1989), and Elston et al. (1989) have also used paleontological and other evidence to establish that the widespread "Rim gravels," critical to the dating of the development of regional drainage systems, are deposits which are much older than previously believed; they are Eocene in age. These deposits had been thought to be young based on their relative stratigraphic positions just below dated lava flows.

Lucchitta (1972) addressed the problem of the age of the Colorado River in the Basin and Range Province, immediately west of the Grand Canyon. It is in this area, too, that stratigraphic problems have to be resolved before the age of the river in the Grand Canyon can be interpretted.

In 1972, McKee and McKee postulated (mistakenly) that major uplift occurred in the southern Colorado Plateau 5 to 10 million years ago, in early- to mid-Pliocene time. This was also the time of major canyon erosion, including the Grand Canyon. The evidence of these authors' suppositions was found in the sedimentary study of ancient stream deposits along the southern margin of the Colorado Plateau, correlated in part by K-Ar dating of lava flows. However, Shakel (1976) took issue with the findings of McKee and McKee, based on additional evidence in one of the field areas examined by McKee and McKee, in the Corduroy Creek area. Shakel submitted that uplift of the plateau would have had to have taken place before Pliocene time. Drainage reversal along the Mogollon Rim region occurred at different times in different places, as early as Paleocene time. Shakel referred to the plateau uplift as a "persistent myth of Arizona geology."

Bowles (1978) reinterpreted the history of the Colorado River in the Grand Canyon through various gemorphic perspectives. He declared that the Canyon was eroded by the Colorado during two major erosional cycles beginning in late(?) Oligocene or early Miocene time. The paleodrainage pattern was altered by the uplift of the Kaibab Plateau, tilting the Esplanade, and damming the Colorado River in

Nankoweap Canyon by displacement along the Butte fault (Mile 68.5). The second erosional cycle then began, enlarging the Nankoweap lake, recharging the aquifer of the Redwall Limestone, and initiated spring discharging into the Little Colorado River, draining the lake and allowing the Colorado River to flow through again. Piping of the water to Grand Wash (Hunt, 1969) caused headward erosion from the west, and a through-flowing Colorado River was established before the late Pliocene, when erosion of the Inner Canyon began. This grand reinterpretation has not been generally accepted and does not appear in later literature.

XX. ECONOMIC GEOLOGY[1]

28th IGC Guidebook Chapters:

25. Breccia pipes and associated mineralization in the Grand Canyon region, northern Arizona. (Karen J. Wenrich and Peter W. Huntoon)
27. Mining activity in the Grand Canyon area, Arizona. (George H. Billingsley)
28. Bat Cave guano mine, western Grand Canyon, Arizona. (Peter W. Huntoon)

Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
65.4	copper prospects
78.	asbestos [see Mile 77.0]

Breccia Pipes and Paleokarst

17.5, 18.3, 18.8, 23.1, 24.3, 25.0, 26.4, 26.7, 35.9

EXPLORING FOR MINERALS is one of the oldest steady occupations. The Grand Canyon has not escaped man's gaze. In fact, were it not for early prospecting in the Canyon the development of the tourism trade there may have been delayed for decades.

The earliest mining activities of any sort in the Grand Canyon are probably prehistoric. When Native Americans moved into the area, they discovered the nutritionally valuable salt sources near the confluence of the Colorado and Little Colorado Rivers, sources which also have important significance in their beliefs of the history of their peoples. The Hopi hold sacred this area as the Sipapu, the place from which they ascended from the world below, and salt collected from the Sipapu has special purpose in ceremonies. Taylor (1954) thought he had located the salt deposits of the Sipapu and published a chemical analysis of them.

When Spanish Conquistadors were roaming the Southwest, searching more for gold than for God, they were apparently aware of some minor silver deposits near Red Butte, on the Coconino Plateau south of present-day Grand Canyon Village. If this can be substantiated, it would count as the earliest true mining activity in the region, although of little consequence.

In 1858, the Ives Expedition travelled through the area south of the Grand Canyon and saw the chasm itself at Diamond Creek. They were exploring for any worth in the land, but it is clear from Ives' report (1861) that they regarded the region as worthless (see the Introduction herein). Newberry's (1861) geological report of the expedition, while important in the development of geological studies of the Canyon, says nothing of economic interest in the immediate Canyon area; neither do the later monographs on the Grand Canyon by Powell (1875) and Dutton (1882). Still, we know that in the 1800s prospectors were beginning to roam the area. The Canyon is certainly a forbidding obstacle to travel, but the lure of such an opening in the ground is too strong for a prospector to pass up.

By the time that the Ives Expedition reached the Grand Canyon, Euro-americans were already looking for a living in the area, albeit more casually than productively. Ives himself was a bit taken aback that their party did not bring surprise to the native inhabitants. He wrote on 3 April 1858 (Ives, 1861, Pt. 1, p. 100):

> "Our party being, in all probability, the first company of whites that had ever been seen by them, we had anticipated producing a great effect, and were a little chagrined when the old woman, and two or three others of both sexes that were met, went by without taking the slightest notice of us. If pack-trains had been in the habit of passing twenty times a day they could not have manifested a more complete indifference."

We do know, in fact, that Charles Spencer, the scout that led the Ives party, was familiar to the Indians of the area and had himself done some prospecting there. Furthermore, we now know that the Canyon contains no marvelously rich lodes of minerals, except for some copper deposits which include uranium (the latter of which of course would have been worthless in 1858 even if the prospectors had known it was there). That, together with the fact that no nearby settlements could handle bulk processing of new-found ores, probably means that any early prospecting activity in the Canyon would have not brought attention to the outside world anyway.

---

[1] Throughout this section, information has been extracted from an unpublished manuscript on the mines and miners of the Grand Canyon, by George H. Billingsley, Earle E. Spamer, and Dove Menkes.

In the Grand Canyon region, several mining districts were established in the late 1800s and early 1900s, in the Canyon-proper as well as on the surrounding plateaus. The copper minerals were the most actively sought. Gold was looked for, of course, but it always proved elusive (Lauzon, 1934; Malach, 1974). Unfortunately, most of the earliest records of activity are not easily available to researchers. Some are bound up as unique copies in heavy county registers both in Arizona and Utah; others can be found in long-defunct local newspapers. But by examining these various early sources, we see that there was mining activity throughout the Canyon region: the Grand Gulch Mine (Bently District), Copper Mountain lode (Parashant Canyon), Snyder Mine, Music Mountains and Lost Basin mines, Ridenour Mine, Toroweap, Tuckup Canyon, National Canyon, Havasu Canyon, Hacks Canyon, Thunder River, Anita, and Grandview, as well as claims in the Little Colorado River area.

The mine with by far the longest history of activity, and probably the best studied of the Canyon mines, is the Orphan Mine just west of Grand Canyon Village. This will be elaborated on later in this section. Unfortunately, there is not enough space herein to include a discussion of the early mines and the equally interesting story of the miners themselves. These topics have been relegated to a presently unpublished manuscript by Billingsley, Spamer, and Menkes; but early short reviews of the Grand Canyon mines have appeared in print (Billingsley, 1974, 1976, 1989). With the exception of notes drawn from the manuscript, the remainder of this section will be devoted to the published literature on mining in the Grand Canyon region.

The first publication on Grand Canyon region mineral deposits was a short report by Blandy (1897). He described copper deposits "50 or 60 miles nearly due north of Williams," which is the area of the Anita Mine, worked from before 1890 to 1930 (Waesche, 1933a). That deposit occurs in a brecciated zone (not a breccia pipe, for which see the explanation later in this section) extending an undetermined distance in the Harrisburg Member of the Kaibab Formation, although mineralization is known to extend to a depth of 160 feet (48 m). The ore itself was rather rich, but sporadically productive (Waesche, 1933a). When Grand Canyon writer George Wharton James visited the Anita Mine in May 1900, he saw "hundreds of tons of high grade ore" and "not less than fifteen hundred tons of average ore." He noted, too, that in February 1899 "a shipment of non-selected ore" yielded 13 percent copper; and a later 100-ton shipment 21 percent (James, 1901, p. 68).

But the Anita Mine was most successful (unintentionally) at getting the railroad built to the Canyon. Between 1899 and 1901, the Grand Canyon Railroad had been run up from the Santa Fe Railroad at Williams to Anita. Ironically, very little ore was shipped by rail from Anita; the mine operators preferred to haul the ore by tractor to Williams. But the early tourist businesses were quick to offer train-and-stage packages as a means to reach their rustic accommodations at various places on the South Rim. This obviated the harrowing one- or two-day stage ride from Flagstaff (which, as noted in Section II, was the means of travel for some members of the 5th International Geological Congress in 1891). In 1901, the rail line was extended to Grand Canyon Village by the Santa Fe Railroad, laying the way for the tremendous tourist business at the Canyon today (approximately three million visitors per year). The pre-Santa Fe era of tourism at the Grand Canyon was developed by several prospectors who discovered that mining the tourist dollar was far more productive than scratching for minerals in the Canyon. However, with the January 1905 opening of the Santa Fe's deluxe hotel, El Tovar, the various small tourist camps eventually went out of business. (For more on the railroad and stage lines, see Richmond, 1985; Robertson, 1986; Way, 1980; and Woods, 1899. An account of a stage ride from Flagstaff was written by Martin, 1894, 1982.)

In 1904, Jennings described the copper deposits of the Kaibab Plateau, noting that they are best developed in the Jacob Lake area, near the head of Warm Springs Canyon. These deposits were worked by various individuals and companies by 1885. The settlement, now ruins, grew up around 1900 while the mines were worked; it was known as Coconino City and Ryan. The claims were last worked by the Apex Mining Company (Tainter, 1947; Hall, 1975). The ore beds at Ryan are mostly white brecciated chert (not breccia pipes) in the horizontal beds of the Harrisburg Member of the Kaibab Formation, at the axis of the Kaibab Plateau. The ore beds are impregnated with malachite and azurite, yielding from 2 to 40 percent copper but averaging 7 percent (Jennings, 1904).

At about the same time that the Anita and Ryan mines were working, at the turn of the century, mines located in the late 1800s along the South Rim of the Grand Canyon were also being worked. The Grandview Mine is probably the most well-known of the early mines because of the very high grade of copper ore it produced. Located in the Redwall Limestone at the southern end of Horseshoe Mesa, 4 miles (6.4 km) down the Grandview Trail and nearest to the river at about Mile 80, the mine was then known as the Grand View Copper Project. Initial assay reports indicated a 37 percent copper content in the ore, and at the 1893 Columbian Exposition in Chicago cuprite from the Grandview Mine was awarded the top prize in that category for assaying out at over 70 percent pure copper (Waesche, 1934). Emmons (1905) and Day (1905) also discussed the productivity of the Grandview Mine, and Leicht (1971) described the minerals found in the mine. Nonetheless, the mine eventually proved unprofitable as copper prices dropped and transportation costs rose. In 1911, the mine changed hands for the last time and its owner, Pete Berry, tried to keep open the Grandview Hotel he had built at Grandview Point, but failed to compete with the more comfortable and more accessible accommodations at the railhead in Grand Canyon Village.

Not much remains of the Grandview Mine. The workings are dangerous, and the structures almost completely erased. Colin Fletcher, the first person to hike the length of the Grand Canyon, passed by the Grandview Mine in 1963 during his journey. He wrote a sad epitaph (Fletcher, 1967, pp. 147-148):

> "On...Horseshoe Mesa, I found the ruins of an old mining camp. for two hours I wandered among its handful of tottering buildings. I examined rusty machinery. I handled trenchant relics: fragments of blue glass, a chipped dish, a battered kerosene lamp. I looked long and thoughtfully at many warped and weathered timbers and I listened to them creaking in the wind. But the place, barely 60 years old, refused to crackle into life. I heard no echoes, met no wraiths gliding across the wooden thresholds."

By the end of the second decade of the 20th Century, the aesthetic worth of the Canyon was well recognized and well exploited. Moves were being made to incorporate the Canyon into the National Park system, which it finally was on 16 February 1919. Because of this, citizens and politicians alike were sensitive to the haphazard kinds of development that were taking place at the Canyon. Mining claims were filed as a means of land control rather than for mineral development, to force monopolization of the economic development of tourist use of services and facilities at the Canyon. Chapman (1917) discussed some of the fraudulent claims.

One of the celebrated early cases of misrepresented mining claims was that of Ralph Cameron, a principal in the establishment of Arizona statehood and, as "the man who owned the Grand Canyon," claimed some 13,000 acres in dozens of mining claims. He controlled the head of the Bright Angel Trail (the route taken by most tourists into the Canyon, reaching the river at Mile 88.9), Indian Gardens (the only water on the trail), and sections along the Colorado River. He operated the Bright Angel Trail as a "toll road," charging fees for people and animals who set foot on it. Coconino County took title to the trail when Cameron's franchise expired in 1906, but Cameron still owned many claims along the trail. Even though he became a U.S. Senator, Cameron finally failed in legal and Congressional battles to maintain control of his holdings, and by 1928 had lost everything to the Grand Canyon National Park.

Litigation and wealth-mongers aside, the mines of the Grand Canyon region have always been most successfully worked for their copper minerals. McKee (1930b) was the first to summarize the copper occurrences in the Canyon. But although many claims were not economically viable, a few mines have been successful producers. Those that lay outside the National Park boundaries also survived due to their location on lands less tightly barred from development. The Hacks Canyon mines are probably the most productive mines in this latter category.

Hacks Canyon is a tributary of Kanab Canyon, in the central Grand Canyon region north of the Colorado River. Copper deposits were long known there, perhaps since 1890, but the remote locale did not make commercial ventures worthwhile (see also Billingsley and Ellis, 1984, for a description of the mineral potential of this area). When copper prices rose in the 1930s, the development of claims in Hacks Canyon finally got under way. Production began on a small scale in 1944 and continued sporadically; but virtually no production records exist for the early years of operation, at least through the 1950s.

Tobernite is the prominent green mineral of the Hacks Canyon mine; it is a uraniferous copper mineral. When the claims were first patented, uranium was not a commercial ore, and it was not discovered there until after World War II (Dunning, 1948). (A review of uranium deposits in Arizona was published by Granger and Raup, 1962.) Uranium production from the Hacks Canyon mine did not amount to much until the 1980s when Energy Fuels, Inc., assumed ownership of the mine. By that time, the structural nature of the ore deposit was understood.

Early work at the Hacks Canyon mine was almost random; miners were searching blindly for the ore deposits, removing the minerals wherever they were found. The ore bodies seemed to be discontinuous, frustrating the miners' efforts. Actually, the mineral deposits are confined to three pipe-shaped vertical zones of mineralized breccias--and there is the key to mineral prospecting in this part of the Colorado Plateau. These are collapse-breccia structures, or more simply, breccia pipes.

Breccia pipe genesis, prospecting, and development, are subjects currently at the forefront of research in economic geology in northern Arizona. Not all breccia pipes are mineralized, but all apparently are created in the same way. The genesis of these pipes lies in a seemingly unlikely place, in the Redwall Limestone hundreds of meters below the surface. The top of the Redwall is an erosional unconformity in which a karst surface developed prior to the deposition of the Watahomigi Formation in Pennsylvanian time. This paleokarst surface is reactivated by the chemical solution processes of groundwater, and cave development is common. Structural weakening of the caves causes them to collapse, partly filling the cavity with rubble. Continued ceiling and wall cave-ins has the effect of upward stoping, reaching into all of the overlying rock formations. Finally, there reaches a point that the solution process has filled the pipe-shaped time-transgressive collapse structure with the mixed debris of overlying formations. This breccia allows continuous circulation of groundwater. Minerals dissolved in the water accumulate, eventually cementing most of the breccia in an ore-rich matrix, often rich in copper and uranium. The direction of movement of the groundwater is most often interpreted to be gravity-controlled; but Huntoon (1986) has suggested that water flow is from beneath, controlled by elevated recharge areas of deep aquifers and artesian circulation patterns. The source of these minerals is thought to have been in the copper- and uranium-bearing sandstones of the Triassic strata of the Colorado Plateau (e.g., Finch, 1967). In the Grand Canyon region, these strata are absent; but they were eroded away from the uplifted area of the Canyon long after the development of the breccia pipes. It is thought that mineralization of the pipes took place in the interval 200-220 Ma (Ludwig et al., 1986).

Of course, to get anything out of the breccia pipes, they must be recognized in the first place (Wenrich and Sutphin, 1988). Hundreds of pipes have been discovered in northern Arizona; some are small areas of mineralization, some are small depressions, some are huge circular basins, and other are exposed in three dimensions where canyons have been cut past them. Airborne surveys are most often required to locate likely occurrences of mineralized breccia pipes because of the large tracts of roadless areas involved. Structural control of the placement of breccia pipes is certain (Sutphin et al., 1983; Sutphin and Wenrich, 1986, 1988), and to better identify these locations and their extent a variety of geochemical criteria are used. This was the topic of symposia and a field trip sponsored by the 39th Annual Meeting of the Rocky Mountain Section of the Geological Society of America, held in Flagstaff, Arizona, 30 April-2 May 1986 (Casebolt et al., 1986; Flanigan et al., 1986; Mascarenas et al., 1986; Reimer and Been, 1986; Verbeek, 1986; Waters and Best, 1986; Wenrich, 1986; Wheeler, 1986; and [field trip] Wenrich and Billingsley, 1986.)

Perhaps the best-known and most intensely studied breccia pipe is the one in which the Orphan Lode occurs. The lode, the Orphan Mine, is just 2.5 miles (4 km) west of Grand Canyon Village, between Maricopa and Powell Points. Visitors to the Canyon can see the surface buildings from Powell Point. The pipe itself crops out in the sloping canyon wall, where the collapse has visibly affected the Coconino Sandstone and Hermit Shale. Inside the canyon wall, workings have also been made in the Esplanade Sandstone and Wescogame Formation. By inference, the pipe extends to the Redwall Limestone. Formations above the Coconino Sandstone were presumably also affected by the collapse, but they have been removed by erosion.

Around 1890, Daniel L. Hogan began prospecting in the Grand Canyon. He and his partner, Henry Ward, located the Orphan claim on 8 February 1893, intending to mine copper from what he thought was a vein. Very little production was realized. The claim changed hands, but was not affected by various Presidential and Congressional protective measures that were enacted to stop future mining claims in the National Park. At no time was any significant mining done; that is, until uranium was discovered in 1951 (Granger, 1951). After assaying, testing, and mapping, the Golden Crown Mining Company shipped the first load of ore (20.89 tons, average 0.53 percent U_3O_8 [Chenoweth, 1986, who has written a comprehensive geological and historical account of the mine]). The mine was last worked in 1969. In 1987, ownership reverted to the U.S. Government, and the land is administered by the National Park Service.

The Orphan Mine was the subject of Gornitz's (1969) doctoral dissertation. Her work on the mineralization of the mine has produced the most detailed of published investigations into the petrogenesis of breccia pipes (Gornitz, 1986; Gornitz and Kerr, 1970; Gornitz et al., 1988), although other pipes are now being examined in detail (e.g., Wenrich et al., 1988).

Other occurrences of copper and other minerals in the Grand Canyon are for the most part sporadic, and no prospector who worked these deposits really made much of a living off of the Canyon's minerals. Havasu Canyon (Mile 156.8) was a popular area for prospecting, and work there dates from the 1800s when that canyon was called Cataract Canyon. The first record of work there was in 1873, when Charles Spencer located a claim for silver and lead minerals. Many more miners came to Havasu Canyon, where one of them, Daniel W. Mooney, died in a fall at a waterfall; his name was given to Mooney Falls on Havasu Creek. Virtually every tributary of Havasu Canyon was explored, and in fact one old mining tunnel in Carbonate Canyon occurs at the base of a spire now recognized as a breccia pipe weathering out in relief; however, it does not appear that that prospect was much worked.

Around 1902, rumors of platinum created the Grand Canyon Gold and Platinum Company. Claims were made near the bottom of Havasu Canyon, nearly at the Colorado River, in the Muav Limestone. No platinum has ever been found. Dozens of other mining ventures went bust in Havasu Canyon, ambition and scenery being about the only things of worth to outsiders. Only the high-grade lead deposits made some ventures worthwhile, but the expense of removal discouraged serious development. (Ferriss and Busch, 1924, were also referred to for information on the Havasu Canyon mines.)

Other mines which have been worked in the Grand Canyon were small, sometimes one-man operations. Asbestos was actively mined for a while (Day, 1905; Butler, 1929). The most notable of these mines--more for the miner than for the product--were the workings of John Hance, who ran the Hance Asbestos Company of New York City (as he called it). They are located about 800 feet (240 m) above the Colorado River on the north side opposite the foot of the Old Hance Trail (Mile 78). The asbestos was formed in contact metamorphism, where a diabase sill has intruded the Middle Proterozoic Bass Limestone; associated minerals are chlorite, serpentine, and talc. Hance never made much money, but someone bought the claims for $10,000, which Hance spent in ten days in San Francisco (Corle, 1946). Hance instead turned to another industry, claiming the copper and silver of tourists' pockets. He did very well because of his ability to tell extraordinarily tall tales for the visitors. (After all, he did admit to having dug out the Canyon.)

William Bass was another asbestos miner who worked further down the river, 3 miles (4.8 km) west of Shinumo Creek in Hakatai Canyon (Mile 108.5). As with Hance's asbestos deposits, Bass' asbestos was formed in contact metamorphism of diabase with the Bass Limestone. In just a few years, though, Bass realized that tourists were a profitable venture. When the railroad had reached Anita, south of the Canyon, Bass bought a four-horse stage and began ferrying passengers from the railhead to Bass Camp. The railroad later passed him by when it was extended to Grand Canyon Village, but it did maintain a flag stop, Bass Station, 5 rail miles from the village (as shown on early editions of the Bright Angel quadrangle). But Bass never gave up work on his asbestos mines. Some of the asbestos showed the highest grade of any mined to that time, and it was shipped to France to be used in the world's first fireproof theater curtains (Hughes, 1967, 1978). A prize-winning specimen of crysotile was included in a collection of Grand Canyon minerals at the 1931 Northern Arizona State Fair, in Prescott (Waesche, 1931).

One of the most unusual mines of the Canyon was productive for a while. The product was bat guano, layered thick in a cave on the north side of the Colorado River. This was a valuable fertilizer in the early 1920s, but, despite the profit, the bat guano mine was the most expensive mining venture in the Grand Canyon. Beatty (1962) has described the mine and its contents. (See also Huntoon, 1989.)

The bat cave was discovered in the 1930s, 600 feet (180 m) above the river near Mile 266.3. Ownership changed hands a couple of times when mishaps stymied the efforts of various individuals to remove the guano. In 1958, the U.S. Guano Corporation bought the mine, and an engineering survey estimated that the cave contained 100,000 tons of the guano. A cable system was determined to be the only way to get the material from the cave to the South Rim, and at great expense towers and cables were put into place, spanning 7,500 feet horizontally (2,250 m) and rising more than 2,500 feet (675 m). An accident soon severed a cable, and a new one was fabricated and sent to the mine. More than a year later, the cable was installed and mining began. But after only four or five months, irreparable wear was noted on the 20,200-foot-long (6,060 m) pull cable, calling for its replacement. When production again resumed, a very bitter truth was revealed: the cave contained just 1,000 tons of guano; the rest was decomposed limestone. If anyone had any designs on using the cable again, the bad-luck bat mine had one more misadventure. Several months after the mine was closed, a jet fighter clipped the cable, sending the cable crashing into the canyon below. The jet made it back to Nellis Air Force Base in Nevada, minus a wing tip.

XXI. ENGINEERING GEOLOGY

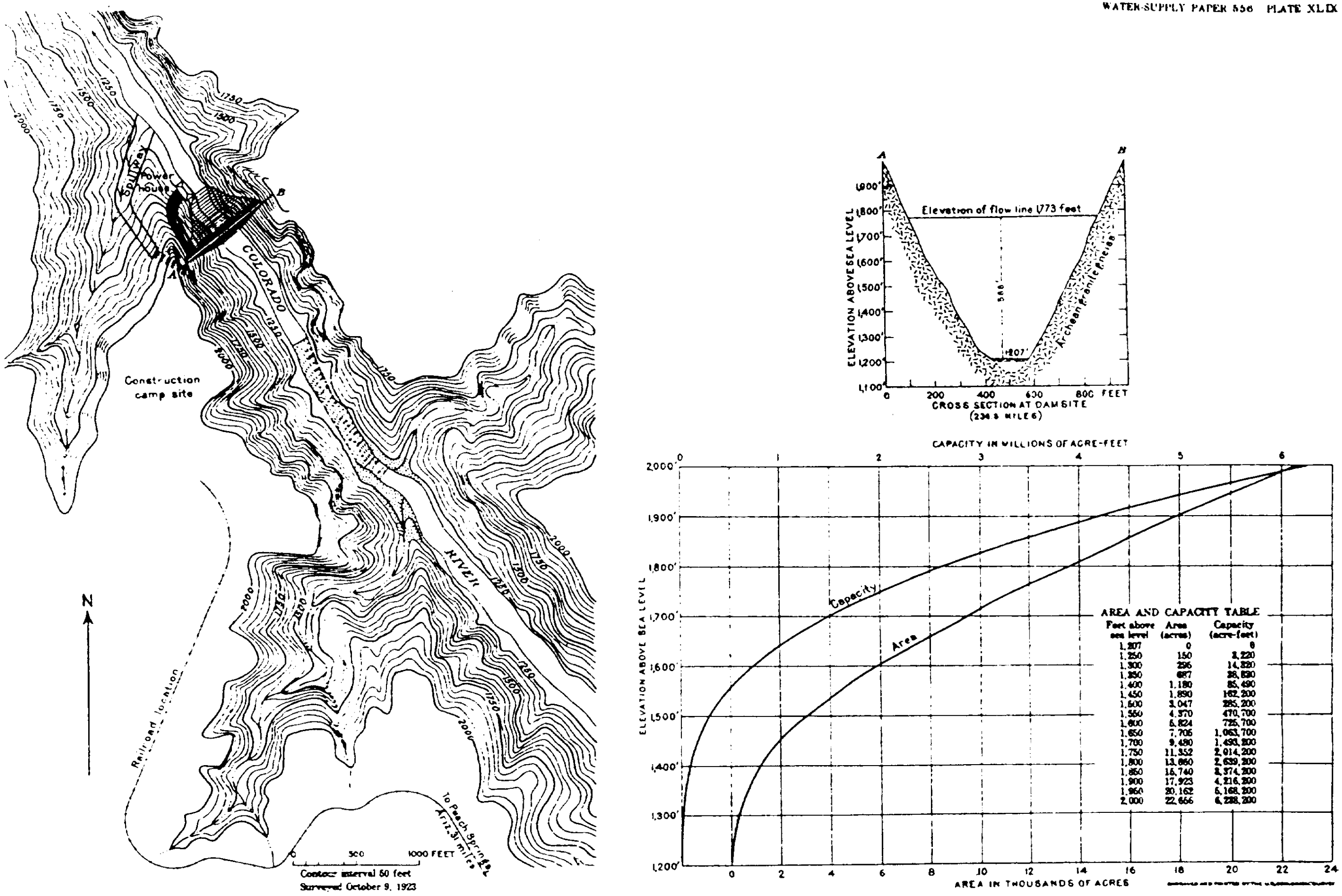
Features of Interest as Noted in IGC River Guide by Billingsley and Elston (1989):

Mile	
32.8	Marble Canyon test adits
39.3	Marble Canyon test adits
236.0	begin Lake Mead
237.5	Bridge Canyon dam site

THE GRAND CANYON has been dramatically affected by two great engineering projects, the Hoover and Glen Canyon Dams. Hoover Dam closed off the river in 1935, ponding the waters for power production and flood control. (For a history of the dam's construction, see Stevens, 1988.) Lake Mead was created, which backed up into the western part of the Grand Canyon. At normal lake levels, the impoundment reaches to Mile 236. Many rapids described by Powell and later travellers are now flooded. The most thorough published geological survey of the area now flooded by Lake Mead was produced by Longwell (1936). Glen Canyon Dam, another power-generating and flood control dam 15.8 miles (25.3 km) upstream from Lees Ferry, was closed in 1963; the result has been that the

U. S. GEOLOGICAL SURVEY

WATER-SUPPLY PAPER 556 PLATE XLIX



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
1,207	0	0
1,250	150	3,220
1,300	296	14,820
1,350	687	38,890
1,400	1,180	85,490
1,450	1,890	162,200
1,500	3,047	285,200
1,550	4,370	470,700
1,600	6,824	725,700
1,650	7,706	1,063,700
1,700	9,480	1,493,200
1,750	11,352	2,014,200
1,800	13,860	2,639,200
1,850	15,740	3,374,200
1,900	17,923	4,216,200
1,950	20,162	5,168,200
2,000	22,656	6,238,200

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR BRIDGE CANYON POWER SITE

Figure 11. Detailed topographic map and engineering data for the proposed Bridge Canyon dam site (Mile 237.5), as calculated by La Rue (1925, pl. 49). Note emplacement of dam on topographic map.

Colorado River through the Grand Canyon flows cold and clear, with infrequent surges of truly wild, muddy water. Sediment is no longer carried in the hugh amounts that gave the red river its Spanish name, beach erosion is commonplace, and vegetational changes have geomorphically stabilized many other beach locales.

In the 1920s, when the U.S. Bureau of Reclamation was beginning its grand plans to tame the American West--to harness what waters there are and to "make the desert bloom"--a detailed survey of the Colorado River was made, specifically to identify dam sites and to establish the hydrographic parameters of the Colorado River basin. Longwell et al. (1923) reported on the reconnaissance geology of the Lees Ferry area, investigating the suitability of the area for water storage. La Rue's (1925) report of the Colorado River survey includes large-scale topographic maps, accompanied by technical descriptions, of many localities within the Grand Canyon that were identified as potential dam sites (e.g., Bridge Canyon; Fig. 11). Freeman (1924) wrote a lengthy, well-illustrated popular article about this expedition. This survey was as equally ambitious as was the Stanton Survey of 1889-1890, which surveyed the entire length of the Colorado River canyons to map a route for the Colorado Canyon and Pacific Railroad (Stanton, 1965; Smith and Crampton, 1987). The railroad was considered feasible, even through the Grand Canyon, but the money for it was never obtained. Stanton even envisioned a switchyard north of Bass Rapids at about Mile 108. Certainly, had the railroad been built, mining in the Canyon would have been much more economically viable, and our view of the Canyon would today no doubt have been very different.

In the 1970s, test adits were drilled in Marble Canyon in preparation for dam construction (Mile 32.8, Mile 39.3). The project was eventually halted when environmental concerns of damming the upper Grand Canyon were strongly publicized. Until that time, Marble Canyon had been treated as a separate entity, but today it is incorporated into Grand Canyon National Park.

In 1961, Metzger did a study of the water supply for Grand Canyon Village. He noted that the Indian Gardens spring would not be able to supply the water necessary to support the anticipated increase in visitors to the National Park and suggested that sources in Hermit Basin or on the north side of the Colorado River could be tapped. As it turned out, the Roaring Springs sources in Bright Angel Canyon were developed, from which all of the village's water is obtained.

To get the water from Roaring Springs, though, required a difficult engineering project--difficult at least for the rugged Inner Canyon. A pipeline was built, mostly beneath the North Kaibab Trail, south to the Colorado River, where it crosses hanging beneath a newly constructed steel suspension footbridge, the Silver Bridge (Mile 87.9). (Prior to the building of this bridge, the only crossing was at the Kaibab Bridge [Mile 87.5].) The pipe then goes up the Inner Gorge and connects to a pump station at Indian Gardens. Between Roaring Springs and Indian Gardens the line is artesian in operation, but pumps are necessary to lift the water the rest of the way to the South Rim. A pumphouse at Roaring Springs also delivers water to the few facilities on the North Rim.

While the pipeline was being built through Bright Angel Canyon, a very large storm in December 1966 sent huge debris flows down several major tributaries of the Colorado, including Bright Angel Canyon. The North Kaibab Trail, several bridges, campgrounds, buildings, trees--and the pipeline--were destroyed (Aldridge, 1971; Cooley et al., 1977). The needed pipeline was rebuilt.

Until recently, the water was pumped up to the South Rim through the original Indian Gardens-to-rim pipe, which is still visible where it climbs the canyon wall to the rim just west of Bright Angel Lodge. But the pipe was aging, and water demand was increasing. So the National Park Service contracted an oil-drilling firm to drill a guided hole through the solid rock from the rim to Indian Gardens (Fritz, 1986). A derrick was put up near Yaki Point and the hole was drilled through the strata, guided so that it emerged from the canyon wall near Indian Gardens. Although the technology used is proprietary, some information was gleaned from the path followed by the hole, particularly that no structural features were encountered. After the hole was drilled, it was cased and is now in operation.

XXII. CARTOGRAPHY

MAPPING THE GRAND CANYON is a big order. But ever since the first expedition reached the Canyon there has not been a lack of maps. In fact, the Grand Canyon has several times in a century and a quarter been the beneficiary of the latest methods of cartography. Figures 22A-D illustrate the evolution of topographic mapping for one location in the Grand Canyon, from 1886 to 1988.

When J. C. Ives led his expedition into the Grand Canyon region in 1858, he was accompanied by Baron F. W. von Egloffstein, a cartographer already having had experience in the American West with the Pacific Railroad Surveys. Many cartographers had earlier drawn the Colorado River country into their maps (see Pyne, 1982), but the baron was the first to actually travel to the Canyon, and he was the first to (more or less) show the canyon system as it appears in nature.

Egloffstein's map of "Big Cañon" and the surrounding region, issued with Ives' (1861) report of the expedition, is celebrated as the first shaded relief map of the area, conveying the imagery of topographic contours. Yet despite the technical accuracy of translating form to map, he carried on the habit of embellishing maps with detail that was, at best, imprecise. The form of the Canyon is recognizable--even quite faithful for the time--but the side canyons feather away from the main body of the chasm in fine dendrites, like frost delicately tracing a window. Newberry (1861) used the map drawn by Eggloffstein as a base for his very broad geological map of the region, another first. When the survey under the command of George M. Wheeler released its 1871 map of the Canyon region (Wheeler, 1889), the Grand Canyon itself was sketched in more boldly, with side canyons more accurately portrayed and with much less fanciful feathering.

The second Powell expedition down the Colorado River in 1871-1872 established primary triangulation lines and

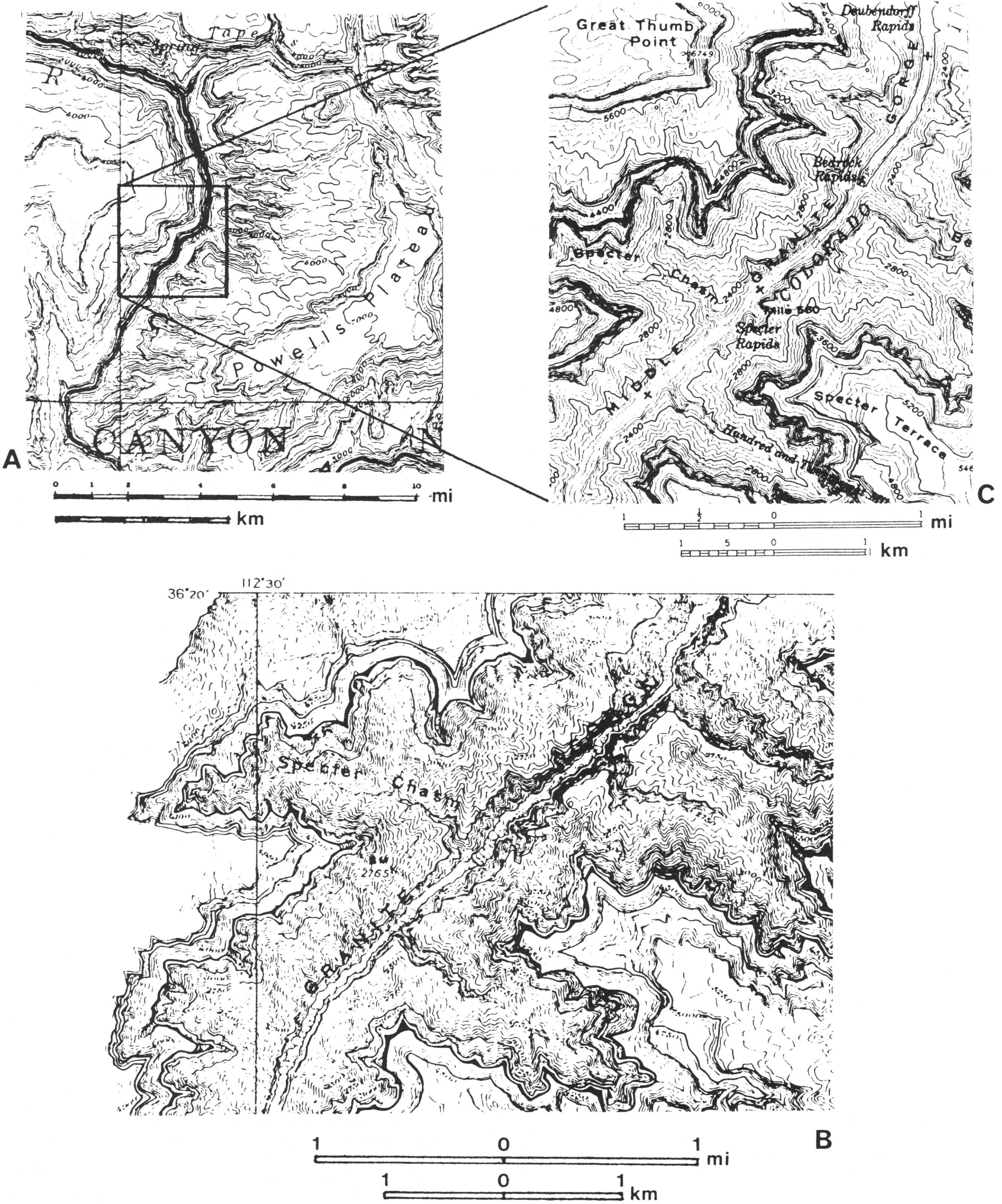
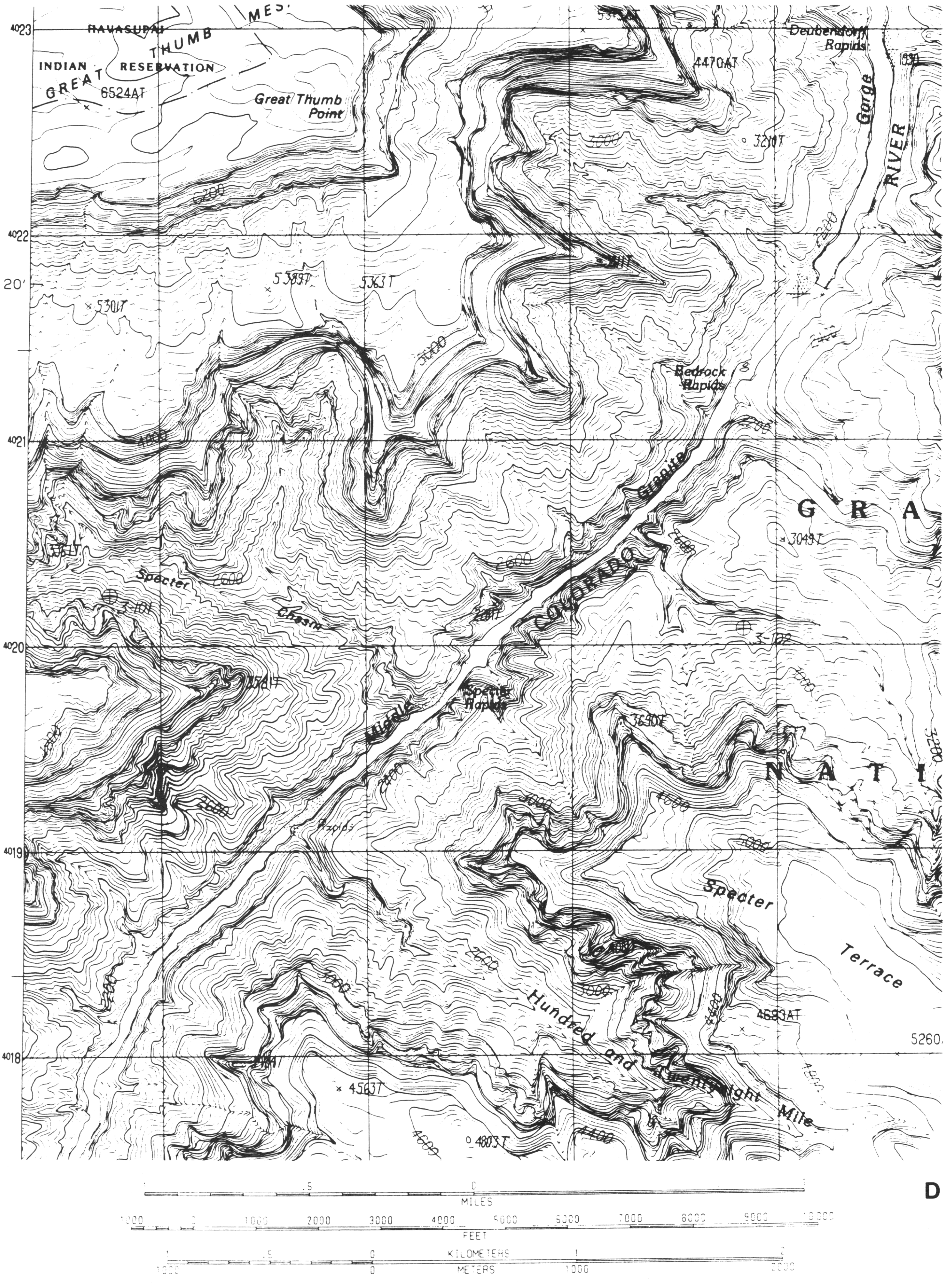


Figure 12. Evolution of topographic mapping of the Grand Canyon by the U.S. Geological Survey. The area illustrated is the Specter Chasm area of the Middle Granite Gorge, approximately between Miles 128 and 131, west-northwest of Powell Plateau. All maps reproduced actual size from the original sheets. **A.** 1:250,000-scale Kaibab sheet (1886); contour interval 250 ft (76.2 m). Boxed area delineates the approximate area of the other maps. **B.** 1:48,000-scale Shinumo quadrangle (1908); contour interval 50 ft (15.2 m). Note that this detail from the northwest corner of the sheet has different boundaries than those sheets from which C and D have been reproduced, and that the topographic contouring of the Inner Gorge has been extended beyond the normal western boundary of this sheet. **C.** 1:62,500-scale Powell Plateau quadrangle (1962); contour interval 80 ft (24.4 m). **D.** 1:24,000-scale Powell Plateau quadrangle (Provisional edition, 1988); contour interval 40 ft (12.2 m).


HAVASUPAI
INDIAN RESERVATION
GREAT THUMB MESA
6524AT
Great Thumb Point
4470AT
Deubendorff Rapids
Gorge
RIVER
3210T
5389T
5363T
5301T
Bedrock Rapids
Granite
COLORADO
GRA
3049T
Specter Chasm
3-101
3-102
Specter Rapids
Middle
Rapids
3690T
NATI
Specter Terrace
Hundred and Twentyeight Mile
4693AT
5260
4563T
4803T
4023
4022
4021
4020
4019
4018
20'
MILES
FEET
KILOMETERS
METERS

D

baseline surveys for topographic mapping of the Grand Canyon region. The river surveys were combined with overland traverses, the data from which were used to produce a series of 1:250,000-scale topographic sheets, first released in 1886. Powell (1873b), in a report to Congress, briefly described the completion of various aspects of his surveys, and offered projections for continuing work. About this, Powell very casually summarized a tremendous task in one sentence (Powell, 1873b, p. 5):

> " * * * Professor Thompson, taking three assistants, and a small party of Indians, crossed the Kaibab plateau to a point on the brink of the cañon opposite the mouth of the Little Colorado, and ran a system of triangles across the river from point to point, sketching the topography of the upper portion of the cañon and the upper ends of the lateral cañons, and carried this work down to the Grand Wash, thus completing the topography of this monstrous gorge, with all its accessory canons [sic]."

In 1880, Dutton included in a report a map of the canyons and plateaus of Utah and northern Arizona, as delineated by the explorations made by John Wesley Powell. The sketch showed for the first time geomorphic form, being neither a shaded relief map nor geological map. Dutton's (1882) magnificent Atlas, accompanying his monograph on the Grand Canyon district, presented the first true geological maps of the area. They showed with colors the outcrop patterns of several time-stratigraphic units, as broadly grouped by the analysis in the monograph, and other maps showed structural features of the region. These maps also included the first topographic map of the Canyon-proper, so far as could be determined from his vantage points on the North Rim. Dutton's maps stood for decades as the authoritative view of the Grand Canyon.

The U.S. Geological Survey used the triangulation surveys of Powell to produce 1:125,000-scale topographic sheets of the Grand Canyon region. The first one published was the Kaibab quadrangle, in 1886. This series contained many errors, especially of geographic positioning, but remained in print until 1927, long after better 1:48,000-scale maps were available.

In 1902, the U.S. Geological Survey began an ambitious plan to topographically map the eastern Grand Canyon at a larger scale than ever attempted there. François E. Matthes was selected for the job, and he and three assistants began work on the South Rim that spring. Months of triangulation, leveling, and plane table mapping were carried out, using the preliminary sketch method of contour plotting. In describing the work, Matthes (1905a,b) noted that while the methods used were not new, they certainly had "never before been applied on so extensive a scale and with so much systematic elaboration." The final product was a set of two atlas sheets at a scale of 1:48,000, covering some 500 mi^2 (1,300 km^2) with contour intervals of 50 ft (15 m). The Bright Angel quadrangle, first issued in 1903 and reprinted several times before being replaced in 1967 by a map made from aerial photography, is an exquisite art work. On its back was printed a text by Matthes on the geological features of the Bright Angel quadrangle. (Matthes revisited the Canyon in 1925 and 1927, and wrote a short article recounting the travels of the mapping party [Matthes, 1927b, reprinted 1935].) Even though these maps superseded some of the 1:250,000-scale sheets based on field work of the Powell Survey, the older maps remained in print into the 1920s. Matthes' text still appears on the reverse of the 1967 1:62,500-scale Bright Angel topographic sheet.

In 1915, Marshall directed the compilation of a list of spirit leveling results in Arizona as done from 1899 to 1915. Primary leveling in the Grandview, Bright Angel, Vishnu, and Shinumo quadrangles located survey routes and placed benchmarks throughout the Canyon. Some of these benchmarks were used decades later by Washburn in his remapping of the Bright Angel area of the Canyon (see later in this section).

In 1923, the U.S. Geological Survey sent a team of geologists down the Colorado River through the Grand Canyon. The primary purpose of this expedition was to map the Inner Gorge and conduct a reconnaissance of potential dam sites. The report issued by La Rue (1925) included many detailed topographic maps of selected areas of the Inner Gorge, and was accompanied by calculations of reservoir areas and capacities as well as geological descriptions (see also the section herein, Engineering Geology). After this expedition, though, virtually nothing was done for some time with regard to mapping the Grand Canyon.

The year 1961 was a turning point in Grand Canyon cartography. Maxson prepared the first geological map of the Bright Angel quadrangle, including four cross-sections (Maxson, 1961b). Mapped units included landslide deposits, Maxson's "Rama formation" and "Brahma schist," and his redefined Nankoweap Formation and Zoroaster Granite. The Rama formation was never retained because it simply named intrusive diabases of the Middle Proterozoic strata. The Brahma schist was simply a different metamorphic phase of the Vishnu Schist. Maxson supplemented the map with a booklet on the geologic history of the region (Maxson, 1961a).

Also in 1961, Snell published some preliminary investigations into predicting line-of-sight capabilities from topographic maps. He did this by mathematically modelling two sample terrains; one of them was the Grand Canyon quadrangle of the U.S. Army Map Service 1:250,000 Series.

A brief lull in cartographic activity followed the 1961 publications. The next flurry of activity, in 1967, was an even more important year. The U.S. Geological Survey released a series of new 1:62,500-scale topographic sheets of Grand Canyon quadrangles based on aerial photography, with contour intervals of 80 feet (24.4 m). Maxson (1967) released a preliminary geological map of the eastern Grand Canyon to the same scale. He retained his Rama formation and Brahma schist. He also mapped an outlier of the Cambrian Tapeats Sandstone capping Nankoweap Butte, which other workers would soon recognize as the Late Proterozoic Sixtymile Formation. His was a welcomed task, but later workers faulted Maxson for relying too much on aerial photography and not enough on field work. In 1969, Maxson supplemented the geologic map with one for the central and western Grand Canyon, but this map was not colored.

The eastern Grand Canyon geological map was superseded in 1976 by a joint effort of eight principal workers, each contributing the area of his field experience: Peter W. Huntoon (post-Paleozoic structural geology); George H. Billingsley (Paleozoic and younger stratigraphy); William J. Breed, James W. Sears, and Trevor D. Ford (younger Precambrian geology); and Malcolm D. Clark, R. Scott Babcock, and Edwin H. Brown (older Precambrian geology). After minor changes in later editions, it is today the standard map for the area, based on extensive field work in addition to aerial photography. A map by Billingsley et al. (1985) shows the geology of the Coconino Point and Grandview quadrangles of the Canyon's eastern South Rim, extending the coverage of the 1976 map in that area. Although no single western Grand Canyon geological map has followed Maxson's 1969 map, several uncolored maps replace that work: Huntoon and Billingsley (1981, Hurricane fault zone; 1982, Lower Granite Gorge and vicinity) and Billingsley and Huntoon (1983, Vulcan's Throne and vicinity).

In 1969, Wilson et al. produced a 1:500,000-scale geological map of Arizona. Some resolution is lost, however, by combining related formations as single mappable units. This map was revised by Reynolds (1988).

In 1971, Dr. and Mrs. Bradford Washburn of the Museum of Science in Boston, Massachusetts, essentially took it upon themselves to map part of the Grand Canyon at a larger scale than ever before attempted. Envisioned were manuscript sheets at a scale of 1:4,800. After considerable preparations, using teams of volunteers, and with grants from the National Geographic Society, the monumental effort began. The principal equipment used was a theodolite and a laser ranging instrument. Targets were set up at critical points on the Canyon rim and atop buttes within the Canyon, accomplished with the aid of helicopters--a spectacular view of the Washburns atop Dana Butte appeared in the July 1978 issue of National Geographic (National Geographic, 1978, p. 36). Washburn (1983) has elaborated on the methods used in surveying in the Canyon and in preparing the final map sheets.

The Washburn map of "The Heart of the Grand Canyon" (Washburn et al., 1978; scale 1:24,000) combined elements of several cartographic techniques--topographic contours (100-ft [30 m] intervals, shaded relief, cliff-face hachures (new to Grand Canyon maps), and vegetational shading. A slightly trimmed version of the map (to accommodate printing presses) was issued with the July 1978 issue of National Geographic; 10,400,000 copies were printed.

Part of the Washburn mapping project involved mapping five of the Grand Canyon's trails to a scale of 1:2,400: the Bright Angel, North Kaibab, South Kaibab, Hermit, and Rim Trails. Only one map, the Bright Angel Trail, has been published (Washburn, 1981; 1:4,800 scale with 25-ft [7.5 m] contours). Billingsley and Breed (1986) used this map as a base for their geologic map of the Bright Angel Trail, which was accompanied by a booklet (Breed et al., 1986) describing the geology of the Canyon as seen along the trail. The unpublished manuscript sheets can be seen at the Museum of Science in Boston.

In 1988, the U.S. Geological Survey began releasing provisional editions of 1:24,000-scale topographic maps of the Grand Canyon region. This series of maps will bring this area into line, cartographically, with the mapping available for most areas of the United States.

Lastly, readers who are interested in more about mapping the Grand Canyon should consult several references. Maps from the pre-Powell era are discussed by Pyne (1982). Mapping from the time of Ives to 1972 is well summarized by Seavey (1979). Washburn's grand mapping project of 1971-1978 is recounted by Washburn (1983).

XXIII. REMOTE SENSING

SPACE-AGE TECHNOLOGY allows us to explore the surface of our planet from afar, at high altitudes as well as from space. The Grand Canyon from space appears only as a pattern of contrasting shades of not much relief, feathered by the scratches of side canyons. But the tremendous chasm we see at ground level presents an interesting testing area for some kinds of remote sensing technology. We know in detail what the Canyon looks like, so we can compare the results of the remote sensors to the real thing. The application of this test of resolution is obvious to astrogeologists.

Airborne radar and infrared observations were made at various locations in northern Arizona, including the Grand Canyon (Schaber, 1968). In the Canyon, radar observations of lineaments and joint structures correlated well with mapped geologic structures. Some stratigraphic features were easily seen in part of the South Rim, this due to radar shadowing by slope- and cliff-forming rock units. But rock types and sharp stratigraphic contacts could not be discerned. Cultural features and some physiographic details along the South Rim were well portrayed in the radar imaging.

Jefferis (1969) used side-looking airborne radar (SLAR) imagery in the Grand Canyon area. Larger faults and jointing patterns were recognized in the images. In some areas, the radar maps showed lineaments where no structural features had been mapped, supporting the usefulness of SLAR in locating unrecognized tectonic features.

The use of images from the Earth Resources Technology Satellite (ERTS), together with enhanced image processing, was examined by Lucchitta (1975) in northern Arizona. Applications to geological mapping were discussed in that paper.

Photographs from hand-held cameras on the Skylab 4 mission were studied by Silver et al. (1977). Previously unrecognized fracture systems were revealed on photographs of the Grand Canyon region.

In 1979, Elachi and Farr used airborne imaging radar to examine the Yaki Point area of the Grand Canyon. Vertical cliffs were seen in much greater detail than in optical images of comparable resolution. But the authors noted that from those observations no new information was obtained on the geology of the Grand Canyon.

Berlin et al. (1982) used Seasat radar imagery to study the topography of part of the Grand Canyon. Erosionally resistant formations, forming cliff faces, were sharply defined where they face away from the radar beam; these are backslopes. Slope-forming rock units and the Vishnu Schist of the Inner Gorge showed little backscatter on the faces away from the radar beam. Foreslopes could not be resolved into cliff- and slope-forming units.

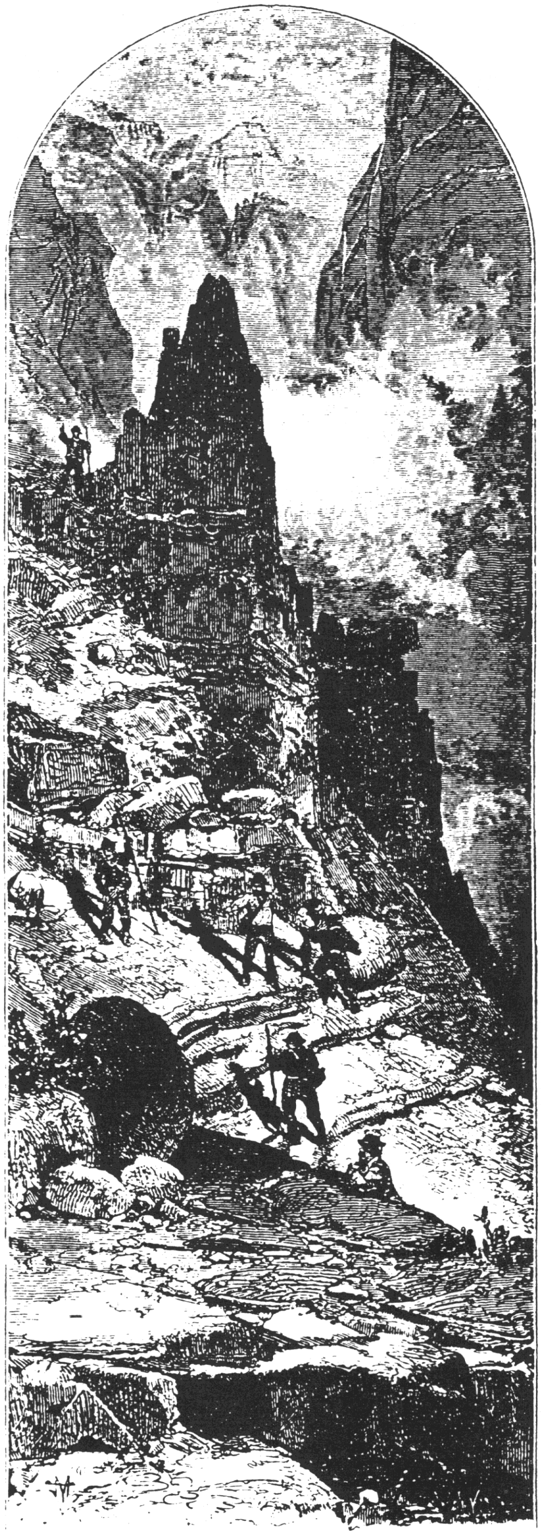
XXIV. GEOLOGICAL EDUCATION

THE GRAND CANYON is one of the traditional tools of geological education. Its grand panorama of uninterrupted exposures, classic "layer cake" stratigraphy incorporating all three major rock groups, and its representation of nearly a quarter of the history of the earth, are all parts of the Canyon's great lesson of geology. Gilbert (1876) was the first to promote the Canyon as an instructive aid in educating geologists.

Nations and Beus (1974) reviewed the logistics and objectives of a three-day hiking trip into the Grand Canyon, descending South Kaibab Trail and ascending Bright Angel Trail, spending a day in the Phantom Ranch area. Beus and Carothers (1984) have supported the combination of classwork and field instruction on a Colorado River trip as a means of merging instruction in geology and biology. They noted that observations of conditions in the Inner Canyon can be communicated to the National Park Service, as contributions to ongoing monitoring of the Canyon environment.

Many field guides have also been written about the Grand Canyon, concentrating on the whole area or emphasizing smaller segments. The segmented field guides are in the form of trail and river logs for hikers and boaters. For a summary of the geologically oriented separately published guides, see the next section.

XXV. FIELD GUIDES TO THE COLORADO RIVER AND THE GRAND CANYON



AT THE BEGINNING of most sections of this paper appear lists of pertinent features seen along the course of the Colorado River, as noted in the Colorado River guidebook of the 28th International Geological Congress (Billingsley and Elston, 1989, and Graf et al., 1989). But there are many published geological guides to the Colorado River and the Grand Canyon to which the reader may want to refer. Those that appear as papers within periodical publications are often abbreviated and for the most part are overlooked here. None of the references listed in this section are included in the bibliography for this volume unless they are mentioned for a particular purpose elsewhere in the text.

Colorado River Guides

BACHHUBER, Frederick W., Stephen ROWLAND, and Peter HUNTOON. 1987. Geology of the lower Grand Canyon and upper Lake Mead by boat--An overview. In: S. S. Beus, ed., Rocky Mountain Section of the Geological Society of America. Geol. Soc. America Centennial Field Guide, Vol. 2, pp. 36-51.

BEUS, Stanley S., and Ivo LUCCHITTA. 1987. Field-trip guide for Marble Canyon and eastern Grand Canyon. In: G. H. Davis and E. M. VandenDolder, eds., Geologic diversity of Arizona and its margins: Excursions to choice areas; field trip guidebook, 100th Annual Meeting, Geological Society of America. Arizona Bureau of Geology and Mineral Technology, Special Paper 5, pp. 3-19.

BILLINGSLEY, George H., John D. HENDRICKS, and Ivo LUCCHITTA. 1987. Field guide to the lower Grand Canyon, from Peach Springs to Pierce Ferry, Arizona. In: G. H. Davis and E. M. VandenDolder, eds., Geologic diversity of Arizona and its margins: Excursions to choice areas; field trip guidebook, 100th Annual Meeting, Geological Society of America. Arizona Bureau of Geology and Mineral Technology, Special Paper 5, pp. 20-38.

BELKNAP, Buzz. 1969. Grand Canyon river guide. Boulder City, Nevada: Westwater Books, [unpaginated].

HAMBLIN, W. Kenneth, and J. Keith RIGBY. 1968. Guidebook to the Colorado River, Part 1: Lee's Ferry to Phantom Ranch in Grand Canyon National Park. Brigham Young University Geology Studies, 15(5), 84 pp.

HAMBLIN, W. Kenneth, and J. Keith RIGBY. 1969. Guidebook to the Colorado River, Part 2: Phantom Ranch in Grand Canyon National Park to Lake Mead, Arizona-Nevada. Brigham Young University Geology Studies, 16(2), 126 pp.

Figure 13. John Wesley Powell and party explore the walls of the Grand Canyon. (Powell, 1875, fig. 34.)

LUCCHITTA, Ivo. 1987. the mouth of the Grand Canyon and edge of the Colorado Plateau in the upper Lake Mead area, Arizona. In: S. S. Beus, ed., Rocky Mountain Section of the Geological Society of America. Geological Society of America, Centennial Field Guide, Vol. 2, pp. 365-370. [A general review, not a river or road guide; but an important summary which can be used as a field guide.]

PÉWÉ, Troy L. 1974. Colorado River guidebook; a geologic and geographic guide from Lees Ferry to Phantom Ranch. Tempe, Arizona: Troy L. Péwé, 3rd ed., 79 pp.

SIMMONS, George C., and David L. GASKILL. [1969]. River runners' guide to the canyons of the Green and Colorado River; with emphasis on geologic features. Volume III. Marble Gorge and Grand Canyon. Flagstaff, Arizona: Northland Press; in cooperation with Powell Society, Ltd., Denver, Colorado, 132 pp.

STEVENS, Larry. 1983. The Colorado River in Grand Canyon; a comprehensive guide to its natural and human history. Flagstaff, Arizona: Red Lake Books, 107 pp.

Those who wish some historical information on the Colorado River will find the following references of interest:

CRUMBO, Kim. 1981. A river runner's guide to the history of the Grand Canyon. Boulder, Colorado: Johnson Books, 61+ pp.

LAVENDER, David. 1985. River runners of the Grand Canyon. Grand Canyon Natural History Association, 147 pp.

Grand Canyon Geologic Guides

Geologic guides to the Grand Canyon area, such as road logs and trail guides, are scattered through the literature. A selected group of more recently published items is listed in this section.

BEUS, Stanley S. 1987. Geology along the South Kaibab Trail, eastern Grand Canyon, Arizona. In: S. S. Beus, ed., Rocky Mountain Section of the Geological Society of America. Geological Society of America, Centennial Field Guide, Vol. 2, pp. 371-378.

BREED, William J., Vern STEFANIC, and George H. BILLINGSLEY. 1986. Geologic guide to the Bright Angel Trail. Tulsa, Oklahoma: American Association of Petroleum Geologists, [44] pp.

HAMBLIN, W. Kenneth, and Myron G. BEST. 1970. Road log. In: W. K. Hamblin and M. G. Best, eds., The western Grand Canyon district. Utah Geological Society, Guidebook to the Geology of Utah, no. 23, pp. 93-154.

HAMBLIN, W. Kenneth, and Joseph R. MURPHY. 1969. Grand Canyon perspectives; a guide to the scenery by means of interpretive panoramas (illustrations by William L. Chesser). Brigham Young University Geology Studies, Special Publication 1, 48 pp.

HEREFORD, Richard. 1987. Upper Holocene alluvium in the southern Colorado Plateau: A field guide. In: G. H. Davis and E. M. VandenDolder, eds., Geologic diversity of Arizona and its margins: Excursions to choice areas; field trip guidebook, 100th Annual Meeting, Geological Society of America. Arizona Bureau of Geology and Mineral Technology, Special Paper 5, pp. 53-67.

LUCCHITTA, Ivo, and Richard A. YOUNG. 1986. Structure and geomorphic character of western Colorado Plateau in the Grand Canyon-Lake Mead region. In: J. D. Nations, C. M. Conway, and G. A. Swann, eds., Geology of central and northern Arizona; field trip guidebook of Geological Society of America Rocky Mountain Section Meeting, Flagstaff, Arizona, 1986, pp. 159-176.

RIGBY, J. Keith. 1977. Southern Colorado Plateau; field guide. Dubuque, Iowa: Kendall/Hunt Publishing Co., 148 pp.

THAYER, Dave. 1986. A guide to Grand Canyon geology along Bright Angel Trail. Grand Canyon Natural History Association, 66 pp.

VANDERSLUIS, George D., and Charles B. HAUF. 1969. Road log; Yaki Point (top of Kaibab Trail on South Rim of the Grand Canyon) to Lee's Ferry, Arizona via Cameron. In: Geology and natural history of the Grand Canyon region. Four Corners Geological Society, 5th Field Conference, pp. 201-212.

APPENDICES

A. Grand Canyon Stratigraphic Column

B. Development of Grand Canyon Paleozoic Stratigraphic Nomenclature

C. Development of Stratigraphic Nomenclature of the Middle and Late Proterozoic Grand Canyon Supergroup

D. Development of Stratigraphic Nomenclature of the Early Proterozoic Vishnu Group

Appendix A

Original Description of Formation	Supergroup	Group	Formation	Member		Thickness (ft)	(m)	General Lithology	Environment of Deposition		Stage	Period	Era
Gregory (1915)			Chinle Formation	Shinarump Conglomerate		25	(7.6)	Conglomerate	Fluvial			Triassic	Mesozoic
Ward (1901)			Moenkopi Formation			481	(147)	Sandstone, shale, limestone	Fluvio-deltaic				
Darton (1910)			Kaibab Formation	alpha	5 facies	200	(61)	Redbeds, thin limestones, local gypsum	Regressing sea		Leonardian	Early Permian	Paleozoic
				beta	5 facies			Limestones to west, grades into sandstones to east	Maximum advance				
				gamma				Redbeds; other sandstones, shales; reworked underlying units	Transgressing sea				
McKee (1938)			Toroweap Formation	alpha	Eastern & Transition Phases Western Phase 2 facies	300	(91)	Redbeds, thin limestones, local gypsum	Regressing sea				
				beta	2 facies			Massive limestone, more magnesian to east; thick to west, thin to east	Maximum advance				
				gamma				Redbeds; other sandstones, shales; reworked underlying units	Transgressing sea				
Darton (1910)			Coconino Sandstone			60-300	(18-91)	Cross-bedded clean, well-sorted quartz sand	Desert dunes				
Noble (1922)			Hermit Shale			300-1,000	(91-305)	Shales, sandstones	Fluvio-deltaic				
White (1929) (Pakoon: McNair, 1951)		Supai Group	Esplanade Sandstone Pakoon Limestone			250-800	(76-244)	Sandstones, sandy mudstones (*Pakoon:* Limestones)	Convergence of two transgressing seaways (?) *Pakoon:* Barrier build-up	Four Transgressive-Regressive Cycles	*indeterminate boundary* Wolfcampian		
McKee (1975)			Wescogame Formation			100-250	(30-76)	Sandstones, sandy mudstones	Convergence of three transgressing seaways		Virgilian	Pennsylvanian	
McKee (1975)			Manakacha Formation			200-300	(61-91)	Sandstones, sandy mudstones, limestones	Shallow seaway		Des Moinesian(?)		
McKee (1975)			Watahomigi Formation			100-350	(30-107)	Mudstones, sandy mudstones, limestones, conglomerates	Shallow embayment Regressing sea		Atokan Morrowan		
Billingsley and Beus (1985)			Surprise Canyon Formation			0-400	(0-122)	Marine and continental sediments filling buried valleys in surface of Redwall Limestone	Erosion of uplifted area; fluvio-marine infilling of valleys		Chesterian	Missis-sipian	

Gilbert (1875)		Redwall Limestone	Horseshoe Mesa	500 (152)	35-125 (11-38)	Limestones, bedded cherts	Regressing sea	Meramecian ?	Mississippian	Paleozoic
			Mooney Falls		200-350 (61-107)	Dolomites and limestones	Transgressing sea	Osagian		
			Thunder Springs		70-100 (21-30)	Bedded cherts and dolomites	Regressing sea			
			Whitmore Wash		100 (30)	Fine-grained dolomites	Transgressing sea			
Walcott (1890)		Temple Butte Limestone		0-1,000 (0-305)		*Eastern Grand Canyon:* Discontinuous carbonate channel-fill deposits in top of Muav Limestone. *Western Grand Canyon:* Carbonate channel-fill deposits overlain by dolomites.	Intertidal shelf Shallow supratidal shelf	Famennian Frasnian Givetian	Late Devonian Middle Devonian	
		unassigned		70-150 (21-46)		Dolomites	Regressing sea		Devonian or Late or Middle Cambrian	
Noble (1914)	Tonto Group	Muav Limestone	Havasu	150-800 (46-244)		Limestones	Regressing sea		Middle Cambrian	
			Gateway Canyon			Limestones, siltstones	Maximum advance, beginning regression			
			Kanab Canyon			Limestones, siltstones, shales, dolomites, sandstones	Transgressing sea			
			Peach Springs			Limestones	Transgressing sea			
			unnamed unit			Shales	Regressing sea			
			Spencer Canyon			Limestones, siltstones	Transgressing sea			
			unnamed unit			Shales	Regressing sea			
			Sanup Plateau			Limestones, siltstones	Transgressing sea			
			unnamed unit			Shales	Regressing sea			
			Rampart Cave			Limestones, shales	Transgressing sea			
Noble (1914)		Bright Angel Shale	Flour Sack	200-450 (61-137)		Shales, siltstones, limestones	Regressing sea (minor)			
			Meriwitica			Dolomites	Transgressing sea			
			unnamed unit			Shales	Regressing sea			
			Tincanebits			Dolomites	Transgressing sea			
			unnamed unit			Shales				
			"red-brown sandstone"			Sandstones				
			unnamed unit			Shales				
Noble (1914)		*Transition Zone* Tapeats Sandstone		100-300 (30-91)		Coarse- to medium-grained cross-bedded sandstones	Offshore Shoreline		Early Cambrian	

The Great Unconformity

The Great Unconformity

Ford and Breed (1972, 1973)	Grand Canyon Supergroup		Sixtymile Formation	Lower, middle, and upper members; all unconformable	120 *(37)*		Breccias, sandstones, shales, dolomites, quartzites	Landslide debris			Late Proterozoic
Ford and Breed (1972, 1973)		Chuar Group	Kwagunt Formation	Walcott	2,218 *(676)*	838 *(255)*	Dolomites, shales, cherty pisolite beds; basal fine-grained flaky dolomite	Lacustrine			
				Awatubi		1,128 *(374)*	Argillaceous shales, mudstones, thin ferruginous siltstones	Tidal flat(?)/ lacustrine			
				Carbon Butte		252 *(77)*	Mudstones, shales	Subaerial			
Ford and Breed (1972, 1973)			Galeros Formation	Duppa	4,272 *(1,302)*	570 *(174)*	Argillaceous shales, siltstones, limestones, mudstones	Lacustrine			
				Carbon Canyon		1,546 *(471)*	Alternating limestones, shales, sandstones	Lacustrine/subaerial			
				Jupiter		1,516 *(462)*	Argillaceous shales, with sandstones and siltstones; basal 40 ft (12.2 m) stromatolitic limestones	Lacustrine			
				Tanner		640 *(195)*	Shales; basal 60 ft (18.3 m) massive coarsely crystalline dolomite overlain by limestone	Marine/lacustrine			
Van Gundy (1934, 1951)			Nankoweap Formation	upper member ferrugineous member	330 *(101)*		Thick-bedded sandstones; upper 23-ft (7.0-m) calcareous unit with shale laminae	Marine, subaerial(?) Subaerial			Middle Proterozoic
Keyes (1938), Ford et al. (1982)		Unkar Group	Cardenas Basalt		980 *(299)*		Basalts, interbedded sandstones	Shallow-water and subaerial eruptions			
Noble (1914)			Dox Sandstone	upper member (Ochoa Point)	3,145 *(959)*	304 *(93)*	Sandstones, siltstones	Tidal flats			
				upper middle member (Comanche Point)		623 *(190)*	Interbedded siltstones, quartz sandstones	Tidal flats, salt flats			
				lower middle member (Solomon Temple)		927 *(283)*	Sandstones, fine-grained sandstones, shaly siltstones	*Upper:* Channeled floodplain *Lower:* Floodplain			
				lower member (Escalante Creek)		1,291 *(394)*	Siltstones, sandstones, calcareous sandstones, shales	Deltaic; turbidite with basal lagoonal shale			
Noble (1914)			Shinumo Quartzite	5 units	1,132-1,346 *(345-410)*		Dominantly hard-cemented sandstones, conglomerates	Fluvio-deltaic			
Noble (1914)			Hakatai Shale	4 units	558-949 *(170-289)*		Mudstones, sandstones; intruded by sills	Shallow water, subaerial exposure in arid climate			
Noble (1914)			Bass Limestone	Hotauta Conglomerate	187-327 *(57-100)*		*gradational contact* Dolomites, cherts, shales, mudstones; intermittent basal conglomerate	Transgression-regression in embayment(?)			
Vishnu Schist: Walcott (1890)			Vishnu Group *Vishnu Schist, Zoroaster Plutonic Complex, Trinity Gneiss, Elves Chasm Gneiss, Granite Park Mafic Complex*		Basement		Metamorphosed sands, shales, and igneous rocks; plutons; intruded by pegmatites				Early Proterozoic

Notes to Appendix A

A. Primary references for this appendix: Babcock et al. (1979), Beus (1980), Billingsley (1978), Billingsley and Beus (1985), Brown et al. (1979), Clark (1979), Ford and Breed (1973), McKee (1933, 1938, 1963, 1982), McKee and Gutschick (1969), McKee and Resser (1945), Stevenson and Beus (1982).

B. Lithologic thicknesses listed for the Shinarump Conglomerate Member of the Chinle Formation, and for the Moenkopi Formation, are thicknesses where these strata occur at Cedar Mountain, the nearest outcrops of these units to the Grand Canyon.

C. Some formations and stratigraphic members are not continuous through the length of the Grand Canyon. The Pakoon Limestone intertongues with the Supai Group but is not a part of that group.

D. The "Great Unconformity" is an angular unconformity. Where exposed, the Cambrian Tapeats Sandstone lies upon Middle Proterozoic-age rocks of the Grand Canyon Supergroup or upon the Early Proterozoic Vishnu Group. In places, resistant hummocks of the Shinumo Quartzite were islands in the Tapeats Sea.

E. Rocks of the Vishnu Group are most dramatically exposed in the eastern Grand Canyon's Inner Gorge, where >335 m (>1,100 ft) vertical exposures are found.

Appendix B

	Formation	MARCOU (1856, 1858)	MÖLLHAUSEN (1860?, 1861)		NEWBERRY (1861)		GILBERT (1875)	POWELL (1876)		WALCOTT (1880)	DUTTON (1882, fig. 1)	DUTTON (1882, pl. 28)
Permian	Kaibab Fm.	Permian Magnesian Limestone	Unter Steinkohlen-Formation	Upper Carboniferous	Limestone	Carboniferous		Upper Aubrey Group	Carboniferous	Upper Aubrey Group	Upper Aubrey Group	cherty limestones
	Toroweap Fm.							Lower Aubrey Group				Upper Aubrey Limestone
	Coconino Ss.				Cross-stratified sandstones					Lower Aubrey Group		cross-bedded sandstone
	Hermit Sh.				Red calcareous sandstones with gypsum			Red Wall Group			Lower Aubrey Group	Lower Aubrey Sandstones
	Esplanade Ss.										Red Wall Group	
Pennsylvanian	Wescogame Fm.											
	Manakacha Fm.											
	Watahomigi Fm.	Lower Carboniferous Mountain Limestone	Devonische Formation ? ?	Lower Carboniferous?	Limestone		Red Wall Limestone Group			Red Wall Limestone		Upper Red Wall
Miss.	Surprise Canyon Fm.											Red Wall Limestones
	Redwall Ls.					Devonian + Silurian						
Dev.	Temple Butte Ls.								Devonian	sandstone on impure limestone		
	unassigned	Old Red Sandstone	Silurische Formation	Devonian?	Limestones, shales, and grits	Primordial Silurian	Marbled limestone	Tonto Group	Silurian	Tonto Primordial	Base of the Carboniferous	Lower Carboniferous Sandstones
Cambrian	Muav Ls.				Limestones mudrocks, and sandstones							
	Bright Angel Sh.						Tonto Shale				Lower Silurian	
	Tapeats Ss.			Silurian?	Potsdam sandstone		Tonto Sandstone					

Appendix B (continued)

	Formation		WALCOTT (1886)		WALCOTT (1890)		FRECH (1893)			DARTON (1910)		NOBLE (1910, 1914)	SCHUCHERT (1918)	REESIDE & BASSLER (1922)		NOBLE (1922)
Permian	Kaibab Fm.		Aubry Carboniferous Limestone	Carboniferous	Upper Aubrey Limestone	Upper Carboniferous	Aubrey Limestone and Dolomite	Carboniferous	Aubrey Group	Kaibab Limestone	Pennsylvanian	Kaibab Limestone	Kaibab Limestone	Kaibab Limestone[1]	Upper Aubrey Gr.	Kaibab Limestone
	Toroweap Fm.															
	Coconino Ss.						White Aubrey Sandstone			Coconino Sandstone		Coconino Sandstone	Coconino Sandstone	Coconino Sandstone		Coconino Sandstone
	Hermit Sh.		Aubry Carboniferous Sandstone		Lower Aubrey Sandstone		Lower Aubrey Sandstone and Shale			Supai Formation		Supai Formation	Upper Supai Formation	Supai Formation	Lower Aubrey Group	Hermit Shale
	Esplanade Ss.															Supai Formation
Pennsylvanian	Wescogame Fm.												Lower Supai Formation			
	Manakacha Fm.															
	Watahomigi Fm.		Red Wall Carboniferous Limestone		Red Wall Limestone	Lower Carboniferous	Red Wall Limestone			Redwall Limestone	Miss. and Penn.	Redwall Limestone				
Miss.	Surprise Canyon Fm.												Redwall Limestone	Redwall Limestone		Redwall Limestone[2]
	Redwall Ls.															
Dev.	Temple Butte Ls.			Devonian	Temple Butte Limestone			Dev.		Temple Butte Limestone			Upper Devonian			Temple Butte Limestone
	unassigned	Upper Cambrian	Tonto Formation	Upper Cambrian	Tonto Calcareous and Arenaceous Shales	Cambrian	Upper Tonto	Cambrian Tonto Group		Marbled Limestone	Cambrian	Marbled Limestone				Muav Limestone
Cambrian	Muav Ls.															
	Bright Angel Sh.			Middle Cambrian						Shales and Sandstones		Tonto Shale				Bright Angel Shale
	Tapeats Ss.				Tonto Sandstone		Lower Tonto			Sandstone		Tonto Sandstone				Tapeats Sandstone

Appendix B (continued)

	Formation	NOBLE (1928)		WHITE (1929)	McKEE (1938)	SCHENK & WHEELER (1942)	GUTSCHICK (1943)		HOWELL et al. (1944) West. G.C.	HOWELL et al. (1944) East. G.C.	McKEE & RESSER (1945)
Permian	Kaibab Fm.	A B	Kaibab Limestone		Kaibab Limestone[3]						
	Toroweap Fm.	C D E			Toroweap Formation[3]						
	Coconino Ss.										
	Hermit Sh.			Hermit Shale							
	Esplanade Ss.			Esplanade Sandstone			Supai Formation				
Pennsylvanian	Wescogame Fm.			Supai Formation							
	Manakacha Fm.										
	Watahomigi Fm.										
Miss.	Surprise Canyon Fm.						IV III II I	Redwall Limestone			
	Redwall Ls.										
Dev.	Temple Butte Ls.						Jerome Formation		Devonian	Carboniferous	
	unassigned					Mead Formation			unnamed dolomites and limestones	Muav Limestone	undifferentiated dolomites
Cambrian	Muav Ls.					Peasley Ls.			Mead Ls.		Muav Limestone[4]
	Bright Angel Sh.					Lyndon Sh. Pioche Sh.			Peasley Ls. Pioche Sh.	Bright Angel Shale	Bright Angel Shale[5]
	Tapeats Ss.					Tapeats Sandstone			Prospect Mountain Qtzt.	Wood Canyon Formation	Tapeats Sandstone

Appendix B (continued)

	Formation	McNAIR (1951)	EASTON & GUTSCHICK (1953)	WOOD (1956, 1966)	SORAUF (1962)	McKEE (1963)	BISSELL (1969)	McKEE & GUTSCHICK (1969)	McKEE (1975, 1982)
Permian	Kaibab Fm.	Kaibab Limestone			Kaibab Limestone[8]		Kaibab Limestone		
	Toroweap Fm.	Toroweap Fm. (3 mbrs.)			Toroweap Formation[9]		Toroweap Formation		
	Coconino Ss.	Coconino Sandstone					Coconino Sandstone		
	Hermit Sh.	Hermit Shale					Hermit Shale		Hermit Shale
	Esplanade Ss.	Queantoweap Sandstone					Esplanade Ss. Queantoweap Fm Supai Fm.		Supai Group Esplanade Sandstone
Pennsylvanian	Wescogame Fm.	Pakoon Limestone							Wescogame Formation
	Manakacha Fm.	Callville Limestone					Pakoon Fm.		Manakacha Formation
	Watahomigi Fm.						Callville Ls.		Watahomigi Formation
Miss.	Surprise Canyon Fm.							Chesterian	
	Redwall Ls.	Rodgers Springs Limestone	Redwall Limestone[7]			Redwall Limestone[10]		Redwall Limestone	
Dev.	Temple Butte Ls.	Martin Limestone	Jerome Formation	carbonaceous rocks and siltstone					
	unassigned	[Note 6]		Supra-Muav sequence					
Cambrian	Muav Ls.			Muav Limestone					
	Bright Angel Sh.			Bright Angel Shale					
	Tapeats Ss.			Tapeats Sandstone					

Notes to Appendix B

Numbered Footnotes

1. Reeside and Bassler (1922) subdivided the Kaibab limestone into (descending): Harrisburg gypsiferous member, massive limestone member, upper slope member, gray massive limestone member, and lower soft slope member.
2. Noble (1922) recognized three subdivisions in the Redwall Limestone.
3. McKee (1938) divided the Kaibab and Toroweap Formations each into three members (descending): alpha, beta, and gamma.
4. McKee and Resser (1945) subdivided the Muav Limestone into ten formal members (see Appendix A).
5. McKee and Resser (1945) subdivided the Bright Angel Shale into five units, including two formal members (see Appendix A).
6. McNair (1951) adopted Cambrian stratigraphic nomenclature for the western Grand Canyon from Schenk and Wheeler (1942), and from McKee and Resser (1945) for the eastern Grand Canyon.
7. Easton and Gutschick (1953) subdivided the Redwall Limestone into four informal units.
8. Sorauf (1962) subdivided the Kaibab Formation into two name-bearing units (descending): Harrisburg member (of Reeside and Bassler, 1922) and the Fossil Mountain member. They are informal, but have been adopted generally by those who work in the Grand Canyon region. These units will be formalized in 1989 by Sorauf and Billingsley (Sorauf, written communication).
9. Sorauf (1962) subidivided the Toroweap Formation into three name-bearing units (descending): Woods Ranch, Brady Canyon, and Seligman members. They are informal, but have been adopted generally by those who work in the Grand Canyon region. These units will be formalized in 1989 by Sorauf and Billingsley (Sorauf, written communication).
10. McKee (1963) subdivided the Redwall Limestone into four formal members (see Appendix A).

(notes are continued)

	Formation	BILLINGSLEY & McKEE (1982)	BILLINGSLEY & BEUS (1985)
Permian	Kaibab Fm.		
	Toroweap Fm.		
	Coconino Ss.		
	Hermit Sh.		
	Esplanade Ss.		
Pennsylvanian	Wescogame Fm.		
	Manakacha Fm.		
	Watahomigi Fm.		
Miss.	Surprise Canyon Fm.	pre-Supai sediment	Surprise Canyon Formation
	Redwall Ls.		
Dev.	Temple Butte Ls.		
	unassigned		
Cambrian	Muav Ls.		
	Bright Angel Sh.		
	Tapeats Ss.		

Additional Notes

A. The **Moenkopi Formation** was originally spelled Moencopie; revised by Gregory (1917).

B. **Aubrey group:** The "Aubrey group" was defined by Gilbert (1875) and was formally subdivided into the Kaibab limestone, Coconino sandstone, and Supai formation by Darton (1910). The upper "Redwall limestone" of the Aubrey group was assigned to the Supai formation by Noble (1922).

C. **Supai Group:** The Supai formation of Darton (1910) included what now are the Hermit Shale, Esplanade Sandstone, Wescogame Formation, and Manakacha Formation (part). The Supai formation was redefined by Noble (1922) when he named the Hermit Shale. The Supai formation was elevated to the rank of stratigraphic Group by McKee (1975); he raised the Esplanade Sandstone member (White, 1929) to formational rank and named the Wescogame, Manakacha, and Watahomigi Formations.

D. **Redwall Limestone:** The Redwall was originally named as the Red Wall limestone group by Gilbert (1875) and included what now are the Manakacha Formation (part), Watahomigi Formation, and the Redwall Limestone. The group was redefined by Noble (1922) when he restricted the Redwall to its present stratigraphic range (but which also included the Surprise Canyon Formation).

APPENDIX C

	Formation	POWELL (1875)	POWELL (1876)	WALCOTT (1883)	WALCOTT (1886)	WALCOTT (1890)	FRECH (1893)	WALCOTT (1894)	WALCOTT (1895)	DARTON (1910)	NOBLE (1910)	NOBLE (1914)	VAN GUNDY (1934)
	Sixtymile Fm.	Non-Conformable Rocks	Grand Cañon Group	Chuar Group	Grand Cañon Series Chuar Formation	Chuar Group	Grand Canyon Series	Chuar Terrane	upper division Chuar Terrane lower division	Chuar Group			
Chuar Gr.	Kwagunt Fm.												
	Galeros Fm.												
	Nankoweap Fm.			Grand Cañon Group	Grand Cañon Formation	Grand Cañon Group		Unkar Terrane	Unkar Terrane	Unkar Group			Nankoweap Group
Unkar Gr.	Cardenas Basalt												Unkar Group basalt & diabase
	Dox Ss.										micaceous shaly sandstone	Dox Sandstone	Dox Ss.
	Shinumo Qtzt.										sandstone and quartzite	Shinumo Quartzite	Shinumo Qtzt.
	Hakatai Sh.										argil. and arenaceous shale	Hakatai Shale	
	Bass Ls. Hotauta Cgl.										calc. sh. and ls., basal cgl.	Bass Ls. Hotauta Cgl	Bass Ls.

	Formation	HINDS (1936)	KEYES (1938)	VAN GUNDY (1951)	MAXSON (1961, 1967, 1969)	FORD et al. (1972)	FORD and BREED (1972, 1973)	ELSTON & SCOTT (197 ELSTON et al. (1973)	BEUS et al. (1974)	FORD and BREED (1974)	ELSTON and McKEE (1982)	STEVENSON and BEUS (1982)	ELSTON (1988, 1989)
	Sixtymile Fm.	Chuar Group (8 units)	Kwaguntan and Chuaran Series	Tapeats Ss. (Cambrian)	Tapeats Ss. (Cambrian)		Chuar Group Sixty Mile Fm.	Chuar Group	Grand Canyon Supergroup Chuar Group	Chuar Group Sixtymile Formation	Sixtymile Formation		
Chuar Gr.	Kwagunt Fm.			Chuar Group	Chuar Group		Kwagunt Fm.[1]			Kwagunt Fm.	Chuar Gr. Kwagunt Fm.		
	Galeros Fm.						Galeros Fm.[2]			Galeros Fm.	Galeros Fm.		
	Nankoweap Fm.	Nankoweap Group		Nankoweap Group	Nankoweap Formation		Nankoweap Group	Nankoweap Formation	Nankoweap Formation	Nankoweap Formation	Nankoweap Formation	Nankoweap Formation	
Unkar Gr.	Cardenas Basalt	Dox Sandstone and Basalt Flows	Cardenasan Series	Unkar Group basalt flows & intrus.	Unkar Group Rama Fm.	Cardenas Lavas	Cardenas Lavas	Unkar Group Cardenas Lavas	Unkar Group Cardenas Lavas	Unkar Group Cardenas Lavas	Unkar Group Cardenas Lavas	Unkar Group Cardenas Lavas	Cardenas Basalt
	Dox Ss.		Grand Canyon Series	Dox Ss. (4 mbrs)	Dox Fm.	Dox Sandstone		Dox Ss.	Dox Ss. (4 mbrs)	Dox Ss.	Dox Ss.	Dox Fm.[3]	
	Shinumo Qtzt.	Shinumo Quartzite		Shinumo Qtzt.	Shinumo Ss.	Shinumo Quartzite		Shinumo Qtzt.	Shinumo Qtzt.	Shinumo Qtzt.	Shinumo Qtzt.	Shinumo Qtzt.	
	Hakatai Sh.	Hakatai Shale		Hakatai Sh.	Hakatai Sh.	Hakatai Shale		Hakatai Sh.	Hakatai Sh.	Hakatai Sh.	Hakatai Sh.		
	Bass Ls. Hotauta Cgl.	Bass Limestone		Bass Ls.	Bass Ls.	Bass Ls. with Rama sills		Bass Ls Hot. Cgl	Bass Ls. Hot. Cgl	Bass Ls. Hot. Cgl	Bass Ls.		

Notes to Appendix C

Numbered Footnotes

1. Ford and Breed (1972, 1973) subdivided the Kwagunt Formation into three formal members (see Appendix A).
2. Ford and Breed (1972, 1973) subdivided the Galeros Formation into four formal members (see Appendix A).
3. Stevenson and Beus (1982) subdivided the Dox Sandstone into four formal members (see Appendix A).

Additional Notes

A. **Grand Canyon Supergroup:** The Grand Canyon group (Grand Canyon series) was named by Powell (1876); it included the entire Precambrian complex. Walcott (1883) revised the Precambrian nomenclature, naming the Precambrian sedimentary units the Chuar and Grand Canyon groups. Walcott attributed the name of the Chuar group to J. W. Powell, but Powell never used the name in any of his publications, so Walcott is properly the author of that unit. Elston et al. (1973) and Beus et al. (1974) informally raised the Grand Canyon series to "Supergroup" rank; Elston and Scott (1976) formalized the procedure.

B. **Sixtymile Formation:** Ford and Breed (1972, 1973) erected the "Sixty Mile Formation," placing it within the Chuar Group. The name was revised to "Sixtymile Formation" by Elston (1979) to conform with the map spelling of Sixtymile Canyon (Vishnu Temple quadrangle). The formation was removed from the Chuar Group by Elston and McKee (1982).

C. **Nankoweap Formation:** Van Gundy (1934) first named the "Nankoweap Group" and formalized the unit in 1951; it included the top unit of Walcott's (1894) Unkar division and the basal unit of Walcott's (1883, 1894) Chuar division. It was redefined as the Nankoweap Formation of the Unkar Group by Maxson (1961b). Elston and Scott (1973) segregated the Nankoweap as a separate formation between the Unkar and Chuar Groups.

D. **Cardenas Basalt:** The Cardenas Basalt was originally named the Cardenasan Series by Keyes (1938). It was redefined and correlated by Maxson (1961b) to include intrusive diabases which together he called the Rama formation. The "Cardenas Lavas" were regarded as a separate formation and restored by Ford et al. (1972). Elston (1988c, 1989) has redesignated this unit the Cardenas Basalt since the term "lavas" pertains to the rock in the molten erupted form, whereas the rock form is basalt.

E. **Dox Sandstone:** Noble's (1914) Dox Sandstone was redesignated the Dox Formation and subdivided into four stratigraphic members by Stevenson and Beus (1982). Elston (1989) reverts to the original lithologic description "Dox Sandstone."

APPENDIX D

DEVELOPMENT OF STRATIGRAPHIC NOMENCLATURE OF THE EARLY PROTEROZOIC VISHNU GROUP

Reference	Nomenclature (items in parentheses indicate partial nomenclature naming subsidiary rock units within the Vishnu Group)
Newberry (1861)	Granite
Powell (1875)	Granite, dikes, eruptive beds
Gilbert (1875)	Granites, gneisses
Powell (1876)	Grand Cañon schists
Walcott (1883)	Archean
Walcott (1886)	Pre-Cambrian
Walcott (1890)	Vishnu quartzite and schists
Frech (1893, 1895)	Gneiss, intrusives
Walcott (1894, 1895)	Vishnu terrane
Darton (1910)	Vishnu; granite, schist, etc.
Noble (1910)	Vishnu
Ransome (1917)	Schist and granite
Schuchert (1918b)	Vishnu gneiss
Noble (1922)	Granite, gneiss, schist
Wilmarth (1932)	Vishnu schist
Campbell & Maxson (1936)	(Zoroaster granite)
Hinds (1936)	Vishnu schists
Van Gundy (1951)	Archean complex
Maxson (1961, 1967, 1969)	Zoroaster granite, Brahma schist, Vishnu schist
Babcock et al. (1974)	Vishnu Group, Zoroaster gneiss, Trinity Creek-Elves Chasm gneisses, plutons, dikes, sills
Huntoon et al. (1976)	Vishnu Group, Zoroaster plutonic complex, Trinity and Elves Chasm gneisses
Babcock et al. (1979)	Vishnu metamorphic complex, Trinity gneiss complex, Elves Chasm gneiss complex, Zoroaster complex
Brown et al. (1979)	(Trinity gneiss complex, Elves chasm gneiss complex, Zoroaster plutonic complex)
Clark (1979)	(Granite Park mafic complex)

REFERENCES CITED

Common Abbreviations

An effort has been made to spell out citations in full. However, to conserve space, some common abbreviations have been used. Italicized components of each citation are the titles under which most libraries will have shelved that reference.

Acad.	Academy
Amer.	American
Bull.	Bulletin
Congr.	Congress
Dept.	Department
ed., eds.	editor(s)
Geogr.	Geographical
Geol.	Geological
Geophys.	Geophysical
Inst.	Institute
Jour.	Journal
Misc.	Miscellaneous
Mon.	Monograph
Natl.	National
no.	number
p., pp.	page(s)
Paleontol.	Paleontological
pl., pls.	plate(s)
Proc.	Proceedings
Pub.	Publication
Ser.	Series
Soc.	Society
Trans.	Tansactions
U.S.	United States
vol., vols.	volume(s)

ANONYMOUS. 1977. Rampart Cave fire still burning. Grand Canyon SAMA, 3(24):4 [newspaper].

ALDRICH, L. T., G. W. WETHERILL, and G. L. DAVIS. 1957. Occurrence of 1350-million-year-old granitic rocks in western United States. Geol. Soc. America Bull., 68:655-656.

ALDRICH, L. T., G. W. WETHERILL, G. L. DAVIS, and G. R. TILTON. 1958. Radioactive ages of micas from granitic rocks by Rb-Sr and K-A methods. Amer. Geophys. Union Trans., 39:1124-1134.

ALDRIDGE, B. N. 1971. Northwestern Arizona. In: J. O. Rostvedt et al., Summary of floods in the United States during 1966. U.S. Geol. Survey Water-Supply Paper 1870-D, pp. D63-D69.

ALF, Raymond M. 1959. Possible fossils from the early Proterozoic Bass formation, Grand Canyon, Arizona. Plateau, 31:60-63.

ANDERSON, Martin J. 1982. Commentary on Part Two, The affair at Separation Rapids. In: R. B. Stanton, Colorado River controversies (James M. Chalfant, ed.). New York: Dodd, Mead and Co., 232 pp. [Facsimile reprinting, 1982, Boulder City, Nevada, Westwater Books; with commentaries by Otis R. Marston and Martin J. Anderson, 261 pp.; Anderson commentary, pp. 252-259.]

ARONSSON, Gunnar, with an appendix by Krister LINDE. 1982. Grand Canyon--a quantitative approach to the erosion and weathering of a stratified bedrock. Earth Surface Processes and Landforms, 7:589-599. (Appendix, "Some morphological features of the Grand Canyon of the Colorado, Arizona," pp. 593-598.)

BABCOCK, R. Scott. 1980. Middle to late Proterozoic evolution of continental crust in the Grand Canyon region, U.S.A. 26^{e} Congrès Géologique International, Paris, Résumés, Vol. 2, p. 565.

-------. 1988. Proterozoic plutonic superunits in the Grand Canyon. Geol. Soc. America, Abstracts with Programs, 20(6):404.

BABCOCK, R. S., E. H. BROWN, and M. D. CLARK. 1974. Geology of the Older Precambrian rocks of the Upper Granite Gorge of the Grand Canyon. In: W. J. Breed and E. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 2-19.

BABCOCK, R. S., E. H. BROWN, M. D. CLARK, and D. E. LIVINGSTON. 1979. Geology of the older Precambrian rocks of the Grand Canyon. Part II. The Zoroaster Plutonic Complex and related rocks. Precambrian Research, 8:243-275.

BABENROTH, Donald L., and Arthur N. STRAHLER. 1945. Geomorphology and structure of the East Kaibab monocline, Arizona and Utah. Geol. Soc. America Bull., 56:107-150.

BALDWIN, Gordon C. 1946. Notes on Rampart Cave. Masterkey, 20:94-96.

BARTLETT, Katharine. 1940. How Don Pedro de Tovar discovered the Hopi and Don Garcia Lopez de Cardenas saw the Grand Canyon, with notes upon their probable route. Plateau, 12(3):37-45.

BASSLER, R. S. 1941. A supposed jellyfish from the pre-Cambrian of the Grand Canyon. U.S. Natl. Museum Proc., 89:519-522.

BEATTY, William B. 1962. Geology and mining operations in U.S. Guano cave, Mohave County, Arizona. Cave Notes, 4:40-41.

BECK, George L. 1965. Hydrology and structure of the Crazy Jug area, Grand Canyon, Arizona. Geol. Soc. America Abstracts for 1964, pp. 8-9.

-------. 1967. Quantitative analysis of the Muav Aquifer, Grand Canyon National Park, Arizona [abstract]. Natl. Speleological Soc. Bull., 29:105-106.

BECK, George L., and John R. DUNN. 1967. A preliminary report on the Muav Aquifer, Grand Canyon, Arizona [abstract]. Natl. Speleological Soc. Bull., 29:97.

BELSHAW, Michael. 1979. The Dunn-Howland killings: A reconstruction. Jour. Arizona History, 20:409-442.

BERLIN, Graydon L., Gerald G. SCHABER, Richard C. KOZAK, and Pat CHAVEZ, Jr. 1982. Cliff and slope topography of part of the Grand Canyon, Arizona, as characterized on a Seasat radar image. Remote Sensing of Environment, 12:81-85.

BEST, M. G., and W. H. BRIMHALL. 1970. Late Cenozoic basalt types in the western Grand Canyon region. In: W. K. Hamblin and M. G. Best, eds., The western Grand Canyon district. Utah Geol. Soc., Guidebook to the geology of Utah, no. 23, pp. 57-74.

-------. 1974. Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics. Geol. Soc. America Bull., 85:1677-1690.

BEST, M. G., and W. K. HAMBLIN. 1970. Implications of tectonism and volcanism in the western Grand Canyon. In: W. K. Hamblin and M. G. Best, eds., The western Grand Canyon district. Utah Geol. Soc., Guidebook to the geology of Utah, no. 23, pp. 75-79.

-------. 1978. Origin of the northern Basin and Range Province: Implications from the geology of its eastern boundary. In: R. B. Smith and G. P. Eaton, eds., Cenozoic tectonics and regional geophysics of the western Cordillera. Geol. Soc. America Memoir 152, pp. 313-340.

BEST, M. G., W. K. HAMBLIN, and W. H. BRIMHALL. 1966. Preliminary petrology and chemistry of late Cenozoic basalts in the western Grand Canyon region. Brigham Young University Geology Studies, 13:109-123.

BEST, M. G., E. H. McKEE, and P. E. DAMON. 1980. Space-time-composition patterns of late Cenozoic volcanism, southwestern Utah and adjoining areas. Amer. Jour. Science, 280:1035-1050.

BEUS, Stanley S. 1973. Devonian stratigraphy and paleogeography along the western Mogollon Rim, Arizona. Museum of Northern Arizona Bull. 49, 36 pp.

-------. 1984. Erosion and deposition on Colorado River beaches in Grand Canyon, Arizona, resulting from the 1983 high water "spill." Geol. Soc. America, Abstracts with Programs, 16(4):214.

-------. 1985. Topographic changes in fluvial terrace deposits used as campsite beaches along the Colorado River in Grand Canyon [abstract]. Arizona-Nevada Acad. Science, Jour., 20 (1985 Proceedings Supplement):38.

BEUS, Stanley S., and Steven W. CAROTHERS. 1984. Natural history in the Grand Canyon--a combined teaching and research class [abstract]. Arizona-Nevada Acad. Science, Jour., 19 (1984 Proceedings Supplement):59.

BEUS, Stanley S., Steven W. CAROTHERS, and Charles C. AVERY. 1985. Topographic changes in fluvial terrace deposits used in capsite beaches along the Colorado River in Grand Canyon. Arizona-Nevada Acad. Science, Jour., 20:111-120.

BEUS, Stanley S., Richard R. RAWSON, Russell O. DALTON, Gene M. STEVENSON, V. Stephen REED, and Thomas M. DANEKER. 1974. Preliminary report on the Unkar Group (Precambrian) in Grand Canyon, Arizona. In: T. N. V. Karlstrom and G. A. Swann, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 34-53.

BILLINGSLEY, George H. 1974. Mining in Grand Canyon. In: W. J. Breed, and E. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 170-178.

-------. 1976. Prospector's proving ground; mining in the Grand Canyon. Jour. Arizona History, 17(1):69-88.

-------. 1978. A synopsis of stratigraphy in the western Grand Canyon. Museum of Northern Arizona Research Paper 16, 27 pp.

-------. 1989. Mines of the Grand Canyon region, Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th Intl. Geol. Congr., Field Trips T115 and T315, Guidebook, Chapter 27.

BILLINGSLEY, George H., and Stanley S. BEUS. 1985. The Surprise Canyon Formation--an Upper Mississippian and Lower Pennsylvanian(?) rock unit in the Grand Canyon, Arizona. In: Stratigraphic notes, 1984. U.S. Geol. Survey Bull. 1605-A, pp. A27-A33.

BILLINGSLEY, George H., and William J. BREED. 1973. The origin of barbed tributaries in Marble Canyon, Arizona. Plateau, 45:128-132.

-------. 1986. Geologic map of the Bright Angel Trail, Grand Canyon, Arizona. Tulsa, Oklahoma: American Association of Petroleum Geologists, 1 sheet, 2 sides, scale 1:4,800.

BILLINGSLEY, George H., and Clarence E. ELLIS. 1984. Kanab Creek Roadless Area, Arizona. In: S. P. Marsh, S. J. Kropschot, and R. G. Dickinson, eds., Wilderness mineral potential; assessment of mineral-resource potential in U.S. Forest Service lands studied 1964-1984. U.S. Geol. Survey Professional Paper 1300, Vol. 1, pp. 76-78.

BILLINGSLEY, George H., and Donald P. ELSTON. 1989. Geologic log of the Colorado River from Lees Ferry to Temple Bar, Lake Mead, Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of Grand Canyon, Arizona (with Colorado River trip guides). 28th Intl. Geol. Congr., Field Trips T115 and T315, Guidebook, Chapter 1.

BILLINGSLEY, George H., and Peter W. HUNTOON. 1983. Geologic map of Vulcan's Throne and vicinity, western Grand Canyon, Arizona. Grand Canyon Natural History Association, scale 1:48,000.

BILLINGSLEY, George H., and Edwin D. McKEE. 1982. Pre-Supai buried valleys. In: E. D. McKee, The Supai Group of Grand Canyon. U.S. Geol. Survey Professional Paper 1173, pp. 137-153.

BILLINGSLEY, George H., C. W. BARNES, and G. E. ULRICH. 1985. Geologic map of the Coconino Point and Grandview Point quadrangles, Coconino County, Arizona. U.S. Geol. Survey Miscellaneous Investigations Series, map I-1644, 1 sheet, scale 1:62,500.

BISSELL, H. J. 1969. Permian and Lower Triassic transition from the shelf to basin (Grand Canyon, Arizona to Spring Mountains, Nevada). In: Geology and natural history of the Grand Canyon region. Four Corners Geol. Soc., 5th Field Conference, Guidebook, pp. 135-169.

BLACK, Donald M. 1955. Natural dams of Havasu Canyon, Supai, Arizona. Science, 121:611-612.

BLACKWELDER, Eliot. 1934. Origin of the Colorado River. Geol. Soc. America Bull., 45:551-565.

BLAIR, Gerry. 1980. Fire at fossil cave. Lapidary Jour., 34:690-695.

-------. 1981. Canyon calcite in the land of the blue green water. Lapidary Jour., 35:1020-1021, 1024, 1026, 1028-1032.

BLAKEY, Ronald C. 1986. The Coconino Sandstone: Does it contain cross-stratified marine deposits? Geol. Soc. America, Abstracts with Programs, 18(5):342.

-------. 1988. Superscoops: Their significance as elements of eolian architecture. Geology, 16:483-487.

BLANDY, John F. 1897. An Arizona copper deposit. Engineering and Mining Jour., 64(July 24):97.

BLOESER, Bonnie. 1985. Melanocyrillium, a new genus of structurally complex late Proterozoic microfossils from the Kwagunt Formation (Chuar Group), Grand Canyon, Arizona. Jour. Paleontology, 59:741-765.

BOSTICK, Neely H. 1967. The caves of Marble Gorge, Grand Canyon. Caves and Karst, 9:2-4.

BOWLES, C. G. 1978. Reinterpretation of Grand Canyon geomorphology. In: U.S. Geological Survey research 1978. U.S. Geol. Survey Professional Paper 1100, p. 72.

BRAND, Leonard R. 1978. Footprints in the Grand Canyon. Origins, 5:64-82.

-------. 1979. Field and laboratory studies on the Coconino Sandstone (Permian) vertebrate footprints and their paleoecological implications. Palaeogeography, Palaeoclimatology, Palaeoecology, 28:25-38.

BREED, Carol S. 1969. A century of conjecture on the Colorado River in Grand Canyon. In: Geology and natural history of the Grand Canyon region. Four Corners Geol. Soc., 5th Field Conference, Guidebook, pp. 63-67.

BREED, William J., and Trevor D. FORD. 1973. Chapter Two-and-a-half of Grand Canyon history, or the Sixty Mile Formation. Plateau, 46:12-18.

BREED, William J., and Evelyn C. ROAT. 1974. (eds.) Geology of the Grand Canyon. Flastaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, 185 pp.

BREED, William J., Vern STEFANIC, and George H. BILLINGSLEY. 1986. Geologic guide to the Bright Angel Trail. Tulsa, Oklahoma: American Association of Petroleum Geologists, [44] pp.

BRIGHAM, Albert Perry. 1915. History of the excursion. In: Memorial volume of the Transcontinental Excursion of 1912 of the American Geographical Society of New York. New York: American Geographical Society, pp. 9-45.

BROWN, E. H., R. S. BABCOCK, and M. D. CLARK. 1974. A preliminary report on the older Precambrian rocks in the Upper Granite Gorge of the Grand Canyon. In: T. N. V. Karlstrom and R. L. Eastwood, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 2-33.

BROWN, E. H., R. S. BABCOCK, M. D. CLARK, and D. E. LIVINGSTON. 1979. Geology of the older Precambrian rocks of the Grand Canyon. Part I. Petrology and structure of the Vishnu Complex. Precambrian Research, 8:219-241.

BROWN, Robert. 1869a. On the formation of fjords, cañons, and benches. Royal Geogr. Soc. Proc., 13:144-149.

-------. 1869b. On the formation of fjords, cañons, benches, prairies, and intermittent rivers. Royal Geogr. Soc. Jour., 39:121-131.

BRUMBAUGH, David S. 1988. Earthquake sequences on the Colorado Plateau of Arizona [abstract]. Arizona-Nevada Acad. Science, Jour., 23 (1988 Proceedings Supplement):39.

BRYAN, Joseph J. 1936. Barite deposits in the Redwall of Grand Canyon. In: Contributions to Grand Canyon geology. Grand Canyon Natural History Association, Bull. 5, pp. 23-26.

BRYAN, Kirk. 1923. Wind erosion near Lees Ferry, Arizona. Amer. Jour. Science, 5th Ser., 6:291-307.

BUTLER, Gurdon M. 1929. Geological occurrence of Arizona asbestos. Pan-Amer. Geologist, 52:19-26.

CAMPBELL, Ian. 1936. On the occurrence of sillimanite and staurolite in Grand Canyon. In: Contributions to Grand Canyon geology. Grand Canyon Natural History Association, Bull. 5, pp. 17-22.

-------. 1937. Types of pegmatites in the Archean at Grand Canyon. Amer. Mineralogist, 22:436-445.

CAMPBELL, Ian, and John H. MAXSON. 1933a. Geological studies of the Archean rocks at Grand Canyon. Carnegie Institution of Washington Year Book 32, pp. 305-306.

-------. 1933b. Field studies of the Archean in Grand Canyon. Grand Canyon Nature Notes, 8(2):141-151.

-------. 1933c. Archean formations of the Grand Canyon [abstract]. Science, 77:460.

-------. 1933d. Some observations on the Archean metamorphics of the Grand Canyon. U.S. Natl. Acad. Sciences Proc., 19:806-809.

-------. 1934. Geological studies of the Archean rocks at Grand Canyon. Carnegie Institution of Washington Year Book 33, pp. 284-285.

-------. 1935a. Geological studies of the Archean rocks at Grand Canyon. Carnegie Institution of Washington Year Book 34, pp. 323-326.

-------. 1935b. Significance of concretions in Vishnu schist [abstract]. Pan-Amer. Geologist, 64:65. [Also in: Geol. Soc. America Proc. for 1935, pp. 342-343 (1936).]

-------. 1936. Geological studies of the Archean rocks at Grand Canyon. Carnegie Institution of Washington Year Book 35, pp. 329-331.

-------. 1937. Geological studies of the Archean rocks at Grand Canyon. Carnegie Institution of Washington Year Book 36, pp. 345-346.

-------. 1938a. Geological studies of the Archean rocks at Grand Canyon. Carnegie Institution of Washington Year Book 37, pp. 359-364.

-------. 1938b. Archean formations of the Grand Canyon [abstract]. Geol. Soc. America Bull., 49:1871.

-------. 1939a. Studies on the Archean of the Grand Canyon. Carnegie Institution of Washington Year Book 38, pp. 328-330.

-------. 1939b. Geologiya archeya yugo-zapada S.Ch.A. [Archean geology of the southwest U.S.A.] [abstract]. Mezhdunarodnyi Geologischeskii Kongress, Trudy XVII Sessii, CCCR, 1937, Tom vtoroi [International Geological Congress, Report of the XVII Session, USSR, 1937, Vol. 2]. Moscow, p. 275. [In Russian.]

CASEBOLT, L. L, J. M. FAUROTE, and D. M. PILLMORE. 1986. Underground geologic evaluation: Hack Canyon breccia pipe uranium ore body, Mohave County, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):345.

CHAMBERLAIN, K., and S. BOWRING. 1988. Proterozoic crustal boundary in NW Arizona: Evidence from zircon systematics and Pb isotopes. Geol. Soc. America, Abstracts with Programs, 20(7):A50.

CHAPMAN, H. H. 1917. Mining "claims" in the Grand Canyon. Amer. Forestry, 23:225-227.

CHENOWETH, William L. 1986. The Orphan Lode Mine, Grand Canyon, Arizona; a case history of a mineralized, collapse-breccia pipe. U.S. Geol. Survey open-file report 86-510, 91 pp. + pp. A1-A35.

CHESSER, William L. 1971. The nature and development of the Esplanade in the Grand Canyon, Arizona. Brigham Young University Geology Studies, 18(part 3):3-48.

CHILDS, Orlo E. 1948. Geomorphology of the valley of the Little Colorado River, Arizona. Geol. Soc. America Bull., 59:353-388.

CHORLEY, Richard J., Antony J. DUNN, and Robert P. BECKINSDALE. 1964. The history of the study of landforms; or the development of geomorphology. Vol. 1. Geomorphology before Davis. Methuen and Co., Ltd., and John Wiley and Sons, Inc., 678 pp.

CLARK, Malcolm D. 1978. Amphibolitic rocks from the Precambrian of Grand Canyon: mineral chemistry and phase petrology. Mineralogical Magazine, 42:199-207.

-------. 1979. Geology of the older Precambrian rocks of the Grand Canyon. Part III. Petrology of mafic schists and amphibolites. Precambrian Research, 8:277-302.

CLARK, Roger Alan. 1981. Stratigraphy, depositional environments, and carbonate petrology of the Toroweap and Kaibab Formations (Lower Permian), Grand Canyon region, Arizona. Ph.D. dissertation, State University of New York at Binghamton, 395 pp. [University Microfilm International dissertation no. 8110508.]

CLOUD, Preston E. 1960. Gas as a sedimentary and diagenetic agent. Amer. Jour. Science, Bradley Vol., 258-A:35-45.

-------. 1968. Pre-Metazoan evolution and the origins of the Metazoa. In: E. T. Drake, ed., Evolution and environment. New Haven: Yale University Press, pp. 1-72.

COLBERT, Edwin H. 1974. The rocks and fossils of the Mesozoic; a brief statement. In: Breed, W. J., and Roat, E. C., eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 77-80.

COLE, Kenneth L., and Larry MAYER. 1982. Use of packrat middens to determine rates of cliff retreat in the eastern Grand Canyon, Arizona. Geology, 10:597-599.

COLLINSON, D. W., and S. K. RUNCORN. 1960. Polar wandering and continental drift: Evidence from paleomagnetic observations in the United States. Geol. Soc. America Bull., 71:915-958.

CONDIE, Kent C. 1982. Plate-tectonics model for Proterozoic continetnal accretion in the southwestern United States. Geology, 10:37-42.

COOLEY, John. 1988. The great unknown; the journals of the historic first expedition down the Colorado River. Flagstaff: Northland Publishing, 207 pp.

COOLEY, M. E. 1976. Spring flow from pre-Pennsylvanian rocks in the southwestern part of the Navajo Indian Reservation, Arizona. U.S. Geol. Survey Professional Paper 521-F, pp. F1-F15.

COOLEY, M. E., B. N. ALDRIDGE, and R. C. EULER. 1977. Effects of the catastrophic flood of December 1966, North Rim area, eastern Grand Canyon, Arizona. U.S. Geol. Survey Professional Paper 980, 43 pp.

COOLEY, M. E., J. W. HARSHBARGER, J. P. AKERS, and W. F. HARDT. 1969. Regional hydrology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, with a section on Vegetation by O. N. Hicks. U.S. Geol. Survey Professional Paper 521-A, pp. A1-A61.

CORLE, Edwin. 1946. Listen, Bright Angel. New York: Duell, Sloan and Pearce, 312 pp.

COX, Allan, and Richard R. DOELL. 1960. Review of paleomagnetism. Geol. Soc. America Bull., 71:645-768.

CREER, K. M., E. IRVING, and S. K. RUNCORN. 1957. Geophysical interpretation of palaeomagnetic directions from Great Britain. Royal Soc. London Philosophical Trans., Ser. A, 250:144-156.

CUNNINGHAM, Frank F., and Walter GRIBA. 1973. A model of slope development, and its application to the Grand Canyon, Arizona, U.S.A. Zeitschrift für Geomorphologie, 17:43-77.

DALTON, Russell O., and Richard R. RAWSON. 1974. Stratigraphy of the Bass Limestone, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 6:437.

DAMON, Paul E., and Bruno J. GILETTI. 1961. The age of the basement rocks of the Colorado Plateau and adjacent areas. New York Acad. Sciences, Annals, 91(art. 2):443-452.

DANEKER, Thomas M. 1974. Sedimentology of the Precambrian Shinumo Quartzite, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 6:438.

DARTON, N. H. 1910. A reconnaissance of parts of northwestern New Mexico and northern Arizona. U.S. Geol. Survey Bull. 435, 88 pp.

DARTON, N. H., and others. 1915. Guidebook to the western United States. Part C. The Santa Fe route; with a side trip to the Grand Canyon of the Colorado. U.S. Geol. Survey Bull. 613, 194 pp.

DAVIS, George H. 1978. Monocline fold pattern of the Colorado Plateau. In: V. Matthews, III, ed., Laramide folding associated with basement block faulting in the western United States. Geol. Soc. America Memoir 151, pp. 215-233.

DAVIS, William Morris. 1900. Notes on the Colorado Canyon district. Amer. Jour. Science, 4th Ser., 10:251-259.

-------. 1901. An excursion to the Grand Canyon of the Colorado. Harvard College, Museum of Comparative Zoology Bull., 38, Geol. Ser., 5(4):107-201.

-------. 1903. An excursion to the plateau province of Utah and Arizona. Harvard College, Museum of Comparative Zoology Bull., 42, Geol. Ser., 6(1):1-50.

-------. 1915a. Biographical memoir of John Wesley Powell, 1834-1902 (presented to the Academy, 1913). National Academy of Sciences, Biographical Memoirs, 8:9-83 [1919].

-------. 1915b. The development of the Transcontinental Excursion of 1912. In: Memorial volume of the Transcontinental Excursion of 1912 of the American Geographical Society of New York. New York: American Geographical Society, pp. 3-7.

DAY, Allen. 1905. Mining in the Grand Canyon. Scientific Amer., 93:478.

DAY, A. A., and S. K. RUNCORN. 1955. Polar wandering; some geological, dynamical and palaeomagnetic aspects. Nature, 176:422-426.

DECKER, Betty Lou. 1944. Wind markings in the Coconino Sandstone. Plateau, 16:52-56.

DOBYNS, Henry F., and Robert C. EULER. 1980. The Dunn-Howland killings: Additional insights. Jour. Arizona History, 21:87-95.

DOELL, Richard R. 1955. Palaeomagnetic study of rocks from the Grand Canyon of the Colorado River. Nature, 176:1167.

DOLAN, Robert, Alan HOWARD, and Arthur GALLENSON. 1974. Man's impact on the Colorado River in the Grand Canyon. Amer. Scientist, 62:392-401.

DOLAN, Robert, Alan HOWARD, and David TRIMBLE. 1978. Structural control of the rapids and pools of the Colorado River in the Grand Canyon. Science, 202:629-631, and cover.

DRYGALSKI, Erich von. 1915. Talübertiefung im Grand Cañon des Colorado. In: Memorial volume of the Transcontinental Excursion of 1912 of the American Geographical Society of New York. New York: American Geographical Society of New York, pp. 343-348.

DUNNING, C. H. 1948. A report on Hack's Canyon uranium mine, Mohave County, Arizona. U.S. Atomic Energy Commission open-file report RMO-999, 11 pp.

DUTTON, Clarence E. 1880. Report on the geology of the High Plateaus of Utah; with Atlas. Washington: U.S. Government Printing Office, 307 pp., Atlas, 8 sheets.

-------. 1882. Tertiary history of the Grand Cañon district; with atlas. U.S. Geol. Survey Mon. 2, 264 pp., Atlas, 23 sheets.

EASTON, W. H., and R. C. GUTSCHICK. 1953. Corals from the Redwall Limestone (Mississippian) of Arizona. Southern California Acad. Sciences Bull., 52(Part 1):1-27.

EASTWOOD, Raymond L. 1974. Cenozoic volcanism and tectonism of the southern Colorado Plateau. In: T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 236-256.

ELACHI, Charles, and Thomas G. FARR. 1979. Observation of the Grand Canyon wall structure with an airborne imaging radar. Remote Sensing of Environment, 9:171-174.

ELLIOTT, David K., and Daryl L. MARTIN. 1987a. A new trace fossil from the Cambrian Bright Angel Shale, Grand Canyon, Arizona. Jour. Paleontology, 61:641-648.

-------. 1987b. Chancelloria, an enigmatic fossil from the Bright Angel Shale (Cambrian) of Grand Canyon, Arizona. Arizona-Nevada Acad. Science, Jour., 21:67-72.

ELSTON, Donald P. 1979. Late Precambrian Sixtymile Formation and orogeny at top of the Grand Canyon Supergroup, northern Arizona. U.S. Geol. Survey Professional Paper 1092, 20 pp.

-------. 1986. Magnetostratigraphy of late Proterozoic Chuar Group and Sixtymile Formation, Grand Canyon Supergroup, northern Arizona: Correlation with other Proterozoic strata of North America. Geol. Soc. America, Abstracts with Programs, 18(5):353.

-------. 1988a. Paleomagnetic constraints on late Proterozoic-Cambrian continental reconstruction. Geol. Soc. America, Abstracts with Programs, 20(7):A297.

-------. 1988b. Paleomagnetic poles from Cambrian, Devonian, Pennsylvanian, and Permian strata of Arizona and Montana. Geol. Soc. America, Abstracts with Programs, 20(7):A350.

-------. 1988c. Grand Canyon Supergroup, northern Arizona: Stratigraphic summary and preliminary paleomagnetic correlations with parts of other North American Proterozoic successions. In: S. J. Reynolds and J. P. Jenney, eds., Summary of Arizona geology. Arizona Geol. Soc. Digest, 17 [cited by Elston et al., 1989, as in press].

-------. 1989. Middle and late Proterozoic Grand Canyon Supergroup, Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th International Geological Congress, Field Trips T115 and T315, Guidebook, Chapter 9.

ELSTON, Donald P., and George H. BILLINGSLEY. 1989. Geologic log of Colorado River from Lees Ferry to Temple Bar, Lake Mead, Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th International Geological Congress, Field Trips T115 and T315, Guidebook, Chapter 1.

ELSTON, Donald P., and Stephen L. BRESSLER. 1977. Paleomagnetic poles and polarity zonation from Cambrian and Devonian strata of Arizona. Earth and Planetary Science Letters, 36:423-433.

-------. 1980. Paleomagnetic poles and polarity zonation from the middle Proterozoic Belt Supergroup, Montana and Idaho. Jour. Geophys. Research, 85:339-355.

-------. 1984. Devonian polar path from Montana and refined Paleozoic polar path for North America [abstract]. Eos (Amer. Geophysical Union Trans.), 65(45):864-865.

ELSTON, Donald P., and C. Sherman GROMMÉ. 1974. Precambrian polar wandering from Unkar Group and Nankoweap Formation, eastern Grand Canyon, Arizona. In: T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 97-117.

-------. 1979. Paleomagnetic correlation of late Proterozoic strata of Arizona and Lake Superior [abstract]. Eos (Amer. Geophys. Union Trans.), 60:236.

ELSTON, Donald P., and Edwin H. McKEE. 1982. Age and correlation of the late Proterozoic Grand Canyon disturbance, northern Arizona. Geol. Soc. America Bull., 93:681-699.

ELSTON, Donald P., and G. Robert SCOTT. 1973. Paleomagnetism of some Precambrian basaltic flows and red beds, eastern Grand Canyon, Arizona. Earth and Planetary Science Letters, 18:253-265.

-------. 1976. Unconformity at the Cardenas-Nankoweap contact (Precambrian), Grand Canyon Supergroup, northern Arizona. Geol. Soc. America Bull., 87:1265-1272.

ELSTON, Donald P., and Richard A. YOUNG. 1989. Development of Cenozoic landscape of central and northern Arizona: Cutting of Grand Canyon. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona, including Colorado River trip guides. 28th International Geological Congress, Field Trips T115 and T315, Guidebook, Chapter 18.

ELSTON, Donald P., George H. BILLINGSLEY, and Richard A. YOUNG. 1989. (eds.) Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th International Geological Congress, Field Trips T115 and T315, Guidebook.

ELSTON, Donald P., C. Sherman GROMMÉ, and Edwin H. McKEE. 1973. Precambrian polar wandering and behavior of earth's magnetic field from stratified rocks of the Grand Canyon Supergroup, Arizona. Geol. Soc. America, Abstracts with Programs, 5:611-612.

ELSTON, Donald P., Richard A. YOUNG, Edwin H. McKEE, and Michael L. DENNIS. 1989. Paleontology, clast ages, and paleomagnetism of Upper Paleocene and Eocene gravel and limestone deposits, Colorado Plateau and Transition Zone, northern and central Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th International Geological Congress, Field Trips T115 and T315, Guidebook, Chapter 19.

EMMONS, S. F. 1905. Copper in the Red Beds of the Colorado Plateau region. U.S. Geol. Survey Bull. 260, pp. 221-232.

EULER, Robert C. 1978. Archaeological and paleobiological studies at Stanton's Cave, Grand Canyon National Park, Arizona--a report of progress. Natl. Geographic Soc. Research Reports, 1969 Projects, pp. 141-162.

-------. 1984. (ed.) The archaeology, geology, and paleobiology of Stanton's Cave, Grand Canyon National Park, Arizona. Grand Canyon Natural History Association Mon. 6, 141 pp.

FARQUHAR, Francis P. 1953. The books of the Colorado River and the Grand Canyon; a selective bibliography. Los Angeles: Glen Dawson, 75 pp.

FENG, J., E. C. PERRY, Jr., and Robert J. HORODYSKI. 1986. Sulfur isotope geochemistry of sulfate of the Belt Supergroup and the Grand Canyon Supergroup. Geol. Soc. America, Abstracts with Programs, 18(5):355.

FERRIS, H. A., and J. E. BUSCH. 1924. Bridal Veil Mines in Cataract Canyon. Arizona Mining Jour., 8:9-10, 23-34.

FERSMAN, A. E. 1940. Pegmatity. Tome I. Granitnii, pegmatity. [Pegmatites. Vol. 1. Granites, pegmatites.] Moscow: Academii Nauk USSR, 712 pp. [In Russian.]

FINCH, Warren I. 1967. Geology of epigenetic uranium deposits in sandstone in the United States. U.S. Geol. Survey Professional Paper 538, 121 pp.

FLANIGAN, Vincent J., Charles L. TIPPENS, Michael R. SENTERFIT, and Pamela J. MOHR. 1986. Geophysical exploration criteria for collapse breccia pipes, northern Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):355.

FLETCHER, Colin. 1967. The man who walked through time. New York: Alfred A. Knopf, 239 pp.

FORD, Trevor D., and William J. BREED. 1969. Preliminary geologic report of the Chuar Group, Grand Canyon, Arizona; with an appendix on Palynology of the Chuaria shales of the Grand Canyon, by C. Downie. In: Geology and natural history of the Grand Canyon region. Four Corners Geol. Soc., 5th Field Conference, Guidebook, pp. 114-122.

-------. 1970. Carbon Butte--an unusual landslide in the Grand Canyon. Plateau, 43:9-15.

-------. 1972a. The Chuar Group of the Proterozoic, Grand Canyon, Arizona. 24th Intl. Geol. Congr., Montreal, 1972, Section 1, Precambrian geology, pp. 3-10.

-------. 1972b. The problematical Precambrian fossil Chuaria. 24th Intl. Geol. Congr., Montreal, 1972, Section 1, Precambrian geology, pp. 11-18.

-------. 1973a. Late Precambrian Chuar Group, Grand Canyon, Arizona. Geol. Soc. America Bull., 84:1243-1260.

-------. 1973b. The problematical Precambrian fossil Chuaria. Palaeontology, 16:535-550.

-------. 1974a. The Younger Precambrian rocks of the Grand Canyon. In: W. J. Breed and E. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 21-33.

-------. 1974b. The Younger Precambrian fossils of the Grand Canyon. In: W. J. Breed, and E. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 34-40.

-------. 1977. Chuaria circularis Walcott and other Precambrian fossils from the Grand Canyon. Paleontological Soc. India, Jour., 20:170-177.

FORD, Trevor D., William J. BREED, and J. S. MITCHELL. 1972. Name and age of the upper Precambrian basalts in the eastern Grand Canyon. Geol. Soc. America Bull., 83:223-226.

FORD, Trevor D., Peter W. HUNTOON, George H. BILLINGSLEY, Jr., and William J. BREED. 1974. Rock movement and mass wastage in the Grand Canyon. In: W. J. Breed and E. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 116-128.

FRECH, Fritz. 1893. Section in Congress Canyon opposite Point Sublime. In: S. F. Emmons, ed., Geological guide book of the Rocky Mountain excursion. Congrès Géologique International, Compte Rendu de la 5^{me} Session, Washington, 1891. Washington: Imprimerie du Gouvernement [U.S. Government Printing Office], Part 4B, pp. 476-481.

-------. 1895. Das profil des grossen Colorado-Cañon. Neus Jahrbuch für Mineralogie, Geologie und Palaeontologie, 2:153-156.

FREEMAN, Lewis R. 1924. Surveying the Grand Canyon of the Colorado. Natl. Geographic Magazine, 45(5):471-530, 547-548 [see also pp. 536, 537].

FREUND, Raphael. 1979. Progressive strain in beds of monoclinal flexures. Geology, 7:269-271.

FRITZ, Mary. 1986. An oil rig at the Grand Canyon? Fieldnotes (Arizona Bureau of Geology and Mineral Technology), 16(1):9. [Excerpted from "high tech delivers results; oil patch helps in Grand Canyon," Explorer (Amer. Association Petroleum Geologists newsletter), 7(2), 1986.]

GIEGENGACK, Robert, and Richard R. PARDI. 1982. Field measurement of CO$_2$-exchange rate between the atmosphere and the water of Havasu Creek, Arizona. Abstracts, 11th International Radiocarbon Conference, Seattle, Washington, p. 35.

GIEGENGACK, Robert, Elizabeth K. RALPH, and Alan M. GAINES. 1979. Havasu Canyon--a natural geochemical laboratory. In: R. M. Linn, ed., Proceedings of the First Conference on Scientific Research in the National Parks. U.S. Natl. Park Service, Transactions and Proceedings Ser., no. 5, pp. 719-726.

GILBERT, G. K. 1872. Report of G. K. Gilbert, Geological Assistant. In: G. M. Wheeler, Preliminary report concerning explorations and surveys principally in Nevada and Arizona; 1871. Washington, D.C.: U.S. Government Printing Office, Appendix D, pp. 92-96.

-------. 1875. Report on the geology of portions of Nevada, Utah, California, and Arizona. Examined in the years 1871 and 1872. In: G. M. Wheeler, Report upon Geographical and Geological Surveys West of the One Hundreth Meridian, Vol. 3, Geology. Washington, D.C.: U.S. Government Printing Office, Part 1, pp. 17-187.

-------. 1876. The Colorado Plateau province as a field for geological study. Amer. Jour. Science, 3rd Ser., 12:16-24, 85-103.

-------. 1890. The strength of the earth's crust [abstract]. Geol. Soc. America Bull., 1:23-27.

-------. 1893. Flagstaff to the Grand Canyon. In: S. F. Emmons, ed., Geological guide book of the Rocky Mountain excursion. Congrès Géologique International, Compte Rendu de la 5^{me} Session, Washington, 1891. Washington: Imprimerie du Gouvernement [U.S. Government Printing Office], Part 4B, pp. 472-473.

GILETTI, Bruno J., and Paul E. DAMON. 1961. Rubidium-strontium ages of some basement rocks from Arizona and New Mexico. Geol. Soc. America Bull., 72:639-643.

GILMORE, Charles W. 1926. Fossil footprints from the Grand Canyon. Smithsonian Misc. Collections, 77(9), 41 pp.

-------. 1927. Fossil footprints from the Grand Canyon: Second contribution. Smithsonian Misc. Collections, 80(3), 78 pp.

-------. 1928. Fossil footprints from the Grand Canyon: Third contribution. Smithsonian Misc. Collections, 80(8), 16 pp.

GLAESSNER, Martin F. 1969. Trace fossils from the Precambrian and basal Cambrian. Lethaia, 2:369-393.

GORDON, Samuel G. 1923. Recently described "bisbeeite" from the Grand Canyon is cyanotrichite. Amer. Mineralogist, 8:92-93.

GORNITZ, Vivien M. 1969. Mineralization, alteration and mechanism of emplacement, Orphan ore deposit, Grand Canyon, Arizona. Ph.D. dissertation, Columbia University, 186 pp.

-------. 1986. Uranium mineralization at the Orphan Mine breccia pipe, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):357.

GORNITZ, Vivien, and Paul F. KERR. 1970. Uranium mineralization and alteration, Orphan Mine, Grand Canyon, Arizona. Economic Geology, 65:751-768.

GORNITZ, Vivien, K. J. WENRICH, H. B. SUTPHIN, and R. VIDALE-BUDEN. 1988. Origin of the Orphan Mine breccia pipe uranium deposit, Grand Canyon, Arizona. In: A. H. Vassiliou, D. M. Hausen, and D. J. Carson, eds., Process mineralogy VII--As applied to sepration technology. Warrendale, Pennsylvania: The Metallurgical Society, pp. 281-301.

GRAF, Julia B., John C. SCHMIDT, and Susan W. KIEFFER. 1989. Hydraulic log of the Colorado River from Lees Ferry to Diamond Creek, Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th Intl. Geol. Congr., Guidebook, Chapter 2.

GRAF, William L. 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geol. Soc. America Bull., 89:1491-1501.

-------. 1979. Rapids in canyon rivers. Jour. Geology, 87:533-551.

GRAF, William L., Richard HEREFORD, Julie LAITY, and Richard A. YOUNG. 1987. Colorado Plateau. In: W. L. Graf, ed., Geomorphic systems of North America. Geol. Soc. America, Centennial Special Vol. 2, pp. 259-302.

GRANGER, H. C. 1951. Preliminary summary of reconnaissance for uranium in Arizona. U.S. Geol. Survey Trace Elements Memorandum Report 304, 11 pp.

GRANGER, H. C., and R. B. RAUP. 1962. Reconnaissance study of uranium deposits in Arizona. U.S. Geol. Survey Bull. 1147-A, pp. A1-A54.

GRATER, Russell, and Harold H. HAWKINS. 1935. Rock slide in the Coconino sandstone. Grand Canyon Nature Notes, 9(10):368-369.

GRAY, Robert. 1964. Late Cenozoic geology of Hindu Canyon, Arizona. Arizona Acad. Science, Jour., 3(1):39-42.

GREGORY, Herbert E. 1915. The igneous origin of the "glacial deposits" on the Navajo Reservation, Arizona and Utah. Amer. Jour. Science, 4th Ser., 40:97-115.

-------. 1932. Colorado Plateau region. 16th Intl. Geol. Congr., United States, 1933, Guidebook--Excursions C-1 and C-2. Washington, D.C.: U.S. Government Printing Office, 38 pp.

-------. 1947. Colorado drainage basin. Amer. Jour. Science, 245:694-705.

GROVER, Paul W. 1986. Environmental interpretations of the Late Mississippian-Early Pennsylvanian Surprise Canyon Formation, ca carbonate-clastic estuary deposit, Grand Canyon, AZ. Geol. Soc. America, Abstracts with Programs, 18(5):358.

GUTSCHICK, R. C. 1943. The Redwall Limestone (Mississippian) of Yavapai County, Arizona. Plateau, 16:1-11.

HALL, Sharlot M. 1975. Sharlot Hall on the Arizona Strip; a diary of a journey through northern Arizona in 1911 (C. G. Crampton, ed.). Flagstaff: Northland Press, 97 pp.

HALPERN, Yvonne. 1988. The effect of lithology, diagenesis, and low-grade metamorphism on the ultrastructure and surface sculpture of acritarchs from the late Proterozoic Chuar Group, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 20(7):A226.

HAMBLIN, W. Kenneth. 1963a. Transition between the Colorado Plateau and the Basin and Range in southern Utah and northern Arizona. Geol. Soc. America, Abstracts for 1962, p. 85.

-------. 1963b. Origin and significance of reverse drag in fault-flexure displacements. Geol. Soc. America, Abstracts for 1962, pp. 164-165.

-------. 1965. Origin of "reverse drag" on the downthrown side of normal faults. Geol. Soc. America Bull., 76:1145-1164.

-------. 1969. Late Cenozoic lava flows in the Grand Canyon of the Colorado River, Arizona. In: Geology and natural history of the Grand Canyon region. Four Corners Geol. Soc., 5th Field Conference, Guidebook, pp. 41-60.

-------. 1970a. Late Cenozoic basalt flows of the western Grand Canyon. In: W. K. Hamblin and M. G. Best, eds., The western Grand Canyon district. Utah Geol. Soc., Guidebook to the geology of Utah, no. 23, pp. 21-37.

-------. 1970b. Lava dams in the Toroweap and Prospect areas of the Grand Canyon. In: W. K. Hamblin and M. G. Best, eds., The western Grand Canyon district. Utah Geol. Soc., Guidebook to the geology of Utah, no. 23, pp. 81-91.

-------. 1974. Late Cenozoic volcanism in the western Grand Canyon. In: W. J. Breed and E. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 142-169.

HAMBLIN, W. Kenneth, and Myron G. BEST. 1970. (eds.) The western Grand Canyon district. Utah Geol. Soc., Guidebook to the geology of Utah, no. 23, 156 pp.

HAMBLIN, W. Kenneth, and J. Keith RIGBY. 1969. Guidebook to the Colorado River. Part 2. Phantom Ranch in Grand Canyon National Park to Lake Mead, Arizona-Nevada. Brigham Young University Geology Studies, 15(Part 2), 126 pp.

HAMBLIN, W. K., P. E. DAMON, and William B. BULL. 1981. Estimates of vertical crustal strain rates along the western margins of the Colorado Plateau. Geology, 9:293-298.

HAMBLIN, W. K., Paul E. DAMON, and M. SHAFIQULLAH. 1975. Rates of erosion in the Virgin River drainage basin in southern Utah and northern Arizona. Geol. Soc. America, Abstracts with Programs, 7:1097-1098.

HARINGTON, C. R. 1972. Extinct animals of Rampart Cave. Canadian Geographical Jour., 85:178-183.

HARRINGTON, M. R. 1936. A new ground-sloth den. Masterkey, 10:225-227.

HARRIS, David R. 1966. Recent plant invasions in the arid and semi-arid Southwest of the United States. Amer. Association Geographers, Annals, 56:408-422.

HAUFF, Phoebe L., and Edwin D. McKEE. 1979. The use of corrensite as an indicator of depositonal environment in the Supai Group of the Grand Canyon region, Arizona. Clay Minerals Soc., 16th meeting, 28th Annual Clay Minerals Conference, Macon, Georgia, Program and Abstracts, pp. 41-42.

-------. 1981. The clay minerals of the Supai Group--Grand Canyon. Intl. Association for the Study of Clays, 7th Intl. Clay Conference, Bologna and Pavia, Italy, Abstracts, p. 124.

-------. 1982. Clay mineralogy. In: E. D. McKee, The Supai Group of Grand Canyon. U.S. Geol. Survey Professional Paper 1173, pp. 287-331.

HAY, Oliver P. 1922. Descriptions of species of Pleistocene Vertebrata, types or specimens of most of which are preserved in the United States National Museum. U.S. Natl. Museum Proc., 59:599-642. ["Collection of fossil mammals made at Anita, Coconino County, Arizona," pp. 617-638, pls. 118-124.]

HENDRICKS, John D. 1972. Precambrian diabase sills and dikes of the Grand Canyon National Park, Arizona. Geol. Soc. America, Abstracts with Programs, 4:381.

HENDRICKS, John D., and Ivo LUCCHITTA. 1974. Upper Precambrian igneous rocks of the Grand Canyon, Arizona. In: T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 65-86.

HINDS, Norman E. A. 1933. A study of the Algonkian formations in Grand Canyon. Grand Canyon Nature Notes, 8(5):182-183.

-------. 1934. Researches on Algonkian formations of Grand Canyon National Park. Carnegie Institution of Washington Year Book 33, pp. 306-309.

-------. 1935. Researches on Algonkian formations at Grand Canyon National Park. Carnegie Institution of Washington Year Book 34, pp. 326-329.

-------. 1936a. Ep-Archean and Ep-Algonkian intervals in western North America. In: Contributions to pre-Cambrian geology of western North America. Carnegie Institution of Washington Pub. 463, Part 1, pp. 1-52.

-------. 1936b. Uncompahgran and Beltian deposits in western North America. In: Contributions to pre-Cambrian geology of western North America. Carnegie Institution of Washington Pub. 463, Part 2, pp. 53-136.

-------. 1936c. Researches on Algonkian formations at Grand Canyon National Park. Carnegie Institution of Washington Year Book 35, pp. 331-333.

-------. 1937a. Researches on Algonkian formations. Carnegie Institution of Washington Year Book 36, pp. 348-349.

-------. 1937b. Pre-Cambrian geology in western North America [abstract]. Geol. Soc. America, Proceedings for 1936, pp. 305-306.

-------. 1937c. Algonkian [abstract]. Geol. Soc. America, Proceedings for 1936, p. 306.

-------. 1938a. Researches on Algonkian formations. Carnegie Institution of Washington Year Book 37, p. 358.

-------. 1938b. Large landslides in the Colorado Plateau [abstract]. Geol. Soc. America, Proceedings for 1937, pp. 241-242.

-------. 1938c. An Algonkian jellyfish from the Grand Canyon of the Colorado. Science, 88:186-187.

-------. 1939. Late pre-Cambric rocks of western North America. Pan-Amer. Geologist, 71:44-46.

-------. 1940. Pre-Cambrian igneous complexes and orogenies in western North America [abstract]. Geol. Soc. America Bull., 51:1958-1959.

HINTZE, Lehi F. 1988. Geologic history of Utah. Brigham Young University Geology Studies, Special Pub. 7, 202 pp.

HITCHCOCK, Edward. 1857. Illustrations of surface geology. In: Smithsonian Contributions to Knowledge, Vol. 9, 155 pp. [separately paginated paper within the volume].

HODGSON, Robert A. 1961. Reconnaissance of jointing in Bright Angel area, Grand Canyon, Arizona. Amer. Association Petroleum Geologists Bull., 45:95-97.

HORODYSKI, Robert J. 1986. Paleontology of the late Precambrian Chuar Group, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):362.

-------. 1988. Late Proterozoic fossils from the western U.S.: Could they represent the oldest skeletal metaphytes and the oldest meiofaunal traces? Geol. Soc. America, Abstracts with Programs, 20(7):A256.

HOWARD, Alan, and Robert DOLAN. 1981. Geomorphology of the Colorado River in the Grand Canyon. Jour. Geology, 89:269-298.

HOWELL, B. F., and CAMBRIAN SUBCOMMITTEE, NATIONAL RESEARCH COUNCIL COMMITTEE ON STRATIGRAPHY. 1944. Correlation of the Cambrian formations of North America. Geol. Soc. America Bull., 55:993-1003.

HUGHES, J. Donald. 1967. The story of man at Grand Canyon. Grand Canyon Natural History Association Bull. 14, 195 pp.

-------. 1978. In the house of stone and light; a human history of the Grand Canyon. Grand Canyon Natural History Association, 137 pp.

HUNT, Charles B. 1956. Cenozoic geology of the Colorado Plateau. U.S. Geol. Survey Professional Paper 279, 99 pp.

-------. 1969. Cenozoic history of the Colorado River. In: The Colorado River region and John Wesley Powell. U.S. Geol. Survey Professional Paper 669-C, pp. 59-130.

-------. 1974. Grand Canyon and the Colorado River, their geologic history. In: W. J. Breed and R. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 129-141.

HUNTINGTON, Ellsworth, and James Walter GOLDTHWAIT. 1903. The Hurricane fault in southwestern Utah. Jour. Geology, 11:46-63.

-------. 1904. The Hurricane fault in the Toquerville district, Utah. Harvard College, Museum of Comparative Zoology, Bull., 42, Geol. Ser., 6:199-259.

HUNTOON, Peter W. 1967. Karst springs in the Tapeats Amphitheater, Grand Canyon [abstract]. Caves and Karst, 9:50.

-------. 1969. Recurrent movements and contrary bending along the West Kaibab fault zone. Plateau, 42:66-74.

-------. 1970. The hydro-mechanics of the ground water system in the southern portion of the Kaibab Plateau, Arizona. Ph.D. dissert., University of Arizona, 251 pp.

-------. 1971. The deep structure of the monoclines in eastern Grand Canyon, Arizona. Plateau, 43:148-158.

-------. 1973. High-angle gravity faulting in the eastern Grand Canyon, Arizona. Plateau, 45:117-127.

-------. 1974a. Synopsis of Laramide and post-Laramide structural geology of the eastern Grand Canyon, Arizona. In: T. N. V. Karlstrom, G. A. Swann, and R. L. Raymond, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 317-335.

-------. 1974b. The post-Paleozoic structural geology of the eastern Grand Canyon, Arizona. In: W. J. Breed and R. C. Roat, eds., Geology of the Grand Canyon. Flagstaff: Museum of Northern Arizona, and Grand Canyon Natural History Association, pp. 82-115.

-------. 1974c. The karstic groundwater basins of the Kaibab Plateau, Arizona. Water Resources Research, 10:579-590.

-------. 1975. The Surprise Valley landslide and widening of the Grand Canyon. Plateau, 48:1-12.

-------. 1977a. Holocene faulting in the western Grand Canyon, Arizona. Geol. Soc. America Bull., 88:1619-1622.

-------. 1977b. Cambrian stratigraphic nomenclature and ground-water prospecting failures on the Hualapai Plateau, Arizona. Ground Water, 15:426-433.

-------. 1977c. Relationship of tectonic structure to aquifer mechanics in the western Grand Canyon district, Arizona. U.S. Department of the Interior, Office of Water Research and Technology, Completion Report, Project B-31-W70 (14-34-0001-6134), 51 pp.

-------. 1978. Reply to the preceding discussion by R. A. Young of "Cambrian stratigraphic nomenclature and ground-water prospecting failures on the Hualapai Plateau, Arizona." Ground Water, 16:289-291.

-------. 1981a. Grand Canyon monoclines: Vertical uplift or horizontal compression? Contributions to Geology, 19:127-134.

-------. 1981b. Fault controlled ground-water circulation under the Colorado River, Marble Canyon, Arizona. Ground Water, 19:20-27.

-------. 1986. Ground water flow directions in Colorado Plateau breccia pipes. Geol. Soc. America, Abstracts with Programs, 18(5):363.

-------. 1988. Early Tertiary reorganization of stresses, southwestern Colorado Plateau, Arizona--observed strain and a hypothesis on cause. Geol. Soc. America, Abstracts with Programs, 20(3):170.

-------. 1989. Bat Cave guano mine, western Grand Canyon, Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th Intl. Geol. Congr., Guidebook, Chapter 28.

HUNTOON, Peter W., and BILLINGSLEY, George H., Jr.; with Malcolm D. CLARK. 1981. Geologic map of the Hurricane fault zone and vicinity, western Grand Canyon, Arizona. Grand Canyon Natural History Association, scale 1:48,000.

-------. 1982. Geologic map of the Lower Granite Gorge and vicinity, western Grand Canyon, Arizona. Grand Canyon Natural History Association, scale 1:48,000.

HUNTOON, Peter W., and Donald P. ELSTON. 1980. Origin of the river anticlines, central Grand Canyon, Arizona. U.S. Geol. Survey Professional Paper 1126-A, pp. A1-A9.

HUNTOON, Peter W., and James W. SEARS. 1975. Bright Angel and Eminence faults, eastern Grand Canyon, Arizona. Geol. Soc. America Bull., 86:465-472.

HUNTOON, Peter W., George H. BILLINGSLEY, Jr., William J. BREED, James W. SEARS, Trevor D. FORD, Malcolm D. CLARK, R. Scott BABCOCK, Edwin BROWN, et al. 1976. Geologic map of the Grand Canyon National Park, Arizona. Grand Canyon Natural History Association, and Museum of Northern Arizona, scale 1:62,500.

IDDINGS, Joseph Paxson. 1894. Petrographical character of the lavas. In: C. D. Walcott, Pre-Cambrian igneous rocks of the Unkar terrane, Grand Canyon of the Colorado, Arizona; with notes upon the petrographic character of the lavas by Joseph Paxson Iddings. U.S. Geol. Survey, 14th Annual Report, Part 2, pp. 520-524.

IVES, Joseph C. 1861. Report upon the Colorado River of the West. Washington: U.S. Government Printing Office; 36th Congress, 1st Session, Senate Executive Document 90, in five separately paginated parts, with appendices, 1 vol.

JAMES, George Wharton. 1900. In and around the Grand Canyon. Boston: Little, Brown, and Co., 341 pp. [also later editions, 1901, 1911].

JEFFERIS, Lee H. 1969. Lineaments in the Grand Canyon area, northern Arizona--a radar analysis. University of Kansas, Center for Research, Inc., Engineering Science Division; National Aeronautics and Space Administration, Manned Spacecraft Center, CRES rept. 118-9, 16 pp.

JEFFERSON, Mark S. W. 1897. The antecedent Colorado. Science, new ser., 6:293-295.

JENNINGS, E. P. 1904. The copper-deposits of the Kaibab Plateau, Arizona. Amer. Inst. Mining Engineers Trans., 34:839-841.

JOHNSON, Douglas W. 1909. A geological excursion in the Grand Cañon district. Boston Soc. Natural History, Proc., 34:135-161.

JOHNSON, Noye M. 1963. Thermoluminescence in contact metamorphosed limestone. Jour. Geology, 71:596-616.

JOHNSON, P. W., and R. B. SANDERSON. 1968. Spring flow into the Colorado River--Lees Ferry to Lake Mead, Arizona. Arizona State Land Dept., Water-Resources Report 34, 26 pp.

KARLSTROM, Thor N. V., Gordon A. SWANN, and Raymond L. EASTWOOD. 1974. (eds.) Geology of northern Arizona; with notes on archaeology and paleoclimate. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, 2 vols.

KAUFFMAN, Erle G., and Franz FURSICH. 1983. Brooksella canyonensis: A billion year old complex Metazoan trace fossil from the Grand Canyon. Geol. Soc. America, Abstracts with Programs, 15(6):608.

KAUFFMAN, Erle G., and James R. STEIDTMANN. 1981. Are these the oldest metazoan trace fossils? Jour. Paleontology, 55:923-947.

KELLEY, Vincent C. 1955a. Monoclines of the Colorado Plateau. Geol. Soc. America Bull., 66:789-803.

-------. 1955b. Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium. University of New Mexico Publications in Geology, no. 5, 122 pp.

KEYES, Charles R. 1913. Angular amphitheaters of the Grand Canyon [abstract]. Science, new ser., 37:457-458.

-------. 1938. Basement complex of the Grand Canyon. Pan-Amer. Geologist, 70:91-116.

KIEFFER, Susan Werner. 1985. The 1983 hydraulic jump in Crystal Rapid: Implications for river-running and geomorphic evolution in the Grand Canyon. Jour. Geology, 93:385-406.

-------. 1987. The rapids and waves of the Colorado River, Grand Canyon, Arizona. U.S. Geol. Survey open-file report 87-096.

-------. 1988. Hydraulic map of House Rock Rapids, Grand Canyon, Arizona. U.S. Geol. Survey, Miscellaneous Investigations Series, map I-1897-A, 1 sheet, scale 1:1,000.

KNAUTH, L. Paul. 1982. Isotopic analyses of upper Proterozoic cherts with possible implications for upper Precambrian climates and the Phanerozoic explosion of life. Geol. Soc. America, Abstracts with Programs, 14(7):532.

KNAUTH, L. Paul, and Samuel EPSTEIN. 1976. Hydrogen and oxygen isotope ratios in nodular and bedded cherts. Geochimica et Cosmochimica Acta, 40:1095-1108.

KOLB, Ellsworth L. 1914. Through the Grand Canyon from Wyoming to Mexico. New York: Macmillan Co., 344 pp. [New ed., with additional illustrations, 1915, 344 pp.]

KOONS, E. Donaldson. 1943. The Uinkaret volcanic field, Arizona. Plateau, 15:52-59.

-------. 1945. Geology of the Uinkaret Plateau, northern Arizona. Geol. Soc. America Bull., 56:151-180.

-------. 1948. Geology of the eastern Hualpai Reservation. Plateau, 20:53-60.

-------. 1955. Cliff retreat in the southwestern United States. Amer. Jour. Science, 253:44-52.

-------. 1969. Evolution of the Colorado River in Arizona. Geol. Soc. America, Abstracts for 1969, Part 5, pp. 41-42.

KRUGER-KNUEPFER, Joyce L., Marc L. SBAR, and Randall M. RICHARDSON. 1985. Microseismicity of the kaibab Plateau, northern Arizona, and its tectonic implications. Seismological Soc. America Bull., 75:491-505.

KURTÉN, Björn, and Elaine ANDERSON. 1980. Pleistocene mammals of North America. New York: Columbia University Press, 442 pp.

LA RUE, E. C. 1925. Water power and flood control of Colorado River below Green River, Utah. U.S. Geol. Survey Water-Supply Paper 556, 176 pp.

LANDAIS, P. 1986. Geochemical analyses of the organic matters associated with the breccia pipes in the Grand Canyon area. Geol. Soc. America, Abstracts with Programs, 18(5):389.

LANGE, Arthur L. 1955. The role of caves in dating Grand Canyon. Plateau, 27(3):1-7.

-------. 1956. Cave evolution in Marble Gorge of the Colorado River. Plateau, 29:12-21.

-------. 1962. Grand Canyon cave provinces [abstract]. Cave Notes, 4(5):42-43.

LANPHERE, Marvin A., and G. J. WASSERBURG. 1963. Some ages in the Precambrian of Arizona, Nevada, and Utah. Geol. Soc. America, Abstracts for 1962, p. 45.

LARSON, E. E., P. E. PATTERSON, and J. G. ROSENBAUM. 1978. Concerning the origin, chemistry, and age of the Precambrian lavas in the Grand Canyon [abstract]. Eos (Amer. Geophys. Union Trans.), 59:1212.

LAURSEN, Emmett M., Simon INCE, and Jack POLLACK. 1976. On sediment transport through the Grand Canyon. In: Proceedings of the Third Federal Inter-Agency Sedimentation Conference, 1976. Sedimentation Committee, Water Resources Council, rept. PB-245100, pp. 4-76--4-87.

LAUZON, H. R. 1934. Is there gold in the Canyon? Grand Canyon Nature Notes, 8(10):233-234.

LEE, Willis T. 1908. Geological reconnaissance of a part of western Arizona; with notes on the Igneous rocks of western Arizona by Albert Johannsen. U.S. Geol. Survey Bull. 352, 96 pp.

LEEMAN, W. P. 1974. Late Cenozoic alkali-rich basalt from the western Grand Canyon area, Utah and Arizona: Isotopic composition of strontium. Geol. Soc. America Bull., 85:1691-1696.

LEICHT, Wayne C. 1971. Minerals of the Grandview Mine. Mineralogical Record, (September-October):215-221.

LEOPOLD, Luna B. 1969. The rapids and the pools--Grand Canyon. In: The Colorado River region and John Wesley Powell. U.S. Geol. Survey Professional Paper 669-D, pp. 131-145.

LEVINGS, Gary W., and FARRAR, C. D. [1979]. Maps showing ground-water conditions in the Kanab area, Coconino and Mohave Counties, Arizona--1976. U.S. Geol. Survey open-file report 79-1070, 2 sheets, scale 1:250,000.

LINGLEY, William S., Edwin H. BROWN, and R. Scott BABCOCK. 1973. Older Precambrian rocks of the Clear Creek-Zoroaster Canyon area, Grand Canyon National Park, Arizona. Geol. Soc. America, Abstracts with Programs, 5:492.

LIVINGSTON, D. E., E. H. BROWN, and R. S. BABCOCK. 1974. Geochemistry of selected elements in the "Older" Precambrian rocks of the Grand Canyon. Geol. Soc. America, Abstracts with Programs, 6:452-453.

LONGWELL, Chester R. 1928. Geology of the Muddy Mountains, with a section through the Virgin Range to the Grand Wash Cliffs, Arizona. U.S. Geol. Survey Bull. 798, 152 pp.

-------. 1936. Geology of the Boulder Reservoir floor, Arizona-Nevada. Geol. Soc. America Bull., 47:1393-1476, 21 pls.

-------. 1937. Sedimentation in relation to faulting. Geol. Soc. America Bull., 48:433-441.

-------. 1946. How old is the Colorado River? Amer. Jour. Science, 244:817-835.

-------. 1960. Geologic setting of Lake Mead. In: W. O. Smith, C. P. Vetter, G. B. Cummings, and others, Comprehensive survey of sedimentation in Lake Mead, 1948-49. U.S. Geol. Survey Professional Paper 295, pp. 11-20.

LONGWELL, C. R., H. D. MISER, R. C. MOORE, Kirk BRYAN, and Sidney PAIGE. 1923. Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona. U.S. Geol. Survey Professional Paper 132-A, pp. 1-23.

LOVEJOY, Earl M. P. 1956. Hurricane fault [abstract]. Geol. Soc. America Bull., 67:1774.

-------. 1959. Hurricane fault problem, Utah and Arizona [abstract]. Geol. Soc. America bull., 70:1732.

-------. 1964a. Age of the Colorado River in the Colorado Plateau. Geol. Soc. America, Abstracts for 1963, p. 281.

-------. 1964b. The Hurricane fault zone, and the Cedar Pocket Canyon-Shebit-Gunlock fault complex, southwestern Utah and northwestern Arizona. Ph.D. dissertation, University of Arizona, 260 pp.

-------. 1969. Grand Wash problem at Grand Canyon. Geol. Soc. America, Abstracts for 1969, Part 5, p. 46.

-------. 1973. Major early Cenozoic deformation along Hurricane fault zone, Utah and Arizona. Amer. Association Petroleum Geologists Bull., 57:510-519.

-------. 1974. Laramide inception of Grand Wash faulting, Colorado Plateau. Geol. Soc. America, Abstracts with Programs, 6:454.

-------. 1976. Pre-Pliocene river system development, Colorado Plateau and southern Rocky Mountains: A theory. Geol. Soc. America, Abstracts with Programs, 8:603.

-------. 1977. Neogene Colorado River development in Colorado Plateau: A theory. Geol. Soc. America, Abstracts with Programs, 9:457.

LUCCHITTA, Ivo. 1967. Cenozoic geology of the upper Lake Mead area adjacent to the Grand Wash Cliffs, Arizona. Ph.D. dissertation, Pennsylvania State University, 218 pp.

-------. 1969. Early history of the Colorado River in the Basin and Range province. Geol. Soc. America, Abstracts for 1969, Part 5, pp. 47-48.

-------. 1972. Early history of the Colorado River in the Basin and Range province. Geol. Soc. America Bull., 83:1933-1947.

-------. 1974. Structural evolution of northwest Arizona and its relation to adjacent Basin and Range province structures. In: T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 336-354.

-------. 1975. The Shivwits Plateau. In: Application of ERTS images and image processing to regional geological problems and geological mapping in northern Arizona. California Inst. Technology, Jet Propulsion Laboratory, Technical Report 32-1597, pp. 41, 45.

-------. 1979. Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region. Tectonophysics, 61:63-95.

-------. 1984. Development of landscape in northwest Arizona: The country of plateaus and canyons. In: T. L. Smiley, J. D. Nations, T. L. Péwé, J. P. Schafer, eds., Landscapes of Arizona; the geological story. Lanham, Maryland: University Press of America, pp. 269-301.

-------. 1987. The mouth of the Grand Canyon and edge of the Colorado Plateau in the upper Lake Mead area, Arizona. In: S. S. Beus, ed., Rocky Mountain Section of the Geological Society of America. Geological Society of America, Centennial Field Guide, Vol. 2, pp. 365-370.

-------. 1988. Canyon maker; a geological history of the Colorado River. Plateau, 59(2), 32 pp..

LUCCHITTA, Ivo, and John D. HENDRICKS. 1972. Precambrian lava flows at Basalt Canyon, eastern Grand Canyon National Park, Arizona. Geol. Soc. America, Abstracts with Programs, 4:388-389.

-------. 1980. Paleogeography and tectonism at the time of the Precambrian Lavas, eastern Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 12(6):279.

-------. 1983. Characteristics, depositional environment, and tectonic interpretations of the Proterozoic Cardenas Lavas, eastern Grand Canyon, Arizona. Geology, 11(3):177-181.

LUCCHITTA, Ivo, and Edwin H. McKEE. 1975. New geochronologic constraints on the history of the Colorado River and its Grand Canyon. Geol. Soc. America, Abstracts with Programs, 7:342.

LUCCHITTA, Ivo, and Richard A. YOUNG. 1986. Structure and geomorphic character of western Colorado Plateau in the Grand Canyon-Lake Mead region. In: J. D. Nations, C. M. Conway, and G. A. Swann, eds., Geology of central and northern Arizona; field trip guidebook for Geological Society of America, Rocky Mountain Section meeting, Flagstaff, Arizona, 1986. Geol. Soc. America, Rocky Mountain Section, pp. 159-176.

LUCCHITTA, Ivo, John D. HENDRICKS, and Richard HEREFORD. 1983. Revision to the middle Proterozoic paleomagnetic path for the eastern Grand Canyon, Arizona, on the basis of reassignment of two key stratigraphic units. Geol. Soc. America, Abstracts with Programs, 15(5):422-423.

LUDWIG, K. R., and K. R. SIMMONS. 1988. Progress in U/Pb isotope studies of collapse-breccia pipes in the Grand Canyon region, northern Arizona. Geol. Soc. America, Abstracts with Programs, 20(7):A139.

LUDWIG, K. R., J. D. RASMUSSEN, and K. R. SIMMONS. 1986. Age of uranium ores in collapse-breccia pipes in the Grand Canyon area, northern Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):392.

LYLE, D. A. 1872. Report of Second Lieutenant D. A. Lyle, Second United States Artillery. In: George M. Wheeler, Preliminary report concerning explorations and surveys principally in Nevada and Arizona; 1871. Washington: U.S. Government Printing Office, Appendix B, pp. 76-90.

MALACH, Roman. 1974. Colorado River gold placers. Treasure, 5(6):36-37.

MARCOU, Jules. 1856. Resumé and field notes; with a translation by William P. Blake [and with other remarks]. From: Part 4, Report upon the geology of the route, No. 2. In: Reports of the explorations and surveys, to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean. Vol. 3. 33rd Congress, 2nd Session, Senate Executive Document 78, pp. 121-175.

-------. 1858. Geology of North America. Zurich: Zürcher and Furrer, for the author, 144 pp.

MARSAGLIA, Kathleen M., and George DeVries KLEIN. 1983. The paleogeography of Paleozoic and Mesozoic storm depositional systems. Jour. Geology, 91:117-142.

MARSHALL, R. B. 1915. (Chief Geographer) Results of spirit leveling in Arizona; 1899 to 1915, inclusive. U.S. Geol. Survey Bull. 573, 123 pp.

MARTIN, Daryl L., Larry T. MIDDLETON, and David K. ELLIOTT. 1986. Depositional systems of the Middle Cambrian Bright Angel Shale, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):394.

MARTIN, J. C. 1894. [Description of a trip to the Grand Canyon.] Prescott Journal Miner (newspaper), September [first appearance; other installments followed].

-------. 1982. Grand Canyon by stage (edited and introduction by Stephen G. Maurer). Albuquerque: Heritage Associates, 21 pp.

MARVINE, A. R. 1875. Report on the geology of the route from St. George, Utah, to Gila River, Arizona. Examined in 1871. In: George M. Wheeler, Report upon Geographical and Geological Surveys West of the One Hundreth Meridian. Vol. 3, Geology. Washington: U.S. Government Printing Office, Part 2, pp. 189-225.

MASCARENAS, J. F., Betsi BURMASTER, B. S. VAN GOSEN, and K. J. WENRICH. 1986. The use of soil sampling for breccia pipe exploration. Geol. Soc. America, Abstracts with Programs, 18(5):394.

MATSON, Dean W., David W. MUENOW, and Michael O. GARCIA. 1984. Volatiles in amphiboles from xenoliths, Vulcan's Throne, Grand Canyon, Arizona, USA. Geochimica et Cosmochimica Acta, 48:1629-1636.

MATTHES, François E. 1905a. Topographic methods used for the new detail maps of the Grand Canyon of the Colorado [abstract]. Report of the Eighth International Geographic Congress, held in the United States, 1904. Washington: U.S. Government Printing Office, p. 801.

-------. 1905b. Mapping the Grand Canyon. Technology Review, 7(1):1-25.

-------. 1927a. Influence of secondary faults on the development of the Grand Canyon topography [abstract]. Washington Acad. Sciences Jour., 17:233-234.

-------. 1927b. Breaking a trail through Bright Angel Canyon. Grand Canyon Nature Notes, 2(6).

-------. 1935. Breaking a trail through Bright Angel Canyon. In: History and exploration of the Grand Canyon region. Grand Canyon Natural History Association, Natural History Bull. 2, pp. 18-22.

MAXSON, John H. 1940. Colorado River system in Arizona [abstract]. Geol. Soc. America Bull., 51:1961.

-------. 1949. Lava flows in the Grand Canyon of the Colorado River, Arizona. Geol. Soc. America Bull., 60:9-16.

-------. 1961a. Grand Canyon origin and scenery. Grand Canyon Natural History Association Bull. 13, 31 pp.

-------. 1961b. Geologic map of the Bright Angel quadrangle, Grand Canyon National Park, Arizona. Grand Canyon Natural History Association, scale 1:48,000.

-------. 1967. Preliminary geologic map of the Grand Canyon and vicinity, Arizona; eastern section. Grand Canyon Natural History Association, scale 1:62,500.

-------. 1969. Preliminary geologic map of the Grand Canyon and vicinity; western and central sections. Grand Canyon Natural History Association, scale 1:62,500.

MAXSON, John H. and Ian CAMPBELL. 1934. Archean ripple mark in the Grand Canyon. Amer. Jour. Science, 5th Ser., 28:298-303.

-------. 1939. Archean pseudo ripple mark in the Grand Canyon. Amer. Jour. Science, 237:606.

McHENRY, Donald Edward. 1935. Earthquake; Grand Canyon. Grand Canyon Nature Notes, 9(11):372-377.

McKEE, Edwin D. 1929. Surface topography of the Kaibab. Grand Canyon Nature Notes, 4(2):10-12.

-------. 1930a. Vanadinite in the Grand Canyon. Grand Canyon Nature Notes, 4(8):52.

-------. 1930b. Copper deposits of Grand Canyon. Grand Canyon Nature Notes, 4(9):61.

-------. 1931. The origin of Hermit Basin. Grand Canyon Nature Notes, 5(3):27.

-------. 1933. The Coconino Sandstone--its history and origin. In: Papers concerning the palaeontology of California, Arizona, and Idaho. Carnegie Institution of Washington Pub. 440 [1934], Part 7, pp. 77-115.

-------. 1934. Remnants of the Age of Dinosaurs on South Rim of Grand Canyon. Grand Canyon Nature Notes, 9(5):310-314.

-------. 1935. Occurrence of Triassic sediments on the rim of Grand Canyon. Washington Acad. Sciences Jour., 25:184-187.

-------. 1938a. The environment and history of the Toroweap and Kaibab formations of northern Arizona and southern Utah. Carnegie Institution of Washington Pub. 492, 268 pp.

-------. 1938b. Original structures in Colorado River flood deposits of Grand Canyon. Jour. Sedimentary Petrology, 8:77-83.

-------. 1945. Small-scale structures in the Coconino Sandstone of northern Arizona. Jour. Geology, 53:313-325.

-------. 1946. Kanab Canyon: The trail of scientists. Plateau, 18:33-42.

-------. 1960. Cycles in carbonate rocks. Amer. Jour. Science, Bradley Vol., 258-A:230-233.

-------. 1963. Nomenclature for lithologic subdivisions of the Mississippian Redwall Limestone, Arizona. In: Geological Survey research 1963. U.S. Geol. Survey Professional Paper 475-C, pp. C21-C22.

-------. 1967. Arizona and western New Mexico. In: E. D. McKee, S. S. Oriel, and others, Paleotectonic investigations of the Permian System in the United States. U.S. Geol. Survey Professional Paper 515-J, pp. 201-223.

-------. 1969. Stratified rocks of the Grand Canyon. In: The Colorado River region and John Wesley Powell. U.S. Geol. Survey Professional Paper 669-B, pp. 23-58.

-------. 1975a. The Supai Group--subdivision and nomenclature. U.S. Geol. Survey Bull. 1395-J, pp. J1-J11.

-------. 1975b. Arizona. In: E. D. McKee and E. J. Crosby, coordinators, Paleotectonic investigations of the Pennsylvanian System in the United States. Part I. Introduction and regional analyses of the Pennsylvanian System. U.S. Geol. Survey Professional Paper 853-P, pp. 295-309.

-------. 1982. The Supai Group of Grand Canyon. U.S. Geol. Survey Professional Paper 1173, 504 pp.

-------. 1983a. Foreword. In: E. E. Spamer, Geology of the Grand Canyon: An annotated bibliography, 1857-1982; with an annotated catalogue of Grand Canyon type fossils. Geol. Soc. America Microform Pub. 13, pp. 5-7.

-------. 1983b. Sand deposits of the Rio Oronoco: An analog of the Wescogame Formation. Symposium on Southwestern Geology and Paleontology, Abstracts (Museum of Northern Arizona), p. 11.

-------. 1984. Sand deposits of the Rio Oronoco: An analog of the Wescogame Formation [abstract]. Eos (Amer. Geophys. Union Trans.), 64:701.

McKEE, Edwin D., with Joao J. BIGARELLA. 1979. Ancient sandstones considered to be eolian. In: E. D. McKee, ed., A study of global sand seas. U.S. Geol. Survey Professional Paper 1052, pp. 187-238.

McKEE, Edwin D., and William J. BREED. 1968. The Toroweap Formation and Kaibab Limestone [abstract]. New Mexico Geol. Soc., 22nd Annual Meeting, May 10, 1968, Hobbs, N.M., p. 9.

-------. 1969. The Toroweap Formation and the Kaibab Limestone. In: W. K. Summers and F. E. Kottlowski, eds., The San Andres Limestone, a reservoir for oil and water in New Mexico. New Mexico Geol. Soc. Special Pub. 3, pp. 12-26.

McKEE, Edwin D., and Raymond C. GUTSCHICK. 1969. History of the Redwall Limestone of northern Arizona. Geol. Soc. America Memoir 114, 726 pp.

McKEE, Edwin D., and Edwin H. McKEE. 1972. Pliocene uplift of the Grand Canyon region--time of drainage adjustment. Geol. Soc. America Bull., 83:1923-1932.

McKEE, Edwin D., and Charles E. RESSER. 1945. Cambrian history of the Grand Canyon region. Carnegie Institution of Washington Pub. 563, 232 pp.

McKEE, Edwin D., and Edward T. SCHENK. 1942. The Lower Canyon Lavas and related fetures at Toroweap in Grand Canyon. Jour. Geomorphology, 5:245-273.

McKEE, Edwin D., Richard F. WILSON, William J. BREED, and Carol S. BREED. 1967. (eds.) Evolution of the Colorado River in Arizona; an hypothesis developed at the Symposium on Cenozoic geology of the Colorado Plateau in Arizona, August 1964. Museum of Northern Arizona Bull. 44, 67 pp.

McKEE, Edwin D., W. Kenneth HAMBLIN, and Paul E. DAMON. 1968. K-Ar age of lava dam in Grand Canyon. Geol. Soc. America Bull., 79:133-136.

McKEE, Edwin H., and Donald C. NOBLE. 1974. Radiometric ages of diabase sills and basaltic lava flows in the Unkar Group, Grand Canyon. Geol. Soc. America, Abstracts with Programs, 6:458.

-------. 1976. Age of the Cardenas Lavas, Grand Canyon, Arizona. Geol. Soc. America Bull., 87:1188-1190.

McNAIR, Andrew H. 1951. Paleozoic stratigraphy of part of northwestern Arizona. Amer. Association Petroleum Geologists Bull., 35:503-541.

MERIFIELD, P. M., and D. L. LAMAR. 1970. Paleotides and the geologic record. In: S. K. Runcorn, ed., Palaeogeophysics. London: Academic Press, pp. 31-40.

MERRIAM, C. Hart. 1890. Results of a biological survey of the San Francisco Mountain region and desert of the Little Colorado in Arizona. U.S. Dept. Agriculture, North American Fauna, no. 3, 136 pp.

METZGER, D. G. 1961. Geology in relation to availability of water along the South Rim, Grand Canyon National Park, Arizona. U.S. Geol. Survey Water-Supply Paper 1475-C, pp. 105-135.

MÖLLHAUSEN, Balduin. [1860?], 1861. Reisen in die Felsengebirge Nord-Amerikas bis zum Hoch-Plateau von Neu-Mexico, unternommen als Mitglied der im Auftrage der Regierrung der Vereinigten Staaten ausgesandten Colorado-Expedition. Leipzig: Otto Pursurst, 2 vols., 455, 406 pp. [An undated edition may have been printed in 1860.]

MOOMAW, B. F., Jr. 1932. Identification of the common pink mineral found near Phantom Ranch. Grand Canyon Nature Notes, 6(5):46-47.

MOORE, Raymond C. 1926a. Origin of inclosed meanders on streams of the Colorado Plateau. Jour. Geology, 34:29-57.

-------. 1926b. Significance of inclosed meanders in the physigraphic history of the Colorado Plateau country. Jour. Geology, 34:97-130.

MOWAT, George D. 1960a. A magnesium-bearing speleothem from Silent River Cave, Grand Canyon, Arizona. Cave Notes, 2:18-19, cover.

-------. 1960b. Gypsum in Silent River Cave. Cave Notes, 2:25-26.

"NATIONAL GEOGRAPHIC." 1978. Mapping the canyon. Natl. Geographic Magazine, 154(1):36-37.

NATIONS, J. Dale, and Stanley S. BEUS. 1976. Teaching historical geology in the Grand Canyon. Jour. Geol. Education, 24:77-81.

NEWBERRY, J. S. 1861. Geological report. In: J. C. Ives, Report upon the Colorado River of the West. 36th Congress, 1st Session, Senate Executive Document 90, Part 3, 154 pp. [separately paginated].

NIELSON, Russell LaRell. 1981. Stratigraphy and depositional environments of the Toroweap and Kaibab Formations, southwestern Utah. (Volumes I and II). Ph.D. dissertation, University of Utah, 2 vols., pp. 1-494, 495-1,015. [University Microfilms International dissertation no. 8202202.]

NITECKI, Matthew H. 1971. Pseudo-organic structures from the Precambrian Bass Limestone in Arizona. Fieldiana--Geology, 23:1-9.

NOBLE, L. F. 1910. Contributions to the geology of the Grand Canyon, Arizona. -- Geology of the Shinumo area. Amer. Jour. Science, 4th Ser., 29:369-386, 497-528.

-------. 1914. The Shinumo quadrangle; Grand Canyon district, Arizona. U.S. Geol. Survey Bull. 549, 100 pp.

-------. 1922. A section of the Paleozoic formations of the Grand Canyon at the Bass trail. In: Shorter contributions to general geology, 1922. U.S. Geol. Survey Professional Paper 131-B, pp. 23-73.

NOBLE, L. F., and J. Fred HUNTER. 1917. A reconnaissance of the Archean complex of the Granite Gorge, Grand Canyon, Arizona. In: Shorter contributions to general geology, 1916. U.S. Geol. Survey Professional Paper 98, pp. 95-113.

NORTH AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE. 1983. North American stratigraphic code. Amer. Association Petroleum Geologists Bull., 67:841-875.

O'ROURKE, Mary Kar, and Jim I. MEAD. 1985. Late Pleistocene and Holocene pollen records from two caves in the Grand Canyon of Arizona, USA. In: B. F. Jacobs, P. L. Fall, and O. K. Davis, eds., Late Quaternary vegetation and climates of the American Southwest. American Association of Stratigraphic Palynologists, Contributions Series, no. 16, pp. 169-185.

PALACHE, Charles, and H. E. VASSAR. 1926. A note on cyanotrichite. Amer. Mineralogist, 11:213-214.

PAMPEL, L. C. 1960. Survey of Lower Granite Gorge. In: W. O. Smith, C. P. Vetter, G. B. Cummings, and others, Comprehensive survey of sedimentation in Lake Mead, 1948-49. U.S. Geol. Survey Professional Paper 295, pp. 73-81.

PEARTHREE, P. A., C. M. MENGES, and Larry MAYER. 1983. Distribution, recurrence intervals, and estimated magnitudes of Quaternary faulting in Arizona. Geol. Soc. America, Abstracts with Programs, 15(5):417.

PEIRCE, H. Wesley. 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States--Arizona. U.S. Geol. Survey Professional Paper 1110-Z, pp. Z1-Z20.

PEIRCE, H. Wesley, Paul E. DAMON, and M. SHAFIQULLAH. 1976. The Colorado Palteau margin in Arizona--normal faulting and uplift, drainage reversal and canyon cutting. Geol. Soc. America, Abstracts with Programs, 8:1045.

PEMBERTON, Ernest L. 1976. Channel changes in the Colorado River below Glen Canyon Dam. In: Proceedings of the Third Federal Inter-Agency Sedimentation Conference, 1976. Sedimentation Committee, Water Resources Council, pp. 5-61--5-73.

PENCK, Walthur. 1924. Die morphologische Analyse. Ein Kapitel der physikalischen Geologie. Stuttgart: J. Engelhorns, 283 pp.

-------. 1953. Morphological analysis of land forms; a contribution to physical geology (translated by Hella Czech and Katharine Cumming Boswell). London: Macmillan and Co., Ltd., 429 pp.

PHOENIX, David A. 1963. Geology of the Lees Ferry area; Coconino County, Arizona. U.S. Geol. Survey Bull. 1137, 86 pp.

PIERCE, Walter H. 1977. Early Permian slip and stratigraphic consequences of Hurricane and Grand Wash faults, northwest Arizona [abstract]. Amer. Association Petroleum Geologists Bull., 61:1386-1387.

POLLACK, Henry N. 1969. A numerical model of Grand Canyon. In: Geology and natural history of the Grand Canyon region. Four Corners Geol. Soc., 5th Field Conference, Guidebook, pp. 61-62. [Facsimile reprinting, 1969, under title "Dynamic modeling," in P. Fenner, convenor, Models of geologic processes: An introduction to mathematical geology. Amer. Geol. Inst./Council on Education in the Geological Sciences short course, 7-9 November 1969, Philadelphia, pp. HP29-HP30.]

POOLE, Forrest G. 1957. Paleo-wind directions in late Paleozoic and early Mesozoic time on the Colorado Plateau as determined by cross-strata [abstract]. Geol. Soc. America Bull., 68:1870.

-------. 1962. Wind directions in late Paleozoic to middle Mesozoic time on the Colorado Plateau. In: Geological Survey research 1962. U.S. Geol. Survey Professional Paper 450-D, pp. D147-D151.

-------. 1964. Palaeowinds in the western United States. In: A. E. M. Nairn, ed., Problems in palaeoclimatology; proceedings of the NATO Palaeoclimates Conference held at the University of Newcastle upon Tyne, January 7-12, 1963. London: Interscience Publishers, pp. 394-405.

POOLE, F. G., D. L. BAARS, H. DREWES, P. T. HAYES, K. B. KETNER, E. D. McKEE, C. TEICHERT, and J. S. WILLIAMS. 1967. Devonian and the southwestern United States. In: D. H. Oswald, ed., International Symposium on the Devonian System, Calgary, 1967. Calgary: Alberta Soc. Petroleum Geologists, Vol. 1, pp. 879-912.

POWELL, J. W. 1873a. Some remarks on the geological structure of a district of country lying to the north of the Grand Cañon of the Colorado. Amer. Jour. Science, 3rd Ser., 5:456-465.

-------. 1873b. A report of the survey of the Colorado of the West, and its tributaries. 42nd Congress, 3rd Session, House of Representatives Miscellaneous Document 76, 16 pp.

-------. 1875. Exploration of the Colorado River of the Wet and its tributaries. Explored in 1869, 1870, 1871, and 1872, under the direction of the Secretary of the Smithsonian Institution. Washington, D.C.: U.S. Government Printing Office, 291 pp.

-------. 1876. Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto. With atlas. Washington, D. C.: U.S. Geological and Geographical Survey of the Territories, U.S. Government Printing Office, 218 pp.

PRIEHS, T. J. 1976. Fire in Rampart Cave. Grand Canyon SAMA (newspaper), 3(11):1-2.

PYNE, Stephen J. 1982. Dutton's Point; an intellectual history of the Grand Canyon. Grand Canyon Natural History Association Mon. 5, 64 pp.

RADBRUCH-HALL, Dorothy H., Roger B. COLTON, William E. DAVIES, Betty A. SKIPP, Ivo LUCCHITTA, and David J. VARNES. 1981. Landslide overview map of the conterminous United States. U.S. Geol. Survey Professional Paper 1183, 25 pp.

RAGAN, Donal M., and Michael F. SHERIDAN. 1970. The Archean rocks of the Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 2:132-133.

RANSOME, F. L. 1908a. A comparison of some Paleozoic and pre-Cambrian sections in Arizona. Science, new ser., 27:68-69.

-------. 1908b. Pre-Cambrian sediments and faults in the Grand Canyon of the Colorado. Science, new ser., 27:667-669.

-------. 1917. Some Paleozoic sections in Arizona and their correlation. In: Shorter contributions to general geology, 1916. U.S. Geol. Survey Professional Paper 98, pp. 133-166.

RASMUSSEN, J. D., C. G. CUNNINGHAM, and A. M. GAUTIER. 1986. Primary fluid inclusions in sphalerite from the Hack 1 and 2 mines, Mohave County, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):404.

RAWSON, Richard R., and Norman W. KENT. 1979. Depositional dynamics of the Mississippian Redwall Limestone in northern Arizona. In: S. S. Beus and R. R. Rawson, eds., Carboniferous stratigraphy in the Grand Canyon country, northern Arizona and southern Nevada. 9th International Geological Congress of Carboniferous Stratigraphy and Geology, Field Trip 13. American Geological Institute, AGI Selected Guidebook Series, no. 2, pp. 81-88.

RAWSON, Richard R., and Christine E. TURNER. 1974. The Toroweap Formation: A new look. In: T. N. V. Karlstrom, G. A. Swann, and

R. L. Eastwoods, eds., Geology of northern Arizona; with notes on archaeology and paleoclimate. Part 1. Regional studies. Geol. Soc. America, Rocky Mountain Section meeting, Flagstaff, pp. 155-190.

RAWSON, Richard R., and Christine E. TURNER-PETERSON. 1979. Marine-carbonate, sabkha, and eolian facies transitions within the Permian Toroweap Formation, northern Arizona. In: D. L. Baars, ed., Permianland. Four Corners Geol. Soc., 9th Field Conference, Guidebook, pp. 87-99.

-------. 1980. Paleogeography of northern Arizona during the deposition of the Permian Toroweap Formation. In: T. D. Fouch and E. R. Magatham, eds., Paleozoic paleogeography of west-central United States. West-Central U.S. Paleogeography Symposium 1, Denver, June 1980, pp. 341-352.

RECHES, Ze'ev. 1976. Theoretical analysis of the Palisades monocline, Grand Canyon National Park, Arizona. Geol. Soc. America, Abstracts with Programs, 8:1061-1062.

-------. 1977. The development of monoclines. Ph.D. dissertation, Stanford University, 250 pp.

-------. 1978. Development of monoclines: Part I. Structure of the Palisades Creek branch of the East Kaibab monocline, Grand Canyon, Arizona. In: V. Matthews, III, ed., Laramide folding associated with basement block faulting in the western United States. Geol. Soc. America Memoir 151, pp. 235-271.

RECHES, Ze'ev, and Arvid M. JOHNSON. 1978. Development of monoclines: Part II. Theoretical analysis of monoclines. In: Matthews, III, ed., Laramide folding associated with basement block faulting in the western United States. Geol. Soc. America Memoir 151, pp. 273-311.

REESIDE, John B., and Harvey BASSLER. 1922. Stratigraphic sections in southwestern Utah and northwestern Arizona. In: Shorter contributions to general geology, 1921. U.S. Geol. Survey Professional Paper 129-D, pp. 53-77.

REICHE, Parry. 1938. An analysis of cross-lamination; the Coconino sandstone. Jour. Geology, 46:905-932.

REILLY, P. T. 1960. Aerial discoveries in the Grand Canyon. Plateau, 32:68-72.

-------. 1961. Travertine formations in Grand Canyon. Cave Notes, 3:1-6.

-------. 1967. The pirated spring at Stanton Cave. Caves and Karst, 9:5.

REIMER, G. M., and Josh M. BEEN. 1986. Helium soil-gas surveys of collapse features on the Hualapai Indian Researvation, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):404.

REPENNING, C. A., M. E. COOLEY, and J. P. AKERS. 1969. Stratigraphy of the Chinle and Moenkopi Formations, Navajo and Hopi Indian Reservations; Arizona, New Mexico, and Utah. U.S. Geol. Survey Professional Paper 521-B, pp. B1-B34.

REYNOLDS, Mitchell W., and Donald P. ELSTON. 1986. Stratigraphy and sedimentation of part of the Proterozoic Chuar Group, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):405.

REYNOLDS, Stephen J. 1988. Geologic map of Arizona. Arizona Geological Survey.

RICHMOND, Al. 1985. Cowboys, miners, presidents and kings; the story of the Grand Canyon Railway. Grand Canyon Pioneers Society, Inc., 187 pp.

ROBERTSON, Donald B. 1986. Encyclopedia of western railroad history. The desert states. Arizona, Nevada, New Mexico, Utah. Caldwell, Idaho: Caxton Printers, Ltd., 318 pp.

ROBINSON, H. H. 1907. The Tertiary peneplain of the Plateau District, and adjacent country, in Arizona and New Mexico. Amer. Jour. Science, 4th Ser., 24:109-129.

-------. 1910. A new erosion cycle in the Grand Canyon District, Arizona. Jour. Geology, 18:742-763.

-------. 1911. The single cycle development of the Grand Canyon of the Colorado. Science, new ser., 34:89-91.

ROGERS, Austin F. 1922. The optical properties and morphology of bisbeeite. Amer. Mineralogist, 7:153-154.

ROSVEDT, J. O., and others. 1971. Floods of December, in southwetern United Staes. In: J. O. Rosvedt and others, Summary of floods in the United States during 1966. U.S. Geol. Survey Water-Supply Paper 1870-D, pp. D62-D91.

RUMPP, Norman L. 1961. Three new tiger beetles of the Genus Cicindela from southwestern United States (Cincindelidae--Coleoptera). Southern California Acad. Sciences, Bull., 60(Part 3):165-187.

RUNCORN, S. K. 1955. Palaeomagnetism of sediments from the Colorado Plateau. Nature, 176:505-506.

-------. 1956. Paleomagnetic survey in Arizona and Utah: Preliminary results. Geol. Soc. America Bull., 67:301-316.

-------. 1964. Paleomagnetic results from Precambrian sedimentary rocks in the western United States. Geol. Soc. America Bull., 75:687-704.

SCHABER, Gerald G. 1968. Radar and infrared in geological sutides of northern Arizona. In: Earth resources aircraft program status review. Vol. 1, Geology, geography, and sensor studies. U.S. National Aeronautics and Space Administration, Manned Spacecraft Center, pp. 13-1--13-29.

SCHENK, Edward T. 1937. Gravigrade endates in lower Grand Canyon, Arizona [abstract]. Geol. Soc. America, Proceedings for 1936, p. 399.

SCHENK, Edward T., and Harry E. WHEELER. 1942. Cambrian sequence in western Grand Canyon, Arizona. Jour. Geology, 50:882-899.

SCHMIDT, Jack C. 1986a. Location and characteristics of alluvial deposits, Colorado River, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):410.

-------. 1986b. Controls on flow separation and sedimentation in a bedrock river, Colorado River, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 18(6):741.

SCHMIDT, John C., and Julia B. GRAF. 1988a. Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona--Executive summary. U.S. Geol. Survey open-file report 87-561, 15 pp.

-------. 1988b. Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. U.S. Geol. Survey open-file report 87-555, 120 pp.

SCHUCHERT, Charles. 1918a. On the Carboniferous of the Grand Canyon of Arizona. Amer. Jour. Science, 4th Ser., 45:347-361.

-------. 1918b. The Cambrian of the Grand Canyon of Arizona. Amer. Jour. Science, 4th Ser., 45:362-369.

SCHUMM, S. A., and R. J. CHORLEY. 1966. Talus weathering and scarp recession in the Colorado Plateaus. Zeitschrift für Geomorphologie, 10:11-36.

SEAGLE, Edward F. 1935. Roaring Springs Cave. Grand Canyon Nature Notes, 9(12):391-394.

SEAVEY, Charles A. 1979. Exploration and mapping of the Grand Canyon, 1859-1903. Special Libraries Association, Geography and Map Division, Bull. 119, pp. 4-15.

SEILACHER, Adolf. 1956. Der Beginn des Kambriums als biologische Wende. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, 103(1/2):155-180.

SHAKEL, Douglas W. 1976. Pliocene uplift of the Grand Canyon region--time of drainage adjustment: Discussion. Geol. Soc. America Bull., 87:1205-1207.

SHIRLEY, D. H., and R. A. PARNELL, Jr. 1986. Clay mineralogy in the paleoenvironmental analysis of the Surprise Canyon Formation, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):412.

SHOEMAKER, E. M., R. L. SQUIRES, and M. J. ABRAMS. 1978. Bright Angel and Mesa Butte fault systems in northern Arizona. In: R. B. Smith and G. P. Eaton, eds., Cenozoic tectonics and regional geophysics of the western Cordillera. Geol. Soc. America Memoir 152, pp. 341-367.

SILVER, L. T., T. H. ANDERSON, C. M. CONWAY, J. D. MURRAY, and R. E. POWELL. 1977. Geological featurs of southwestern North America. In: Skylab explores the earth. U.S. Natl. Aeronautics and Space Administration, Special Pub. 380, pp. 89-135.

SITGREAVES, L. 1853. Report of an expedition down the Zuni and Colorado Rivers. 32nd Congress, 2nd Session, Senate Executive Document 59, 198 pp.

SMITH, Dwight L., and C. Gregory CRAMPTON. 1987. (eds.) The Colorado River survey; Robert B. Stanton and the Denver, Colorado Canyon & Pacific Railroad. Salt Lake City: Howe Brothers, 305 pp.

SMITH, Robert B., and Gordon P. EATON. 1978. (eds.) Cenozoic tectonics and regional geophysics of the western Cordillera. Geol. Soc. America Memoir 152, 388 pp.

SMITH, W. O., C. P. VETTER, G. B. CUMMINGS, and others. 1960. Comprehensive survey of sedimentation in Lake Mead, 1948-49. U.S. Geol. Survey Professional Paper 295, 254 pp.

SNELL, Joan B. 1961. Method for predicting line-of-sight capabilities: Preliminary investigations. Geol. Soc. America Bull., 72:479-484.

SORAUF, James E. 1962. Structural geology and stratigraphy of the Whitmore area, Mohave County, Arizona. Ph.D. dissertation, University of Kansas, 361 pp.

SPAMER, Earle E. 1983. Geology of the Grand Canyon: An annotated bibliography, 1857-1982; with an annotated bibliography of Grand Canyon type fossils. Geol. Soc. America Microform Pub. 13, 543 pp.

-------. 1984a. Paleontology in the Grand Canyon of Arizona: 125 years of lessons and enigmas from the late Precambrian to the present. Mosasaur, 2:45-128.

-------. 1984b. Geology of the Grand Canyon: An annotated bibliography; with an annotated catalogue of Grand Canyon type fossils. Volume 2. Supplement to the annotated bibliography (1857-1983); Supplement and revisions to the annotated catalogue. Geol. Soc. America Microform Pub. 14, 229 pp.

-------. 1988. Geology of the Grand Canyon: An annotated bibliography; with an annotated catalogue of Grand Canyon type fossils. Volume 3. Second supplement (to 1987); with an annotated bibliography of the world literature on the Grand Canyon type fossil Chuaria circularis Walcott, 1899, an index fossil for the late Proterozoic. Geol. Soc. America Microform Pub. 17, 343 pp.

-------. 1989a. The late Proterozoic index fossil Chuaria circularis Walcott, 1899: Understanding an enigma. 28th Intl. Geol. Congr., Washington, D.C., Abstracts.

-------. 1989b. A historic piece of petrified wood from the Triassic of Arizona. Mosasaur, 4 [in press].

SPAMER, Earle E., and Earl A. SHAPIRO. 1980. Drainage basin analysis used to distinguish regional geomorphic trends--eastern Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 12:84.

SPAMER, Earle E.; with George H. BILLINGSLEY, William J. BREED, Robert C. EULER, and Grace KEROHER. 1981. Bibliography of the Grand Canyon and the lower Colorado River, 1540-1980. Grand Canyon Natural History Association Mon. 2, 119 pp.

STANTON, Robert Brewster. 1932. Colorado River controversies (James M. Chalfant, ed.). New York: Dodd, Mead and Co., 232 pp. [Facsimile reprinting, 1982, Boulder City, Nevada, Westwater Books; with commentaries by Otis R. Marston and Martin J. Anderson, 261 pp.]

-------. 1965. Down the Colorado (Dwight L. Smith, ed.). Norman: University of Oklahoma Press, 237 pp.

STEGNER, Wallace. 1954. Beyond the hundreth meridian; John Wesley Powell and the second opening of the West. Boston: Houghton Mifflin Co., 438 pp.

-------. 1977. Introduction. In: C. E. Dutton, Tertiary history of the Grand Cañon district; with atlas [facsimile reprinting of 1882 edition (U.S. Geol. Survey Mon. 2)]. Santa Barbara, California, and Salt Lake City, Utah: Peregrine Smith, Inc., pp. vii-xiii [Roman pagination in facsimile is not that of the Dutton original].

STEPHENS, Hal G., and Eugene M. SHOEMAKER. 1987. In the footsteps of John Wesley Powell; an album of comparative photographs of the Green and Colorado Rivers, 1871-72 and 1968. Boulder: Johnson Books; Denver: The Powell Society, 286 pp.

STEVENS, Joseph E. 1988. Hoover Dam; an American adventure. Norman: University of Oklahoma Press, 326 pp.

STEVENSON, Gene M. 1974. Stratigraphy of the Dox Formation, Precambrian, Grand Canyon, Arizona. Geol. Soc. America, Abstracts with Programs, 6:477.

STEVENSON, Gene M., and Stanley S. BEUS. 1982. Stratigraphy and depositional setting of the upper Precambrian Dox Formation in Grand Canyon. Geol. Soc. America Bull., 93:163-173.

STOYANOW, Alexander. 1936. Correlation of Arizona Paleozoic formations. Geol. Soc. America Bull., 47:459-540.

STRAHLER, Arthur N. 1944a. Valleys and parks of the Kaibab and Coconino plateaus, Arizona. Jour. Geology, 52:361-387.

-------. 1944b. A guide to the East Kaibab monocline in the Grand Canyon region. Plateau, 17:1-13.

-------. 1945. Landscape features of the Kaibab and Coconino Plateaus. Plateau, 18:1-6.

-------. 1947. A geological guide to the western part of the Kaibab Plateau. Plateau, 19:53-60.

-------. 1948. Geomorphology and structure of the West Kaibab fault zone and Kaibab Plateau, Arizona. Geol. Soc. America Bull., 59:513-540.

STRINGFIELD, V. T., P. E. LaMOREAUX, and H. E. LeGRAND; with Jan TOLSON (ed.) and C. Raymond RAYFIELD. 1974. Karst and paleohydrology of carbonate rock terranes in semiarid and arid regions with a comparison to humid karst of Alabama. Alabama Geol. Survey Bull. 105, 106 pp.

STURDEVANT, G. E. 1926a. Salt in the Tapeats sandstone. Grand Canyon Nature Notes, 1(6):3-5.

-------. 1926b. Calcite. Grand Canyon Nature Notes, 1(8):3-4.

STURGUL, John R., and Zvi GRINSHPAN. 1975. Finite-element model for possible isostatic rebound in the Grand Canyon. Geology, 3:169-171.

SUMMONS, Roger E., Simon C. BRASSELL, Geoffrey EGLINTON, Evan EVANS, Robert J. HORODYSKI, Neil ROBINSON, and David M. WARD. 1988. Distinctive hydrocarbon biomarkers from fossiliferous sediment of the Late Proterozoic Walcott Member, Chuar Group, Grand Canyon, Arizona. Geochimica et Cosmochimica Acta, 52:2625-2637.

SUTPHIN, Hoyt B., and Karen J. WENRICH. 1986. Redwall Limestone joint control on Orphan-Mine type breccia pipes on the Marble Plateau, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):416.

-------. 1988. Map showing structural control of breccia pipes on the southern Marble Plateau, north-central Arizona. U.S. Geol. Survey, Miscellaneous Investigations Series, map I-1778, 2 sheets.

SUTPHIN, Hoyt B., Karen J. WENRICH, and Earl R. VERBEEK. 1983. Structural control of breccia pipes on the southern Marble Plateau, Arizona. Geol. Soc. America, Abstracts with Programs, 15(5):376.

SZABO, B. J., P. A. O'MALLEY, and J. P. SCHAFER. 1986. Uranium-series dating of travertine deposits in Grand Canyon National Park, Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):417.

TAINTER, Stanton L. 1947. Apex copper property, Coconino County, Arizona. U.S. Bureau of Mines, Report of Investigations R. I. 4013, 16 pp.

TAYLOR, Walter W. 1954. An analysis of some salt samples from the Southwest. Plateau, 27(2):1-7.

THOMAS, H. E. 1960. Drainage basin tributary to Lake Mead. In: W. O. Smith, C. P. Vetter, G. B. Cummings, and others, Comprehensive survey of sedimentation in Lake Mead, 1948-49. U.S. Geol. Survey Professional Paper 295, pp. 21-30.

TURNER, Raymond M., and Martin M. KARPISCAK. 1980. Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona. U.S. Geol. Survey Professional Paper 1132, 125 pp.

U.S. BOARD ON GEOGRAPHIC NAMES. 1988a. Decisions on geographic names in the United States, Decision List 8803. Washington, D.C.: U.S. Board on Geographic Names.

-------. 1988b. Decisions on geographic names in the United States, Decision List 8804. Washington, D.C.: U.S. Board on Geographic Names.

U.S. GEOLOGICAL SURVEY. 1967. Age of lava dam in Grand Canyon. In: Geological Survey research 1967. U.S. Geol. Survey Professional Paper 575-A, p. A85.

-------. 1979. Chesterian channels discovered in western Grand Canyon, Arizona. In: Geological Survey research 1979. U.S. Geol. Survey Professional Paper 1150, p. 29.

VAN GUNDY, C. E. 1934. Some observations of the Unkar Group of the Grand Canyon Algonkian. Grand Canyon Nature Notes, 9(8):338-349.

-------. 1937a. Nankoweap group of the Grand Canyon Algonkian [abstract]. Geol. Soc. America, Proceedings for 1936, p. 304. [See also Van Gundy (1951).]

-------. 1937b. Jellyfish from Grand Canyon Algonkian [abstract]. Science, 85:314.

-------. 1946. Faulting in east part of Grand Canyon of Arizona. Amer. Association Petroleum Geologists Bull., 30:1899-1909.

-------. 1951. Nankoweap group of the Grand Canyon Algonkian of Arizona. Geol. Soc. America Bull., 62:953-959. (Presented before the Cordilleran Section, April 1936.)

VAN HISE, C. R. 1892. Correlation papers; Archean and Algonkian. U.S. Geol. Survey Bull. 86, 549 pp.

-------. 1893. The pre-Cambrian of North America. In: Congrès Géologique International, Compte Rendu de la 5^{me} Session, Washington, 1891. Washington: Imprimerie du Gouvernement [U.S. Government Printing Office], Part 3B, pp. 110-150.

-------. 1904. A treatise on metamorphism. U.S. Geol. Survey Mon. 47, 1,286 pp.

VAN HISE, Charles Richard, and Charles Kenneth LEITH. 1909. Pre-Cambrian geology of North America. U.S. Geol. Survey Bull. 360, 939 pp.

VERBEEK, Earl R. 1986. Fracture pattern of the southern Marble and eastern Coconino Plateaus, north-central Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):419-420.

VIDAL, Gonzalo. 1986. Acritarch-based biostratigraphic correlations and the upper Proterozoic in Scandinavia, Greenland, and North America. Geol. Soc. America, Abstracts with Programs, 18(5):420.

VIDAL, Gonzalo, and Trevor D. FORD. 1985. Microbiotas from the late Proterozoic Chuar Group (northern Arizona) and Uinta Mountain Group (Utah) and their chronostratigraphic implications. Precambrian Research, 28:349-389.

WAESCHE, H. H. 1931. Blue ribbon minerals. Grand Canyon Nature Notes, 5(10):95-98.

-------. 1932. A summary of Grand Canyon minerals. Grand Canyon Nature Notes, 7(5):44-48.

-------. 1933a. The Anita copper mine. Grand Canyon Nature Notes, 7(11):108-112.

-------. 1933b. Feldspars of Phantom Ranch area. Grand Canyon Nature Notes, 8(7):188-190.

-------. 1934. The Grand View Copper Project. Grand Canyon Nature Notes, 8(12):250-258.

WALCOTT, C. D. 1880. The Permian and other Paleozoic groups of the Kanab Valley, Arizona. Amer. Jour. Science, 3rd Ser., 20:221-225.

-------. 1883. Pre-Carboniferous strata in the Grand Cañon of the Colorado, Arizona. Amer. Jour. Science, 3rd Ser., 26:437-442, 484.

-------. 1884. Report of Mr. Charles D. Walcott. U.S. Geol. Survey, 4th Annual Report, pp. 44-48.

-------. 1886. Classification of the Cambrian system of North America. Amer. Jour. Science, 3rd Ser., 32:138-157.

-------. 1890. Study of a line of displacement in the Grand Cañon of the Colorado, in northern Arizona. Geol. Soc. America Bull., 1:49-64.

-------. 1894. Pre-Cambrian igneous rocks of the Unkar terrane, Grand Canyon of the Colorado, Arizona; with notes on the petrographic character of the lavas by Joseph Paxson Iddings. U.S. Geol. Survey, 14th Annual Report, Part 2, pp. 497-524.

-------. 1895. Algonkian rocks of the Grand Canyon of the Colorado. Jour. Geology, 3:312-330.

-------. 1899. Pre-Cambrian fossiliferous formations. Geol. Soc. America Bull., 10:199-244.

WANLESS, Harold R. 1973. Cambrian of the Grand Canyon--A re-evaluation of the depositional environment. Ph.D. dissertation, Johns Hopkins University, 128 pp.

-------. 1981. Environments and dynamics of clastic sediment dispersal across Cambrian of Grand Canyon [abstract]. Amer. Association Petroleum Geologists Bull., 65:1004-1005.

WARD, L. F. 1901. Geology of the Little Colorado Valley. Amer. Jour. Science, 4th Ser., 12:401-413.

WARNER, Lawrence A. 1978. The Colorado Lineament: A middle Precambrian wrench fault system. Geol. Soc. America Bull., 89:161-171.

WASHBURN, Bradford. 1981. The Bright Angel Trail, Grand Canyon, Arizona; a new large-scale map of the world's most famous footpath. Boston: Museum of Science, 1 sheet (2 sides), scale 1:4,800.

-------. 1983. Resurvey of the heart of the Grand Canyon, 1971-1978. National Geographic Soc. Research Reports, 15:1-34.

WASHBURN, Bradford, and others. 1978. The heart of the Grand Canyon, Grand Canyon National Park, Arizona. Natl. Geographic Magazine, 154(1):35A, scale 1:24,000.

WASSERBURG, G. J., and M. A. LANPHERE. 1965. Age determinations in the Precambrian of Arizona and Nevada. Geol. Soc. America Bull., 76:735-758.

WATERS, Jeffrey P., and David M. BEST. 1986. Determination of subsurface morphology of collapse features on the Kaibab Plateau, northern Arizona, using gravity surveys. Geol. Soc. America, Abstracts with Programs, 18(5):420.

WAY, Thomas E. 1980. A summary of travel to Grand Canyon. Prescott: Presocott Graphics, 14 pp.

WEBB, Robert H., Patrick T. PRINGLE, Steven L. RENEAU, and Glen R. RINK. 1988. Monument Creek debris flow, 1984: Implications for formation of rapids on the Colorado River in Grand Canyon National Park. Geology, 16(1):50-54.

WENRICH, Karen J. 1986. Mineralized breccia pipes of NW Arizona--an overview. Geol. Soc. America, Abstracts with Programs, 18(5):421.

WENRICH, Karen J., and George H. BILLINGSLEY. 1986. Field trip log--breccia pipes of northern Arizona. In: J. D. Nations, C. M. Conway, and G. A. Swann, eds., Geology of central and northern Arizona; field trip guidebook for Geological Society of Amrica Rocky Mountain Section meeting, Flagstaff, Arizona, 1986. Geol. Soc. America, Rocky Mountain Section, pp. 43-58.

WENRICH, Karen J., and SUTPHIN, Hoyt B. 1988. Recognition of breccia pipes in northern Arizona. Fieldnotes (Arizona Bureau of Geology and Mineral Technology), 18(1):1-4, 11.

WENRICH, Karen J., Bradley S. VAN GOSEN, Richard A. BALCER, James H. SCOTT, Joseph F. MASCARENAS, George M. BEDINGER, and Besti BURMASTER. 1988. A mineralized breccia pipe in Mohawk Canyon, Arizona--Lithologic and geophysical logs. U.S. Geol. Survey Bull. 1683-A, pp. A1-A66.

WHEELER, George M. 1889. Report upon United States Geographical Surveys west of the one hundreth meridian. Vol. 1. Geographical report. Washington: U.S. Government Printing Office, 780 pp.

WHEELER, Russell B., and Albert R. KERR. 1936. Preliminary report on the Tonto group of the Grand Canyon, Arizona. In: Contributions to Grand Canyon geology. Grand Canyon Natural History Association, Bull. 5, pp. 1-15.

WHEELER, Russell L. 1986. Selecting reliable alignments of mapped points: Structural control of breccia pipes on the Marble Plateau, northern Arizona. Geol. Soc. America, Abstracts with Programs, 18(5):422.

WHITE, David. 1929. Flora of the Hermit shale. Carnegie Institution of Washington Pub. 405, 221 pp.

WHITTINGTON, Harry B. 1985. The Burgess Shale. New Haven: Yale University Press, in association with the Geological Survey of Canada, 151 pp.

WILMARTH, M. Grace. 1925. The geologic time classification of the United States Geological Survey compared with other classifications; accompanied by the original definitions of era, period, and epoch terms. U.S. Geol. Survey Bull. 769, 138 pp.

-------. 1932. (compiler) Tentative correlation of the named geologic units of Arizona. U.S. Geol. Survey, 1 sheet.

WILSON, Robert W. 1942. Preliminary study of the fauna of Rampart Cave, Arizona. In: Contributions to paleontology; Studies of Cenozoic vertebrates of western North America and of fossil primates. Carnegie Institution of Washington Pub. 530, Part 6, pp. 169-185.

WILSON, Eldred D., Richard T. MOORE, and John R. COOPER. 1969. Geologic map of Arizona. Arizona Bureau of Mines, and U.S. Geological Survey, scale 1:500,000.

WINSTON, Don. 1988. Proposed intracratonic setting of western U.S. Middle Proterozoic basins. Geol. Soc. America, Abstracts with Programs, 20(6):474-475.

WOODS, G. K. 1899. Personal impressions of the Grand Cañon of the Colorado River near Flagstaff, Arizona, as seen through nearly two thousand eyes, and written in the private visitors' book of the world-famous guide Capt. John Hance, guide, story-teller, and path-finder. San Francisco: Whitaker and Ray Co., 163 pp.

YOUNG, Grant M. 1978. Proterozoic (<1.7 b.y.) stratigraphy, paleocurrents, and orogeny in North America. Egyptian Jour. Geology, 22:45-64.

YOUNG, Richard A. 1966. Cenozoic geology along the edge of the Colorado Plateau in northwestern Arizona. Ph.D. dissertation, Washington University, 220 pp.

-------. 1970. Geomorphological implications of pre-Colorado and Colorado tributary drainage in the western Grand Canyon region. Plateau, 42:107-117.

-------. 1974. Evolution of the Plateau-Basin and Range boundary, northwestern Arizona. Geol. Soc. America, Abstracts with Programs, 6:483.

-------. 1978. Discusion of "Cambrian stratigraphic nomenclature and ground-water prospecting failures on the Hualapai Plateau, Arizona" [Huntoon, 1977b]. Ground Water, 16:287-289.

-------. 1979a. Early Cenozoic structural and geomorphic evolution of the western Grand Canyon region. Geol. Soc. America, Abstracts with Programs, 11:60-61.

-------. 1979b. Laramide deformation, erosion and plutonism along the southwestern margin of the Colorado Plateau. Tectonophysics, 61:25-47.

-------. 1980. Revising the geologic history of the Grand Canyon: A study of regional drainage reversal [abstract]. In: L. J. King, ed., Fourth Annual Scientific Paper Session of the Rochester Academy of Science, 13(2):82-83.

-------. 1981. Origin of the Grand Canyon; myths and theories in modern perspective. Rocks and Minerals, 56(1):5-11.

-------. 1982a. Paleogeomorphic evidence for the structural history of the Colorado Plateau margin in western Arizona. In: E. G. Frost and D. L. Martin, eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada. San Diego: Cordilleran Publishers, in conjunction with a symposium and field trip for the Geological Society of America, April 1982 (Anderson-Hamilton Vol.), pp. 29-39.

-------. 1982b. Paleogeomorphic evidence for the structural history of the Colorado Plateau margin in western Arizona. Geol. Soc. America, Abstracts with Programs, 14(4):246.

-------. 1985. Geomorphic evolution of the Colorado Plateau margin in west-central Arizona: A tectonic model to distinguish between the causes of rapid, symmetrical scarp retreat and scarp dissection. In: M. Morisawa and J. T. Hack, eds., Tectonic geomorphology; proceedings of 15th Annual Binghamton Geomorphology Symposium, September 1984. Boston: Allen and Unwin, pp. 261-278.

-------. 1989. Paleogene-Neogene deposits of western Grand Canyon, Arizona. In: D. P. Elston, G. H. Billingsley, and R. A. Young, eds., Geology of the Grand Canyon, northern Arizona (with Colorado River trip guides). 28th International Geological Congress, Field Trips T115 and T315, Guidebook, Chapter 20.

YOUNG, Richard A., and William J. BRENNAN. 1974. Peach Springs Tuff: Its bearing on structural evolution of the Colorado Plateau and development of Cenozoic drainage in Mohave County, Arizona. Geol. Soc. America Bull., 85:83-90.

YOUNG, Richard A., and J. H. HARTMAN. 1984. Early Eocene fluviolacustrine sediments near Grand Canyon, Arizona: Evidence for Laramide drainage across northern Arizona into southern Utah. Geol. Soc. America, Abstracts with Programs, 16(6):703.

YOUNG, Richard A., and Edwin H. McKEE. 1978. Early and middle Cenozoic drainage and erosion in west-central Arizona. Geol. Soc. America Bull., 89:1745-1750.

YOUNG, Richard A., William J. BRENNAN, Ivo LUCCHITTA, and Edwin H. McKEE. 1975. Pre-Basin and Range uplift and Miocene volcanism along the west edge of the Colorado Plateau, Mohave County, Arizona. Geol. Soc. America, Abstracts with Programs, 7:1324-1325.

YOUNG, Richard A., H. Wesley PEIRCE, and James E. FAULDS. 1987. Geomorphology and structure of the Colorado Plateau/Basin and Range transition zone, Arizona. In: Geologic diversity of Arizona and its margins: Excursions to choice areas; field-trip guidebook, 100th Annual Meeting, Geological Society of America, Phoenix, Arizona. Arizona Bureau of Geology and Mineral Technology, Special Paper 5, pp. 182-196.

Features Mentioned in Text Listed by River Mileage

This list contains only those features noted in the present volume. Features of interest mentioned in the 28th IGC Colorado River log by Billingsley and Elston (1989), inserted at the beginning of most sections of this volume, are included in this list.

Lees Ferry	Colorado River sedimentary feature
Lees Ferry	Chinle Formation exposed
0.1	first appearance of Moenkopi Formation
0.5	Echo Cliffs monocline
0.8	Colorado River sedimentary feature
0.8	first appearance of Kaibab Formation
2.1	first appearance of Toroweap Formation
3.4	graben
4.5	Coconino Sandstone cross-beds
4.5	first appearance of Coconino Sandstone
7.2	rockfall
7.7	Colorado River sedimentary feature
8.5	first appearance of Hermit Shale
10.0	landslide
11.4	first appearance of Esplanade Sandstone
13.2	Esplanade Sandstone cross-beds
14.8	Esplanade Sandstone cross-beds
14.8	burrows and reptilian footprints in Esplanade Sandstone
16.9	House Rock Rapids
17.0	first appearance of Wescogame Formation
17.5	breccia pipe or paleokarst
18.0?	first appearance of Manakacha Formation (contact indistinct)
18.3	breccia pipe or paleokarst
18.5	historic river flood deposits
18.5	rockfall
18.8	breccia pipe or paleokarst
20.2	first appearance of Watahomigi Formation
21.8	mud cracks in fallen block of Watahomigi Formation
23.0	first appearance of Redwall Limestone
23.1	breccia pipe or paleokarst
23.3	first appearance of Surprise Canyon Formation
24.3	breccia pipe or paleokarst
24.5	24.5-Mile Rapids
24.5	repeat appearance of Surprise Canyon Formation
25.0	breccia pipe or paleokarst
26.4	breccia pipe or paleokarst
26.7	breccia pipe or paleokarst
26.8	rockfall
30.3	spring
30.5	spring
31.7	Stanton's Cave
31.9	Vasey's Paradise
32.8	Marble Canyon test adits
33.0	Redwall Cavern
34.1	spring
34.8	Nautiloid Canyon
35.1	first appearance of unclassified Cambrian dolostones
35.3	first appearance of Muav Limestone
35.7	36-Mile joint system
35.9	breccia pipe or paleokarst
37.8	Temple Butte Limestone noted
39.3	Marble Canyon test adits
39.8	36-Mile joint system
40.5	36-Mile joint system
43.3	Emminence Break graben
43.7	Emminence Break graben
44.4	rockfall
46.6	Triple Alcoves
46.9	first appearance of Bright Angel Shale (gradational contact)
48.0	spring

49.7	Emminence Break fault
51.0	spring
52.1	Colorado River sedimentary feature
56.3	travertine
58.2	first appearance of Tapeats Sandstone (gradational contact)
61.0	salt spring
61.3	travertine
61.5	Little Colorado River confluence
63.0	salt spring
63.	vicinity of Carbon Butte landslide
63.0	Great Unconformity/Dox Formation
64.5	thrust fault in Dox Sandstone
65.4	Palisades fault and monocline
65.4	copper prospects
67.0	Great Unconformity/Cardenas Basalt
68.5	first appearance of Cardenas Basalt
68.5	Butte fault
69.0	Basalt Canyon fault
69.4	Colorado River sedimentary feature
70.	vicinity of axis of East Kaibab monocline
70.	nearest to Ochoa Point, vicinity of Proterozoic lava vents
70.7	Colorado River sedimentary feature
72.4	Colorado River sedimentary feature
74.8	first appearance of Shinumo Quartzite
76.2	first appearance of Hakatai Shale
76.7	Red Canyon/Hance Rapids
77.0	first appearance of Bass Limestone
76.8	Hance Rapids
77.5	Hotauta Conglomerate Member of Bass Limestone/Vishnu Schist
78.	vicinity of John Hance's asbestos mine
80.	Grandview Mine on Horshoe Mesa nearest this point
81.1	Vishnu fault
83.9	Lonetree Canyon
84.7	Vishnu Schist/Zoroaster Pluton contact
86.1	Vishnu Schist/Zoroaster Pluton contact
87.2	Colorado River sedimentary feature
87.5	Cremation fault (associated with Grandview monocline)
87.7	Bright Angel Canyon
87.9	Bright Angel or Silver Bridge
87.9	Bright Angel Rapids
88.0	Tipoff fault
88.2	Bright Angel fault
88.3	Bright Angel fault
88.9	Bright Angel Trail (Pipe Creek)
89.1	Vishnu Schist/Zoroaster Pluton contact
89.8	Vishnu Schist/Zoroaster Pluton contact
90.2	Horn Creek Rapids
91.3	Vishnu Schist/Trinity Gneiss contact
92.5	Vishnu Schist/Trinity Gneiss contact
93.4	Granite Rapids
93.5	Monument Creek
94.0	sillimanite and staurolite studied by Campbell (1936)
95.0	Hermit Creek
95.0	Hermit Rapids
95.3	travertine
96.2-96.5	granitic pluton
97.7-98.0	Zoroaster Pluton
98.0	Slate Creek fault
98.1	Crystal Rapids
98.2	Crystal Creek
98.7-99.1	granitic pluton
99.0	fault associated with Crazy Jug monocline
102.8	Vishnu Schist/Zoroaster Pluton
102.9	Tapeats Sea island
107.8	Bass Rapids
108.5	Shinumo Creek; near W. W. Bass's mines
108.6	Tapeats Sea island
114.4	travertine

114.5	Garnet Canyon
115.5	Monument fault
115.6	Tapeats Sandstone/Vishnu Schist contact
116.5	Royal Arch Creek
116.6	travertine
118.8	first Tapeats Sandstone/Vishnu Schist contact
120.2	Tapeats Sandstone/Vishnu Schist contact
121.5	Colorado River sedimentary feature
122.0	Colorado River sedimentary feature
123.2	Butchart fault
123.2	Bright Angel Sh./Tapeats Ss. (gradational contact)
124.2	travertine
126.6	Tapeats Sandstone/Vishnu Schist contact
127.4	salt spring
130.4	bedrock rapids
130.6	Bass Limestone/Vishnu Schist contact
131.7	Deubendorff Rapids
133.6	spring
134.6	Bass Limestone
135.0	Colorado River sedimentary feature
135.0	travertine
135.0	Surprise Valley landslide
135.	Surprise Valley
135.2	narrowest point of river (76 ft; 23 m)
136.5	Deer Creek
137.7	Tapeats Sandstone/Bass Limestone contact
137.9	spring
138.0	last outcrop of Grand Canyon Supergroup
138.0	Tapeats Sea island
138.7	Sinyala fault
138.8	Stone Creek
140.4	Tapeats Sandstone
142.-202.	river anticlines
143.5	Kanab Creek
147.5	travertine
147.8	spring
148.0	Matkatamiba syncline
151.0	travertine
155.4	spring
156.6	Supai monocline
156.8	Havasu Canyon
159.1	Pleistocene dikes and cinder cones
168.0	Surprise Canyon Formation noted (high up)
168.0	Fern Glen
171.2	Mohawk-Stairway fault
173.2	travertine
175.0	landslide
175.4	travertine
176.5	travertine
177.-187.	lava flows at Toroweap
177.0	basalt flow remnant; source unknown
177.2	basalt flow
178.0	Vulcan's Forge
178.2	basalt flow
178.8	Tapeats Sandstone
179.0	Toroweap fault
179.0	Colorado River sedimentary feature
179.0	basalt flow (Lava Falls)
179.3	Lava Falls Rapids
179.4	Prospect Wash
179.5	travertine
179.8	dated tuff in Muav Limestone
181.3	spring
184.8	Lava Falls cascade
187.7	lava-filled canyon
189.5	Tapeats Sandstone/Vishnu Schist contact
189.6	landslide
190.0	Tapeats Sandstone/granite contact

190.7	first appearance of Hurricane fault zone
192.5	Colorado River sedimentary feature
194.5	undocumented lava dam reported by Maxson (1949)
196.3	Lone Mountain monocline
196.7	Colorado River sedimentary feature
198.0	Parashant graben
205.5	landslide
205.7	dated tuff in Muav Limestone
205.7	*Ollenelus* zone in Tapeats Sandstone
205.8	landslide
207.6	Tapeats Sandstone/Vishnu Schist contact
209.0	Bright Angel Shale/Vishnu Schist contact
209.5	landslide
212.0	Tapeats Sea island
213.	travertine
215.0	Zoroaster Pluton
215.8	Zoroaster Pluton
223.5-227.0	Diamond Creek Pluton
225.3	basalt flow
227.0-230.0	229-Mile Gneiss
229.2	travertine
230.0-230.9	Travertine Falls Pluton
230.5	Travertine Falls
232.3-236.7	longest exposure of migmatite
236.0	begin Lake Mead
236.7-237.0	237-Mile Pluton
237.5	Bridge Canyon dam site
238.5-240.0	Separation granite pluton
239.6	Separation Canyon
239.6	Separation Canyon Rapids (now flooded by Lake Mead)
242.3-243.2	Spencer granitic pluton
246.0	basalt flow
246.1	last exposure of Vishnu Schist
246.1-261.0	Surprise-Quartermaster Pluton
249.0	basalt flow
252.2-255.4	Meriwitica fault
254.2	basalt flow
259.0	travertine
259.5	travertine
259.5	spring
266.3	Bat Cave
266.5	reactivated landslide
266.5	landslide
267.6	travertine
272.9	spring
274.0	spring
274.2	travertine
274.3	Columbine Falls
274.9	Rampart Cave
275.5	Rampart Cave fault
277.	Grand Wash Cliffs
277.6	Muddy Creek Formation
278.0-278.5	Grand Wash fault
285.	Grand Wash basin
285.	Wheeler fault
285.	Muddy Creek Formation
291.	Muddy Creek Formation
300.	Muddy Creek Formation
301.	Muddy Creek Formation
307.	Muddy Creek Formation
312.	Muddy Creek Formation