CHAPTER 15

HISTORY OF THE GRAND CANYON AND OF THE COLORADO RIVER IN ARIZONA

Ivo Lucchitta

INTRODUCTION

Many desert rivers, including the Nile River of Africa, the Tigris and Euphrates rivers of Asia, and the Colorado River of the western United States, obtain their waters from mountain ranges far removed from the warm and parched lands that border most of their courses. This combination of abundant water and warm climate has made parts of these rivers lifelines, allowing the cultivation of large areas that otherwise are desert.

The Tigris, Euphrates, and Nile led to the establishment of ancient civilizations such as those of Mesopotamia and Egypt—and probably to the development of settled urban living as we know it today. It is no coincidence that cities such as Ur, Babylon, Thebes, and Memphis were sited on the banks of these rivers.

The Colorado River cannot claim to be the cradle of civilization; its virtue, instead, is to support modern cities such as Los Angeles, Las Vegas, and Phoenix that could not flourish in its absence. Many of these cities are far removed from the Colorado, whose waters are brought to them by a system of artificial impoundments and aqueducts. The Colorado, therefore, has enabled us to carry out a great experiment, based on contemporary technology, in settling areas that are in themselves inhospitable.

Great demands are made on the waters of the Colorado River, yet the amount of available water is finite. This has resulted in a host of social, political, and engineering problems that have centered chiefly on how many reservoirs should be built and who should get the water. Many of these problems are fertile areas of endeavor for geologists concerned with the practical application of their science.

For other geologists, however, the river has been the source of quite different interests and controversies. These interests are theoretical in nature and have to do with the general problem of how rivers are born and develop. When and how did the Colorado River come into being? How do rivers like the Colorado evolve? When did canyon cutting and correlative uplift occur? How and why has the Colorado cut across the many belts of high ground astride its course? How quickly was the Grand Canyon cut? Might the answers to these questions give us an insight into how rivers in general establish their courses?

This chapter considers the history of the Colorado River and its Grand Canyon (Fig. 1). To understand what follows, it is important to remember two contrasting views regarding the history of the Colorado River. The first is that the river from birth has been part of an integrated drainage system with a course approximating the present one.

According to the first view, the river came into being pretty much as it is today and at some well-defined time, such as the Eocene. A statement that is made about any part of the river applies to the river as a whole; the entire river is young, or old, as the case may be.

The second view is that most rivers are continually changing entities that have evolved from various ancestors and will continue evolving into progeny whose configuration depends on factors such as tectonism and climate. According to this view, the answer to the question "When was the Colorado River born?" can only be another question: "How much departure from the present configuration is one willing to tolerate and still speak of the Colorado?"

It is important to remember that the Colorado traverses two contrasting terrains in Arizona. The first is the canyon country, typified by the Grand Canyon. This is highly dissected terrain, commonly with substantial topographic relief. The second is the plateau country, which is typified by most of the Navajo and

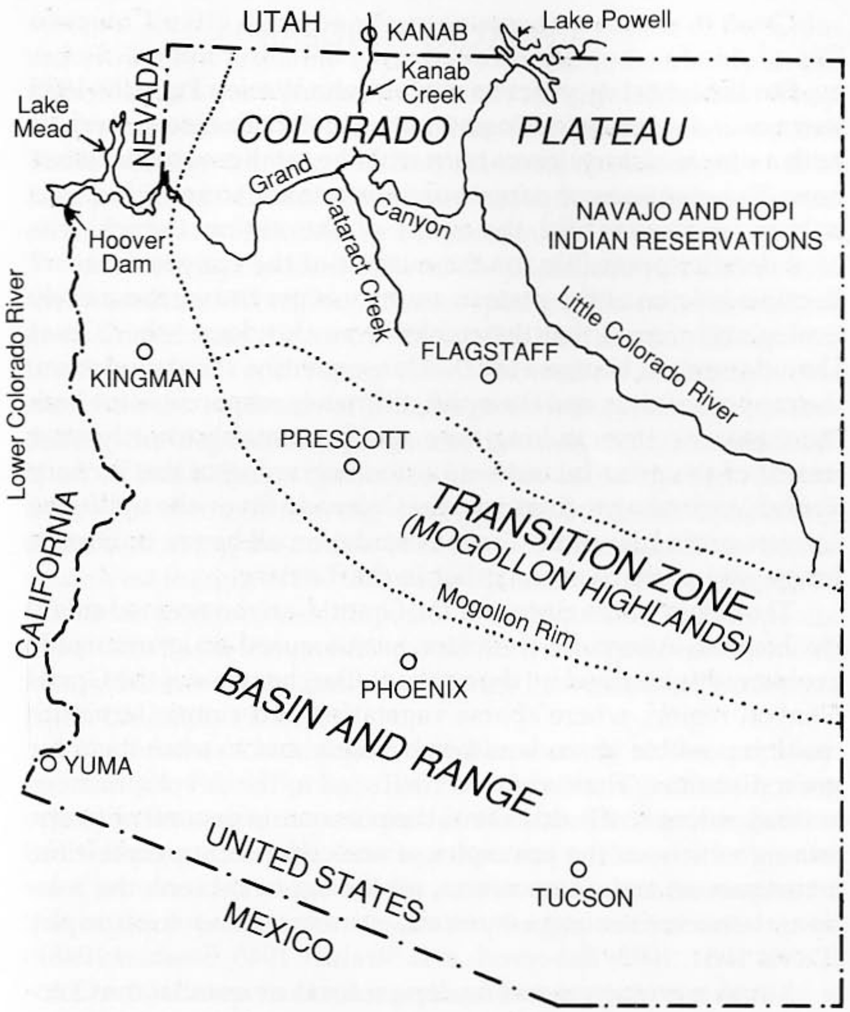

Figure 1. Location map, Arizona

Hopi reservations (Fig. 1). This landscape is characterized by low relief, wide mature valleys, and scarps that develop on beds of contrasting resistance and retreat down structural slopes. The plateau country is older and more widespread than the canyon country, which is encroaching on it.

A HISTORY OF IDEAS

For the first sixty years or so after John Wesley Powell's 1875 journey of discovery, geologists subscribed to the idea of a river with a simple history; it was born with the same course that it has now. The questions of paramount importance were: when was it born and when did the uplift of the region (which was considered responsible for the cutting of the canyons) occur? Because erosion of the plateau country is pervasive, these early geologists inferred that the erosion was also deep—the "Great Denudation" of Dutton (1882). Consequently, the denudation, the canyon cutting, and the uplift ultimately responsible for both must have occurred a long time ago, presumably shortly after retreat of the great inland seas at the beginning of the Tertiary Period. According to this view, the Colorado River, the uplift, the canyon cutting, and the Great Denudation all began in Eocene time—and perhaps even earlier in the Tertiary.

The origin of the river and the Grand Canyon seemed safely established. Attention, therefore, was focused on geomorphic problems highlighted by the textbooklike character of the Grand Canyon region, where sparse vegetation and simple structure make it possible to see landforms clearly and to trace them for great distances. These characteristics led to the development of several concepts of fundamental importance in geomorphology, among which are the principles of antecedence, superposition, consequence, and anteposition, all having to do with the relations between drainage systems, structure, and topography (Davis 1901, 1903; Babenroth and Strahler 1945; Strahler 1948).

Storm warnings signaling danger for the view that the Colorado River is old were hoisted in the 1930s and 1940s by geologists studying the Basin and Range country (Fig. 1). These geologists found that interior-basin deposits of late Miocene and Pliocene age are common along the course of the Colorado River. They also could find no evidence for an older drainage system that could be called the Colorado. In conformity with the concept of a monophase history for the river, these geologists concluded that the entire river, and thus the Grand Canyon as well, was no older than late Tertiary (Blackwelder 1934; Longwell 1936, 1946).

The next development occurred in the plateau country of Arizona, Utah, and Colorado. Here, widespread evidence, eventually summarized by Hunt (1969), showed that drainage

systems, locally departing from the present course of the Colorado River but arguably ancestral to it, existed certainly in the Miocene and very probably as early as the Oligocene. They might have existed even earlier, but if so, the evidence is gone. There was now a major paradox; the same river seemed to be at least as old as Miocene-Oligocene in its upper reaches, but no older than latest Miocene or Pliocene in its lower ones.

In an attempt to shed light on the paradox, E. D. McKee and the Museum of Northern Arizona sponsored studies on critical areas at and near the mouth of the Grand Canyon. Results by Lucchitta (1966) and Young (1966) showed no stratigraphic or morphologic evidence of a through-flowing drainage system during the deposition of Miocene interior-basin materials related to Basin-Range deformation. Nor could the lack of evidence for through-flowing drainage be bypassed by looking elsewhere along the course of the lower Colorado River or the southwest margin of the Colorado Plateau in Arizona (Fig. 1). In this area, interior-basin deposits are ubiquitous, and deposits older than Basin-Range rifting indicate drainage northeastward, from what now is the Basin and Range Province onto what now is the Colorado Plateau.

The northeast drainage existed as recently as the emplacement of the Peach Springs Tuff, as 18-million-year-old ignimbrite that flowed onto the Colorado Plateau. Before rifting of the Basin-Range, therefore, drainage was not to the west or southwest (as would be required for a river with a course similar to that of the present Colorado) but in the opposite direction—to the northeast.

The next step in the conceptual journey was the idea of a polyphase history for the river. Hunt (1969) contributed to it by proposing drainage systems initially departing markedly from the present Colorado River, but gradually evolving into this configuration. However, Hunt, as well as Lovejoy (1980), still postulated an ancestral Colorado River flowing westward from the Colorado Plateau even before Basin-Range deformation, a concept not supported by the evidence.

The concept of a polyphase history for the Colorado River was developed fully for the first time by McKee and others (1967). These authors accepted the antiquity of the upper part of the drainage system, as documented by Hunt, but could not accept a continuation of this drainage westward through the

Grand Canyon into the Basin and Range Province. Instead, they proposed that the ancestral Colorado followed its present course as far as the eastern end of the Grand Canyon, but then continued southeastward (not westward) along the course of the present Little Colorado (Fig. 1) and Rio Grande rivers into the Gulf of Mexico. In Pliocene time, a youthful stream, emptying into the newly formed Gulf of California and invigorated by a steep gradient, eroded headward and captured the sluggish ancestral river somewhere in the eastern Grand Canyon area. It was then that the river became established in its present course, and the carving of the Grand Canyon began.

The concept is pivotal because it introduces the idea (even though the point is not made explicitly) that drainage systems evolve continually—and do so chiefly through headward erosion and capture and in response to tectonic movements. During this process, the configuration and course of a drainage system may change so much that it becomes difficult and rather arbitrary to continue calling the ancestral drainage system by its present name.

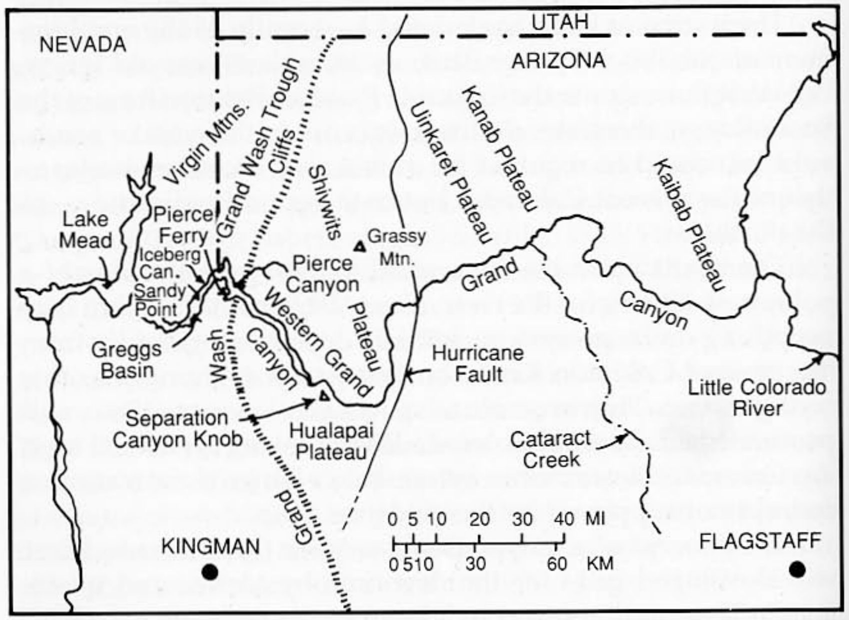

Figure 2. Map showing selected geologic and geographic features in northern Arizona

Evidence accumulated since 1967 argues against drainage southeastward along the Little Colorado and Rio Grande rivers, as proposed by McKee and others (1967). On the other hand, evidence has continued to grow that an ancient river could not have flowed through the western Grand Canyon region (Fig. 2) into the nearby Basin and Range Province (Lucchitta 1972, 1975; Young 1975; Young and Brennan 1974).

Analysis of deposits along the course of the lower Colorado River in the Basin and Range Province has confirmed that this part of the river is no older than latest Miocene. It also has shown that the capture of the ancestral Colorado River is documented by the appearance within river deposits (Imperial Formation of Miocene and Pliocene age) in California's Salton trough of coccoliths otherwise found only in the Cretaceous Mancos Shale of the Colorado Plateau (Lucchitta 1972).

An attempt to synthesize current information led Lucchitta (1975, 1984) to postulate that the ancestral Colorado did not flow to the southeast along the valley of the Little Colorado River, as proposed by McKee and others (1967). Instead, the river crossed the Kaibab Plateau along the present course of the Grand Canyon, then continued northwestward along a strike valley in the area of the Kanab, Uinkaret, or Shivwits plateaus (Fig. 2) to an as yet unknown destination. After the opening of the Gulf of California, this ancestral drainage was captured west of the Kaibab Plateau by the lower Colorado drainage. According to this concept, the upper part of the Grand Canyon in the Kaibab Plateau area is old and related to the ancestral river, whereas the lower part of the canyon in this area and in all of the western Grand Canyon postdates the capture and was carved in a few million years, a process aided by nearly 0.6 miles(0.9 km) of regional uplift since the inception of the lower river (Lucchitta 1979).

This hypothesis is based on (1) the occurrence of gravels of probable river origin in the area of the Kanab, Uinkaret, and Shivwits plateaus and (2) the observation that northwest-trending drainages along strike valleys were common and persistent before canyon cutting, as evidenced by fossil valleys preserved under Miocene lavas in many places in the southwestern Colorado Plateau and by ancient valleys in the plateau country. Examples of such valleys are those of Cataract Creek (Fig. 2) and the Little Colorado River (Fig. 1), which predate canyon cutting and have not yet been affected appreciably by it.

The old problem of how the Colorado could have crossed the Kaibab Plateau can be analyzed by going backwards in time and restoring rocks removed from this upwarp in the past few million years (Fig. 3). This shows that a river such as the ancestral Colorado could have flowed readily across the Kaibab (then lower topographically than its surroundings) in an arcuate racetrack corresponding to the present configuration of the eastern Grand Canyon. The racetrack was localized by north-facing monoclinal flexures that cross the Kaibab and interrupt the general southward plunge of this dome.

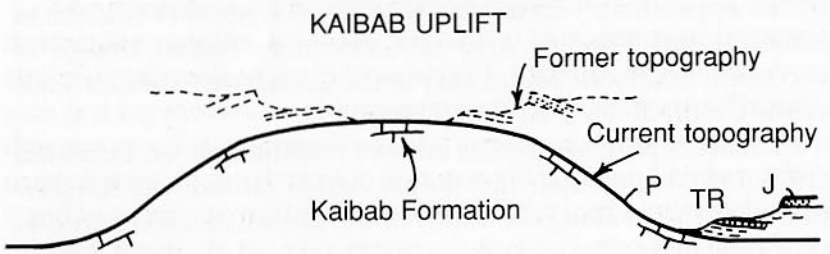

Figure 3. Cross section showing uplift of the Kaibab Plateau both a few million years ago and currently. P - Permian; TR - Triassic; J - Jurassic

THE EVIDENCE

The Colorado River and its tributaries have been cutting down vigorously during the last several million years of their history. Such erosion—or at least nondeposition—may have been typical of this river system through most of its life. This characteristic creates great difficulties for the geologist intent on reconstructing the history of the river because such a history can only be pieced together from evidence left behind by the river.

The evidence is of two kinds—river deposits such as gravel, sand, and silt and landforms such as river valleys and canyons. Of the two, the deposits are by far the more useful because most can be attributed unequivocally to a specific river, on whose provenance, direction of flow, and age they provide valuable information. In contrast, a landform such as a valley can result from a river other than the one of interest or even from the action of an entirely different agent, such as a glacier.

Any river (even one that is cutting down) leaves behind deposits. For rivers that are cutting down, such as the Colorado, most of the deposits are removed soon after deposition. This means that deposits with which the geologist can work are few and scattered, especially in the Grand Canyon. Furthermore, the deposits preserved tend to reflect only the most recent part of the river's history.

Because of these factors, study of the Colorado River consists largely of a detectivelike piecing together of circumstantial evidence, most of which is negative. In other words, the evidence is more likely to show that the Colorado River did *not* go through some area at a specified time than to document its existence in some specific place at a specific time. When circumstantial evidence is not negative, it typically attributes to an inferred Colorado River the properties known to be widespread at the time in question. For example, if at some time in the past most drainages followed northwest-trending strike valleys, one can reasonably infer that the Colorado also followed such a valley.

These points may seem too obvious to be worth repeating, but they need to be made once more because many people are taken aback by the lack of hard data pertaining to the history of the Colorado River. It is true that we do not have much direct evidence, given the problems mentioned above, but the circumstantial information is of many different kinds and from different places. Collectively taken, it enables us to construct a solid history that has a good chance of being correct, at least in its major aspects.

The history of the Colorado River and the Grand Canyon is best subdivided into three periods of tectonism that profoundly affected the drainage patterns of their time. These periods are:

1. *Pre-rifting*. The interval between the beginning and the middle of the Tertiary, at which time basin-range rifting got underway along the present course of the Colorado River, and the Colorado Plateau became distinct structurally and morphologically from the adjacent Basin and Range Province.

2. *Rifting*. The time of basin-range extension, with intensity tapering off toward the end of the interval—five to eight million years ago, at most. This was a time of widespread interior drainage in the Basin and Range Province.

3. *Post-rifting*. During this time—between five to eight million years ago and the present—rifting ceased, the Gulf of

California opened, and through-flowing drainage became established.

Pre-rifting

Before the onset of rifting in late Oligocene to Miocene time, the terrain south and southwest of the Colorado Plateau (Fig. 1) was higher than the nearby plateau, both topographically and structurally (Fig. 4). It remains high structurally today, even after the rifting. This belt of uplift, often referred to as the Mogollon Highlands, presumably was formed during the orogenic events at the end of the Mesozoic Era and the beginning of the Tertiary Period. It caused the gentle northeastward tilting of strata near the southwest margin of the plateau, as witnessed by the widespread "rim gravels" (Finnell 1962, 1966; McKee and

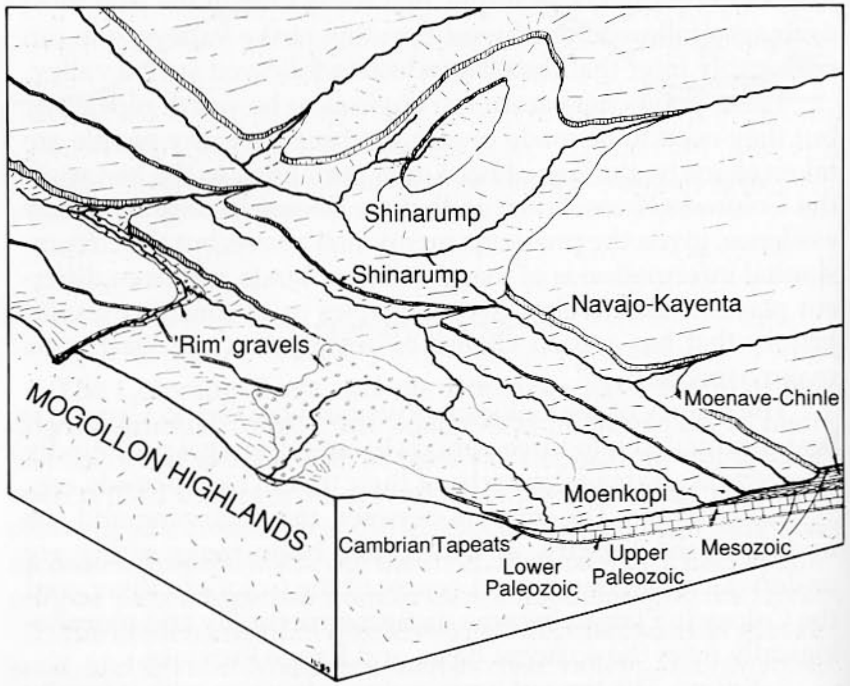

Figure 4. Block diagram showing schematically the relation of Mogollon Highlands to the Colorado Plateau before Miocene rifting. Diagram shows scarps composed of hard-over-soft couplets retreating down structural slope, the inferred topography on the Kaibab uplift, and the trellis drainage network. Looking about northwest, Hualapai Plateau would be at left side of diagram, the area of the Little Colorado River at the right side.

McKee 1972; Peirce 1984; Peirce and others 1979; Peirce and Nations 1986). Along much of the rim, these gravels were deposited on rocks high in the Paleozoic section. They occur locally on Mesozoic rocks as well, yet they contain clasts of Precambrian igneous and metamorphic rocks that could have come only from the belt of uplift south of the rim, where such rocks were exposed.

Along the southwestern margin of the Colorado Plateau, in the area of the Hualapai Plateau, the rim gravels are present within ancient canyons trending northeastward, down the structural slope (Fig. 4). Clast provenance, imbrication, and gradient of the canyon floors all indicate derivation from the southwest (Young 1966, 1970). A similar drainage direction is indicated by the 18 million-year-old Peach Springs Tuff, an ignimbrite that flowed northeastward onto what now is the Colorado Plateau from a source area in the Basin and Range Province (Young 1966; Young and Brennan 1974; Glazner and others 1986). In the area southwest of the present plateau rim, erosion already had cut down to the Precambrian basement by Miocene time, and Phanerozoic strata were retreating northward from a structural and topographic high near Kingman (Lucchitta 1966, 1972).

At the southern margin of the Colorado Plateau, "rim gravels" are widely distributed (Fig. 4) along the Mogollon Rim (Fig. 1), which is the physiographic southern edge of the Colorado Plateau. Even though gravel-filled channels are not as prominent there as they are on the Hualapai Plateau, gravel-filled channels do occur, notably along the Little Colorado River. These gravels delineate the probable drainage pattern near the southern margin of the Colorado Plateau for much of Tertiary time (Lucchitta 1984).

For most of its course, the Little Colorado River flows in a mature and subdued valley that trends northwestward—parallel to the regional strike of Mesozoic and Paleozoic units (Figs. 1, 5). The valley is at the erosional featheredge of the Triassic Moenkopi Formation on the Permian Kaibab Formation. The northeast side of the valley is in the Moenkopi, capped by the resistant Shinarump Member of the Triassic Chinle Formation, which dips gently to the northeast and is very resistant to erosion. Because of this resistance, the topographic surface is near the top of the Kaibab over wide areas of the Colorado Plateau.

Figure 5. High-altitude (U-2) aerial photograph looking north to northeast. The Little Colorado River is in the foreground. Dark mass in middle distance is Black Mesa. Wide valley of the Little Colorado River and scarps forming its northeast side are clearly visible.

The hard-over-soft couplet represented by the Shinarump over the Moenkopi is the lowest, stratigraphically, of several such couplets within the Mesozoic section (Fig. 6). The scarps formed by the couplets face southwest and with time migrate northeastward down the structural slope. The couplets that are stratigraphically highest and youngest have migrated the farthest to the northeast. Those that are lowest and oldest, on the other hand, are found to the south or southwest. These couplets are closest to the belt of uplift (Mogollon Highlands) from which they started. The Grand Staircase described by Dutton (1882) is composed of these couplets.

A northeastward migration can be documented for the valley of the Little Colorado River, where the ancient gravel-filled channels are cut into the top of the Kaibab Formation southwest of the present channel of the river. Both the northwest-trending valleys at the foot of the Shinarump-Moenkopi couplet and the

northeastward migration of such valleys with time can be documented on the Shivwits Plateau (Figs. 2, 6), where various basaltic lavas of late Miocene age have flowed down successive stands of the valleys (Lucchitta 1975).

Most tributaries of the Grand Canyon are short, steep, and immature (Fig. 7). The Little Colorado River, Cataract Creek, and Kanab Creek (Figs. 1, 7) have the length and appearance of conventional, mature river valleys. The Little Colorado and the Cataract Creek flow northwestward—parallel to the strike of beds; Kanab Creek also shows the influence of structure on its course by flowing south around the western flank of the Kaibab uplift, which has overprinted and modified the regional northwestern strike.

These three streams illustrate features characteristic of the pre-Grand Canyon drainage. One feature is the control of drainage by structure, which is represented by the gentle dip of beds modified locally by folds and faults. Another is the marked effect of lithology, as represented by couplets within the Mesozoic section that differ in resistance to erosion and form strike valleys and scarps. Together, these features have given the region a trellis drainage pattern that consists of northwesterly segments parallel to strike and northeasterly segments trending down the structural slope.

The streams bringing rim gravels onto the Colorado Plateau and ancient drainages such as the Little Colorado must have

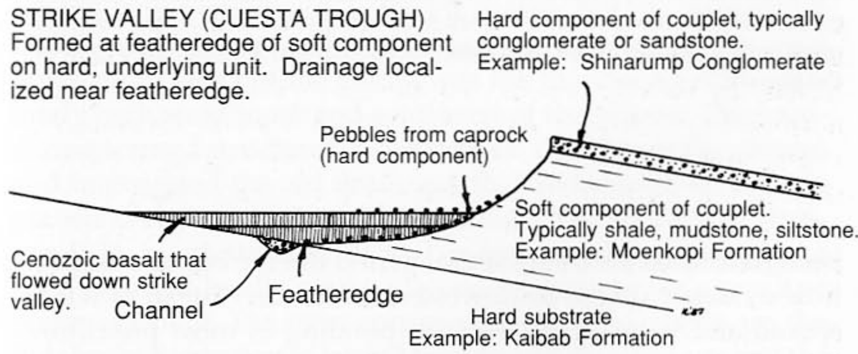

Figure 6. Diagrammatic representation of typical strike valley formed at foot of hard-over-soft scarp retreating (northeast) down structural slope. Also shown are the channel located near featheredge of slope-forming unit, basalt that in many places flowed down strike valleys, and debris derived from caprock. Looking northwest. Width of valley typically is a few km.

Figure 7. High-altitude (U-2) photograph looking west, down much of Grand Canyon. Shivwits Plateau is visible in the distance on the right. The short, steep, and immature tributaries to the Grand Canyon are evident, in contrast to the well-developed Cataract Creek in the middle distance on the left. The confluence of Kanab Creek with the Colorado River is in the middle right of the picture.

been functional for a substantial period of time because there is little evidence on the southwestern Colorado Plateau of widespread and long-lasting Tertiary ponding in most pre-rifting time. The conclusion is that the drainages must have been tributary to a master stream that presumably also reflected the effects of structure and stratigraphy (Fig. 4). The inference is that this was the ancestral Colorado River and that it flowed chiefly in northwest-trending strike valleys. The Colorado, however,

did not flow through the western Grand Canyon region. Here, the presence of gravels and the Peach Springs Tuff shows instead that drainage near the edge of the Colorado Plateau was to the northeast.

Additional evidence that the river did not flow through the western Grand Canyon itself is provided by a knob on the south rim of the Grand Canyon near Separation Canyon (Fig. 2). The knob is composed of a mid-Miocene basalt flow that caps gravel and colluvium containing upper Paleozoic rocks (Young 1966; Lucchitta and Young 1986). In this area, such rocks crop out only on the Shivwits Plateau to the north. Today, the knob and the Shivwits Plateau are separated by the Grand Canyon, which could not have existed when the colluvium and basalts were emplaced (Young 1966).

Rifting

Mid-to-late Miocene basin-range rifting affected most of the western Cordillera and produced ranges separated by deep structural basins filled with thick sequences of deposits. The basins sank so rapidly that through-flowing drainage was not able to maintain itself, resulting in widespread interior drainage. In western Arizona, rifting began in mid-Miocene time and was essentially over by the end of that epoch.

The southwestern Colorado Plateau was much less affected by rifting than was the Basin and Range terrain to the west and south. Normal displacement occurred on many small faults and several larger ones, such as the Hurricane, but the intensity of faulting did not approach that in the Basin and Range. The most noteworthy effect of the rifting was the foundering of the formerly high areas south and southwest of the plateau. The foundering formed structural basins beyond the edge of the plateau and interrupted the old drainages that had deposited the rim gravels (Peirce and others 1979; Young 1966; Young and Brennan 1974; Lucchitta 1966, 1979). Ponding and deposition of lake beds occurred locally on the plateau, presumably as a result of minor warping. The most conspicuous such lake beds are the Bidahochi Formation of latest Miocene and Pliocene age and the Willow Springs Formation of Pliocene to Pleistocene(?) age. Such deposits, however, are minor in comparison with the ubiquitous interior-basin deposits of the nearby Basin and Range Province.

Figure 8. High-altitude (U-2) photograph looking about north from near mouth of the Grand Canyon (right foreground). Lake Mead is in foreground. North-trending valley in center of picture and west of the prominent Grand Wash Cliffs is the Grand Wash Trough. Iceberg Canyon is the narrow, north-trending arm of the lake in the lower left. Pierce Ferry is at wide area of the lake in the lower center of the picture.

Particularly interesting with respect to the history of the Colorado River is the Miocene Muddy Creek Formation, as exposed in the Grand Wash trough and the Pierce Ferry area (Figs. 2, 8) at the mouth of the Grand Canyon. No evidence of a river emptying into the Grand Wash trough is present in the lithologies and facies distribution of the Muddy Creek, which, instead, records interior drainage with derivation of clastic material from nearby highlands. Analysis of directions of transport and topographic closure leads to the same conclusion.

West-draining canyons are present in the Grand Wash Cliffs, a prominent, west-facing fault scarp formed during basin-range

deformation. The scarp marks the mouth of the Grand Canyon and defines the western edge of the Colorado Plateau (Figs. 2, 8). The west-draining canyons are short and steep. Where they debouch into the Grand Wash trough, the washes that carved the canyons have deposited fans of locally derived material. One such fan emerges from Pierce Canyon, whose mouth is only 1.5 miles (2.5 km) north of the Grand Canyon (Fig. 2, 8). The fan was deposited across the mouth of the present Grand Canyon. This could not have happened if the Grand Canyon and the Colorado River existed in their present location at the time.

The highest unit of the Muddy Creek Formation in the Grand Wash trough is the Hualapai Limestone, which interfingers downward with clastic rocks of the Muddy Creek. The Hualapai was deposited in a shallow lake, which extended about 25 miles (40 km) west from the Grand Wash Cliffs. As with other lithologies of the Muddy Creek, the Hualapai contains no evidence for a major river emptying into the lake in which the limestone precipitated. Instead, the lake waters were highly charged with calcium carbonate and other salts. Deposits younger than the Hualapai record through-flowing drainage.

The Hualapai was the youngest unit to be deposited in the area near the mouth of the Grand Canyon before the lower Colorado River was established. However, geologists have not yet dated it directly. The Muddy Creek Formation near Hoover Dam contains basalts that are five to six million years old (Anderson 1978; Damon and others 1978). A tuff about 1600 feet (500 m) below the Hualapai Limestone in the Pierce Ferry area has been dated by fission-track methods at eight million years (Bohannon 1984). Another tuff low within the limestone in an area about 25 miles (40 km) west of the mouth of the Grand Canyon also has yielded an age of about eight million years (Blair 1978). South of Hoover Dam (Fig. 1), the Bouse Formation (an estuarine deposit associated with the opening of the Gulf of California) records the presence of the Colorado River in its present lower course. The Bouse has been dated by the K-Ar method at 5.47 + 0.2 million years (Damon and others 1978). In the Pierce Ferry area, basalts intercalated with Colorado River gravels flowed down the valley of the Colorado when it was within 330 feet (100 m) of present grade (Lucchitta 1966, 1972). The flows have been dated by K-Ar methods at 3.8 million years (Damon and others 1978). This evidence indicates that the end of interior-basin deposition and the establishment of through-flowing drainage along the lower Colorado River in its Basin and Range course occurred between four and six million years. No lower Colorado River existed before that date.

Evidence of various kinds from the western Grand Canyon region leads to similar conclusions. According to Lucchitta (1975), the Shivwits Plateau is capped for the most part by upper Miocene lavas that overlie uppermost Paleozoic and lowermost Mesozoic rocks. A long and narrow finger of the plateau juts southward for about 20 miles (30 km) into the Grand Canyon (Fig. 7). This finger is surrounded on three sides by the Grand Canyon. Relief of nearly 1 mile (1.5 km) within a horizontal distance of a few miles between the top of the plateau and the Colorado River results in an extremely rugged topography of canyons, cliffs, and buttes. In contrast, the basalt capping the plateau, dated by the K-Ar method at 7.5 and 6.0 million years (Lucchitta and McKee 1975; Lucchitta 1975), overlies a remarkably flat and smooth surface with only a few meters of relief. In several places, cone-shaped vent areas for the basalt are truncated by the cliff-forming edge of the Shivwits Plateau, yet there are no remnants of Shivwits lava within the Grand Canyon.

Lavas of the Shivwits Plateau locally overlie the erosional featheredge of the Triassic Moenkopi Formation on the resistant Permian Kaibab Formation (Fig. 6). The featheredge formed northwest-trending strike valleys bounded on the northeast by a scarp capped by the Triassic Shinarump Member. This is a situation common on the Colorado Plateau. The Shinarump shed its pebbles into the valley in a way that preserved the pebbles both beneath and on top of the basalt (Lucchitta 1975). Today, the scarps are gone, and their place is taken by canyons tributary to the Grand Canyon (Figs. 6, 9).

On Grassy Mountain, which is on the Shivwits Plateau 15 miles (25 km) northeast of the Grand Canyon (Fig. 2), a six-million-year-old basalt overlies remnants of gravels that contain pebbles of igneous and metamorphic rocks. The gravels also contain metamorphosed volcanic rocks similar to rocks of Proterozoic age cropping out south of the present Colorado Plateau margin. The gravels rest on the Moenkopi Formation. The only reasonable source for the pebbles is to the south because in other directions, erosion has cut down only to Paleozoic and Mesozoic rocks. Neither the pebbles nor the arkosic

matrix of the gravels shows much sign of weathering; this suggests that the gravels are not reworked from older deposits. The lack of weathering within the gravels, together with the lack of a weathered zone between the gravels and the basalt, suggest that the two are of approximately the same age. The conclusion is that streams flowed northward across the present course of the western Grand Canyon as recently as six million years ago (Lucchitta 1975). These streams presumably were tributary to a larger stream that may well have been the ancestral Colorado River, but the course of this river would have been north or northwest of the western Grand Canyon. This interpretation is supported by other remnants of gravels that are composed of exotic lithologies and are found in several places in the Arizona Strip country north of the Grand Canyon.

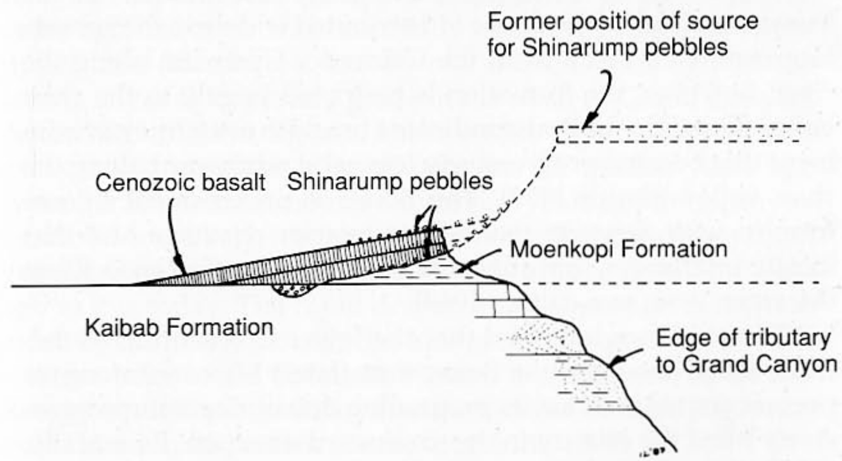

Figure 9. Diagram showing how scarp previously forming northeast side of Shivwits strike valleys occupied by basaltic lavas now is the site of a deep canyon tributary to the Grand Canyon. Looking approximately northwest

Collectively, the various features of the southwestern Colorado Plateau indicate that no rugged canyon topography and no Grand Canyon existed in the western Grand Canyon region as recently as six million years ago, the age of the young lavas in the southern Shivwits Plateau (Lucchitta 1975). The Colorado River must have become established in the western Grand Canyon after that date. It may, however, have flowed northwestward through the Strip country long before.

Post-rifting

The evidence summarized above indicates that the transition from interior drainage to the through-flowing drainage of the lower Colorado River probably occurred between five and six million years ago, or at the Miocene-Pliocene boundary. Miocene, Pliocene, and Quaternary deposits of the Colorado River are distributed widely along its lower course. Included are estuarine deposits (upper Miocene and Pliocene Bouse Formation); probable deltaic deposits (Miocene and Pliocene Imperial Formation); gravels of various ages and degrees of cementation, chiefly reflecting downcutting; and fine-grained deposits (Pleistocene Chemehuevi Formation) produced by temporary aggradation. Information on these deposits has been summarized by Lucchitta (1972), who interpreted the data in light of the history of the lower Colorado River.

The Bouse Formation is particularly informative. In the Yuma area (Fig. 1), the Bouse is distributed widely in the subsurface even well away from the Colorado. Upstream along the river, however, the formation is restricted largely to the river valley. Fossils in the Bouse indicate a brackish estuarine environment that became progressively less salty northward along the river valley (Smith 1970). The Bouse is an erosional unconformity with deposits that reflect interior drainage and that locally interfinger upward with gravels of the Colorado River (Metzger 1968; oral comm. 1969).

The evidence indicates that the lower Colorado River became established early in Bouse time (latest Miocene) along its present course and that its prograding deltaic deposits progressively filled the estuary in the southward direction. Eventually, the delta reached the Salton trough of California, where it is represented by the thick Imperial Formation. This formation contains a well-defined horizon above which Cretaceous coccoliths found elsewhere only in the Mancos Shale of the Colorado Plateau make their appearance; the horizon signals the capture of the old, upper Colorado River by the developing and headward-eroding lower Colorado.

A 3.8 million-year-old basalt flow associated with indurated gravels of the Colorado River occurs about 330 feet (100 m) above present river grade at Sandy Point (Fig. 2) in the upper Lake Mead area (Longwell 1936; Lucchitta 1966). This basalt is part of the extensive basalts of the Grand Wash (Figs. 2, 9) and flowed

for several miles along the valley of the Colorado River, which must have been nearly as low then as it is now.

In the western Grand Canyon, basaltic flows occur at river level for a long distance. These flows, which have their source in the area of the Uinkaret Plateau (Fig. 2), are the intracanyon lavas of McKee and others (1968) and have been dated at about 1.2 million years. The lavas show that at the time of their emplacement, the western Grand Canyon was as deep as it is today.

The upper Cenozoic deposits along the lower course of the Colorado thus show that the river came into being five to six million years ago when the Gulf of California opened up. The river extended itself southward, or downstream, by filling its estuary with deltaic deposits. It also extended itself by headward erosion and the integration of former interior drainages. By the time the delta reached the Salton trough area, the head of the river had captured the old upper Colorado River. By 3.8 million years ago, the river was essentially at its present grade in the upper Lake Mead area, and by one million years ago (at the latest), it was at its present grade in the western Grand Canyon. According to these figures, the western Grand Canyon was excavated during the interval between six million years ago (younger Shivwits lavas) and one million years ago (intracanyon basalts). More likely, it began to be cut shortly before five million years ago and was nearly as deep shortly after four million years ago as it is today. The rapid downcutting almost certainly was aided by the nearly 0.6 mile (0.9 km) of uplift experienced by the western edge of the Colorado Plateau and adjacent Basin and Range terrain since the time when the Lower Colorado River was established in its present course (Lucchitta 1979).

Much of the course of the lower Colorado River in the western Grand Canyon and upper Lake Mead areas can be explained through structural or topographic features. Thus, the Virgin Canyon section (Fig. 2) probably is at the margin of an ancient fan spilling southward from the south Virgin Mountains; the Greggs Basin-Iceberg Canyon section (Figs. 2, 8) is along Wheeler fault; the Pierce Ferry section is through the lowest spot in the old Muddy Creek basin; the Hualapai Plateau section is along a strike valley developed at the foot of the upper Grand Wash Cliffs (southwest-facing rim of the Shivwits Plateau); and the section along the east side of the Shivwits Plateau is developed near the Hurricane fault.

SUMMARY

A striking conclusion that emerges from the study of the Colorado River is that even a canyon as intricate and immense as the Grand can be carved in a surprisingly short time—five million years, probably substantially less, in spite of the tough and remarkably undeformed rocks that make up its walls. Perhaps the key to understanding this phenomenon is the fact that in canyons the volume of material removed per unit of downcutting is small compared with that for more open valleys. In other words, the rate at which material is carved from a canyon is small in relation to the rate at which the floor of the canyon is lowered (Lucchitta 1966).

Another and perhaps even more striking conclusion is that one can draw a parallel between the development of physical systems, such as drainage networks, and the Darwinian concept of biological evolution based on survival of the fittest and natural selection. In river systems, the external agent that triggers change is tectonism rather than the random mutations of biology. Competition between drainages occurs through changes in gradient, whereby rivers whose gradient is increased are favored, and those whose gradient is reduced are handicapped.

The battles for survival are fought with headward erosion and stream piracy or capture. The ultimate result is a succession of drainage configurations that change with time in response to external forces—chiefly, the deformation of Earth's surface. Since any particular configuration is merely a still frame within the movie of evolution, ancestors may bear little resemblance to their descendants.

CHAPTER 16

HYDRAULICS AND GEOMORPHOLOGY OF THE COLORADO RIVER IN THE GRAND CANYON

Susan Werner Kieffer

INTRODUCTION

The Colorado River and its tributaries drain much of the southwestern United States, ultimately emptying into the Gulf of California in Mexico. Only the Mississippi River exceeds the Colorado in length within the United States. The potential use of the water of the Colorado River for irrigation, hydroelectric power, and domestic purposes was recognized more than a century ago. In 1905, severe floods on the Colorado River caused extensive damage in the Imperial Valley of California, and political pressure arose for construction of flood control/storage dams on the river. The development and regulation of the river expanded rapidly until, at the present time, the Colorado River is sometimes referred to as "the world's most regulated river" (National Research Council 1987, p. 18). Additional information about the history of the river's development is summarized in Kieffer and others (1989), and so further discussion in this chapter focuses on the portion of the Colorado River that lies mainly within Marble and Grand canyons—that is, between Glen Canyon Dam and Lake Mead.