Grand Canyon National Park (© F. Labrune).


Grand Canyon National Park

Matkatamiba Canyon has been cut through the Cambrian Muav Limestone, Grand Canyon National Park, Arizona (© W. Ranney).

Geology of Grand Canyon National Park: Sedimentation and Erosion on Planet Earth's Grandest Landform

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Abstract/Résumé

The Grand Canyon, located in the state of Arizona at the southwest edge of the Colorado Plateau geographic province, exposes rocks representing nearly half of all Earth history. Basement rocks are composed of a metamorphic assemblage (the Granite Gorge Metamorphic Suite) and an igneous group (the Zoroaster Plutonic Complex) of nearly equal age, dating between 1840 to 1660 Ma (million years ago). The Grand Canyon Supergroup, a package of now tilted Meso- to Neoproterozoic sedimentary and volcanic rocks, overlies this basement. Flat-lying sedimentary rocks ranging in age from Cambrian to Permian cover these older rocks, composing the classic stratified appearance of the canyon. A thick section of Mesozoic-age rocks once covered these but were mostly eroded. Details of the timing and exact processes involved in the excavation of Grand Canyon are still debated, but a broad outline is known. The canyon formed as a result of erosion by the Colorado River or some ancestor(s) to it. Tectonic uplift began in the Laramide Orogeny (70 to 40 Ma) and an initial river system developed with flow toward the northeast (opposite to that of the modern river). A few hypotheses suggest that this early drainage system carved the canyon to near its present depth; remnant sediments in a few tributary canyons attest to landscape incision at this time. Most hypotheses, however, center on fluvial integration in two separate and distinct drainage systems near the end of the Miocene, between 5 and 6 Ma. This was facilitated by the opening of the Gulf of California along the San Andreas Fault system, which created an extensional corridor where the lower Colorado River developed by sequential closed-basin spillover. River water upstream from the Grand Canyon ultimately found a connection to this corridor through some process: 1) headward erosion and stream piracy; 2) closed-basin spillover; 3) karst collapse; or 4) a combination of processes. After this integration, the through-going Colorado River deepened the Grand Canyon. Spectacular lava flows (<1 Ma) spill into the western part of the canyon and record the growth and destruction of lava dams, and the resulting outburst floods.

Situé dans l'Etat de l'Arizona, sur la bordure sud-ouest du plateau du Colorado, le Grand Canyon présente une coupe naturelle représentant presque la moitié de l'histoire de la Terre. Les roches basales sont formées par un ensemble métamorphique (« Granite Gorge Metamorphic Suite ») et un groupe igné (« Zoroaster Plutonic Complex ») d'âge sensiblement identique, entre 1840 to 1660 Ma (millions d'années). Le Grand Canyon Supergroup forme un second ensemble, composé de roches volcaniques et sédimentaires Méso- à Néoprotérozoique, actuellement incliné et reposant sur le substratum. Des terrains sédimentaires en position horizontale, datant du Cambrien au Permien, recouvrent ces roches très anciennes et donnent au canyon son aspect stratifié bien connu. Les épais terrains du Mésozoïque, qui les recouvraient autrefois, ont été érodés. Les détails de l'âge, de l'évolution et des processus précis à l'origine du creusement Grand Canyon, sont toujours discutés mais nous en connaissons tout de même les grandes lignes. Le canyon est le résultat de l'érosion linéaire par la rivière Colorado ou par plusieurs de ses ancêtres. Le soulèvement tectonique a commencé lors de l'orogénie Laramide (70 à 40 Ma) ; un premier système fluvial s'est développé, coulant vers le nord-est, c'est-à-dire dans le sens opposé de la rivière actuelle. Quelques hypothèses suggèrent que ce système de drainage a creusé le canyon jusqu'à sa profondeur actuelle : des témoins sédimentaires dans les canyons affluents témoigneraient de l'incision du paysage. Cependant, la plupart des hypothèses se concentrent sur l'intégration fluviale en deux systèmes de drainage indépendants et bien distincts vers la fin du Miocène, entre 5 et 6 Ma. Cette évolution a été favorisée par la formation du Golfe de Californie le long du système de la faille de San Andreas, créant un couloir d'extension à l'endroit où la rivière Colorado a commencé à se former par le processus de débordement de bassins fermés. L'eau de la rivière en amont du Grand Canyon a finalement trouvé une connexion avec ce corridor par divers processus : 1) capture par érosion régressive ; 2) débordement de bassins fermés ; 3) effondrement karstique ; 4) combinaison des divers processus. Après cette liaison amont-aval, l'écoulement de la rivière Colorado a creusé le Grand Canyon. Des écoulements de lave spectaculaires (< 1 Ma) se répandent dans la partie occidentale du canyon en formant des barrages de lave dont la rupture a engendré des inondations.

Key words/Mots-clés

Grand Canyon, Colorado River, Stream piracy, Closed-basin spillover, Geomorphology.

Grand Canyon, rivière Colorado, capture, débordement d'un bassin fermé, geomorphologie .

Introduction and Physical Setting

The Grand Canyon is one of Earth's most iconic and recognizable landscapes **(photo 1)**. It is one of the few landforms that can be seen from space and provides an exceptional window for earth scientists who study the growth and fragmentation of continents, sedimentation, tectonic uplift, and erosion on a large scale. The canyon is located entirely within the state of Arizona on the southwestern edge of the Colorado Plateau, one of 26 geographic provinces described within the boundaries of the USA **(figure 1)**. It provides visitors with a multitude of colorful viewpoints. Many trails provide access to the Colorado River, which itself offers an exceptional close-up view of erosion at work and an exciting ride through the canyon. Anyone who visits the canyon is immediately impressed with its immense size, rugged and colorful topography, and stunning skies and changeable weather patterns.

The Colorado River and its tributaries have likely carved the Grand Canyon in only the last 5 to 6 Ma

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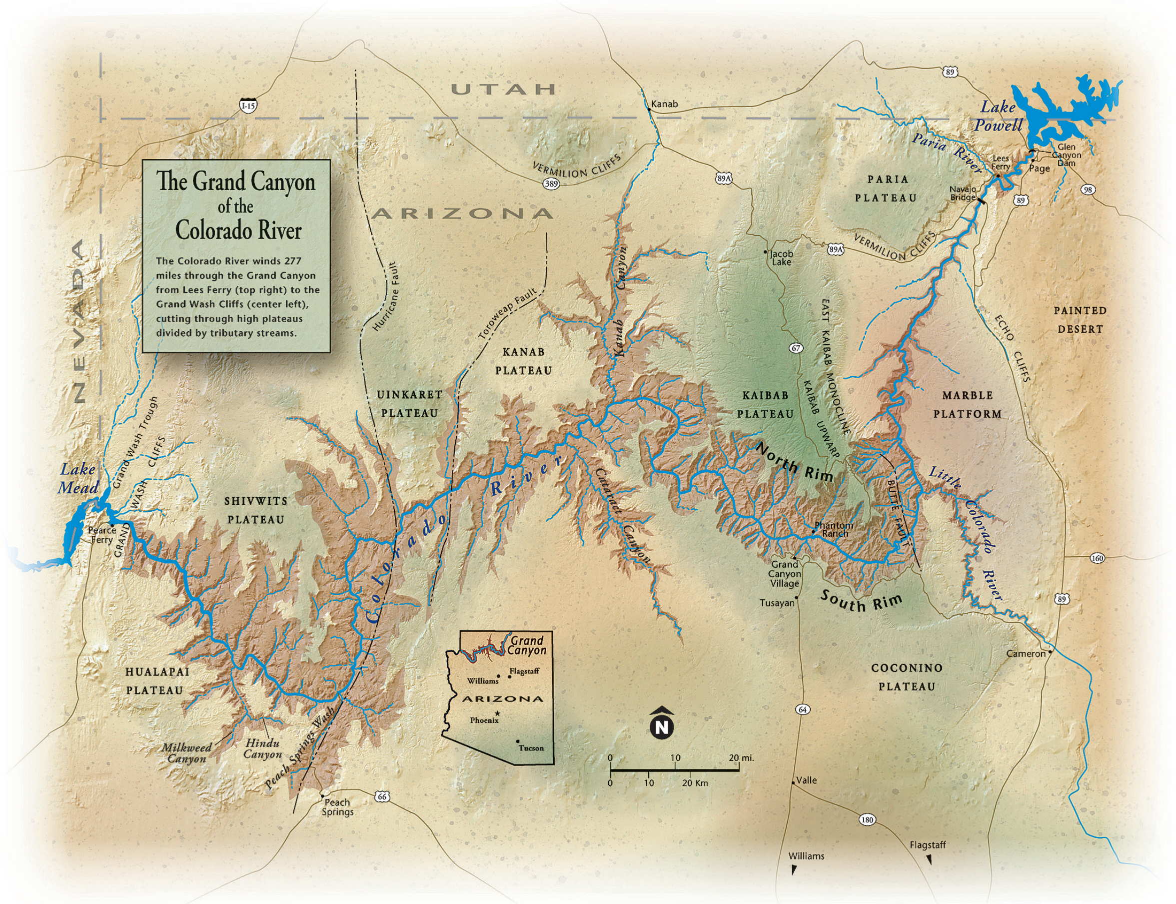

figure 1: Location map of the Grand Canyon in northern Arizona (from Ranney, 2012).

photo 1: The Grand Canyon, in northern Arizona, is Earth's greatest single geologic spectacle. It exposes a broad swath of Earth history from mid-Proterozoic to Holocene. Photo from near Grand Canyon Village on the South Rim (photo : W. Ranney).

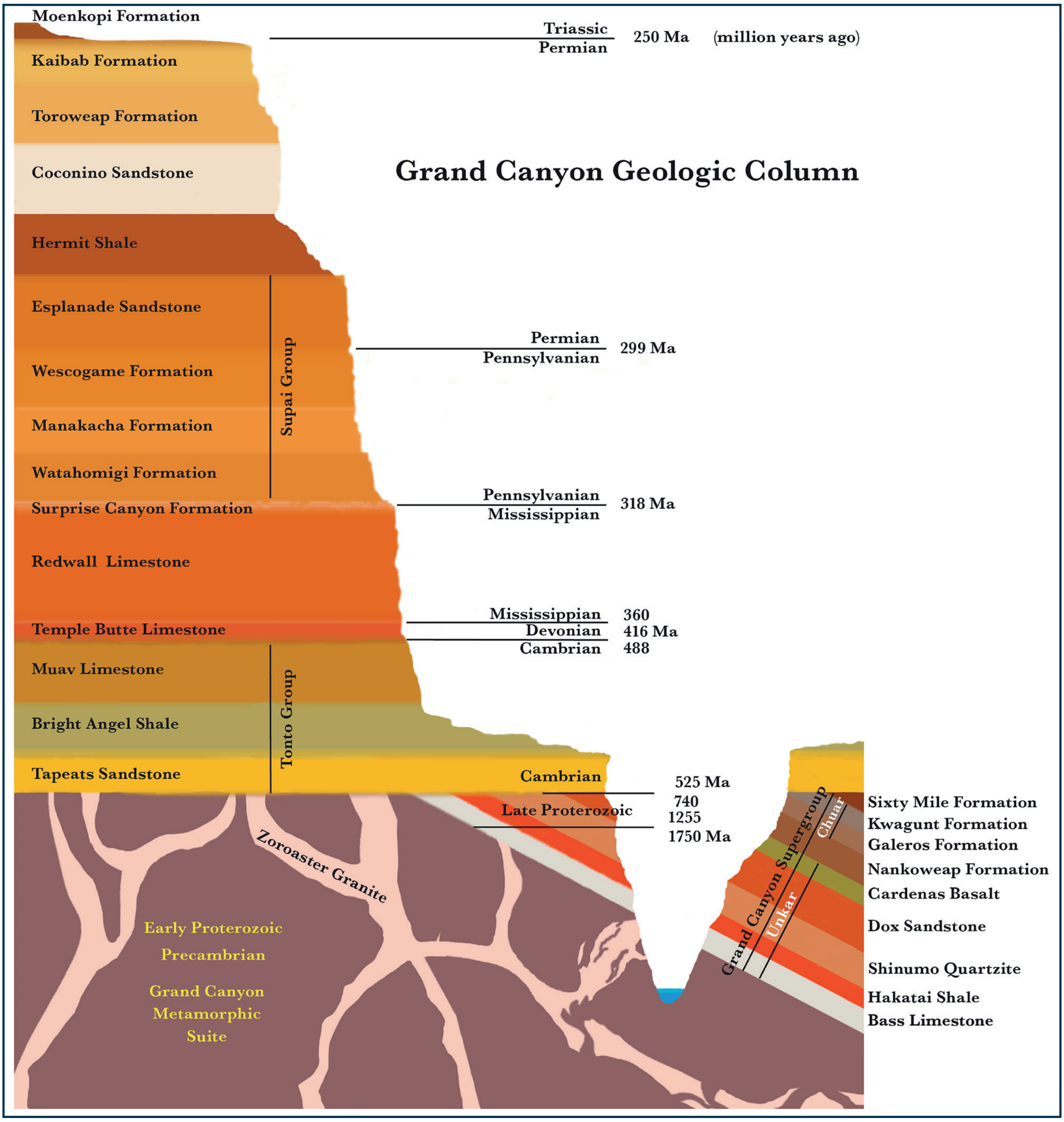

figure 2: Stratigraphic column showing all of Grand Canyon's 25 named rock units and ages (from "Grand Canyon: A Gallery of Art, Science and History" by Wes Timmerman, 2012).

(million years), but this date is not completely resolved, nor are the specific processes that formed it (Ranney, 2012). The river flows through the canyon for 450 km (277 mi), but nowhere can the canyon be viewed in its entirety from the ground. On average the canyon measures about 16 km wide (10 mi), with an extreme width of 29 km (18 mi). It is over 1.6 km deep (1 mi) in most places, with about 4,000 cubic km of rock (1,000 cubic mi) having been removed by erosion. Much of this material now resides in the area of the Gulf of California, where the Colorado River ends its journey to the sea.

With such an immense size, the Grand Canyon contains a great variety of landforms. Some of the more important include three "Granite Gorges" (Upper, Middle, and Lower) carved into Paleoproterozoic metamorphic and igneous rocks; two extensive terraces known as the Tonto Platform and the Esplanade Platform (developed where soft shale or mudstone has been stripped off from harder strata below); numerous buttes and spires, often named "temples" in Grand Canyon; and relatively recent (<1 Ma) volcanic cones and lava flows within the canyon, which contain an informative record of lava emplacement, river damming, occasional catastrophic destruction of dams, and subsequent outburst flooding.

Other aspects of Grand Canyon National Park are equally impressive. Due to its extreme relief and length, it holds 1,750 species of plants (more than any other National Park in the USA), 373 species of birds, 47 reptile species, and 34 species of mammals. Its archaeological record extends back at least 4,500 years, based on radiocarbon-dated willow-stick figurines found in caves. The record may extend back to 12,000 years ago or more, to the time when people first arrived in the Americas (but based only on a single projectile point found on the canyon's rim). Those of European descent first saw the canyon in AD 1541 when native guides led members of the Coronado expedition to the canyon's edge. These explorers were somehow unimpressed, and the canyon was not truly appreciated until the first geologist visited in 1858. From that time onward, people have come to Grand Canyon to experience its sublime grandeur and spectacular vistas. Today it is visited by almost five million people a year, with over 40% of them from outside the USA.

I- Origin of the Rocks – Two Billion Years of Earth History

A- Vishnu Basement Rocks

The various rock layers in the Canyon, their ages, and relation to the geologic time scale are shown in **figure 2**. The geologic story begins at the end of the Paleoproterozoic Period between 1840 and 1710 Ma with the appearance of island arcs and associated sediments (Karlstrom et al., 2012). These sedimentary and volcanic rocks collided with North America, and became attached to it, between 1710 to 1680 Ma. This collision compressed the rocks into very large folds, which were forced to depth and altered into schist and gneiss. Garnet minerals in the schist reveal peak metamorphic temperatures of 750 °C (1380 °F) and burial depths of up to ~ 25 km (15 mi). They are formally known as the Grand Canyon Metamorphic Suite, but are historically known as Vishnu Schist, and many scientists simply refer to them by this latter name **(photo 2)**.

At greater depths, rocks melted and rose buoyantly into the still-deforming metamorphic assemblage. They were intruded as granitic (pegmatite) bodies between 1710 and 1660 Ma. They are historically known as the Zoroaster Granite but are now reclassified as the Zoroaster Plutonic Complex (although the former name is still used). The resulting igneous and metamorphic rocks give evidence for the dynamic changes that added crustal rocks to the North American continent over this 180 million year period (Karlstrom et al., 2012).

The entire package of metamorphic and igneous rocks is informally known as the Vishnu basement. Mica minerals within the schist provide a record of the unroofing and cooling history of the basement rocks and show that most of the erosion occurred between about 1350 and 1254 Ma. As erosion proceeded, the confining pressures were gradually relieved and the rocks rose isostatically (by their own buoyancy). This is how rocks that formed at considerable depth were brought back to the earth's surface. They were eventually eroded down to a nearly flat surface near sea level.

B- Grand Canyon Supergroup

Following this long erosion period, Late Proterozoic sediments began to be deposited about 1254 Ma. This package, called the Grand Canyon Supergroup, is over 3800 m (12,500 ft) thick and is divided into two groups and nine formations, which are mainly sedimentary with small amounts of volcanic and intrusive igneous rocks. These rocks are exposed only in Grand Canyon, but correlative rocks are found in central Arizona, Death Valley, and northern Utah. Their lower part is called the Unkar Group, and it represents deposition in offshore (limestone), nearshore (shale), and continental (sandstone) environments. The Cardenas Basalt caps the Unkar Group and is dated at about 1100 Ma. Spectacular igneous dikes can be observed cutting the sedimentary rocks of the Unkar Group **(photo 3)** and the interaction of these intrusive rocks with the magnesium-rich Bass Limestone produced chrysotile asbestos, which was mined in Grand Canyon in the late 19th century. The Unkar Group was likely deposited in rift basins associated with the building of the supercontinent Rodinia, in which the crust was squeezed in a northwest-southeast direction and accompanied by extension in the northeast-southwest direction.

An interval of erosion followed that lasted up to 200 million years, followed by deposition of the Nankoweap Formation on top of the Unkar Group. After further erosion the Chuar Group was deposited, beginning about 770 Ma. These are among the best-preserved rocks on the planet from this specific time period and immediately preceded the postulated "Snowball Earth," when almost the entire planet was frozen. These rocks were laid down in shallow marine and near-shore settings and contain a record of the diversification of single-celled life and the appearance of heterotrophic life (gaining nutrition from other organisms rather than by photosynthesis). These rocks were deformed during the breakup of the continent Rodinia and show evidence for east-west extensional faulting. Capping the Chuar Group and forming the top of the Grand Canyon Supergroup is the Sixtymile Formation, which was probably a basin fill deposit originating from erosion of nearby mountains.

Rocks of the Grand Canyon Supergroup are found only in about 10% of the canyon and always as fault-bounded, tilted blocks. Elsewhere in the canyon the Paleozoic rocks lie on the Vishnu basement, forming the Great Unconformity, where 1200 million years of the rock record is missing – some eroded away, and some perhaps never deposited **(photo 4)**. Preserved blocks of Supergroup rocks are those that were down-dropped the greatest amount in the Late Proterozoic and thus escaped complete erosion. Blocks that were faulted higher became eroded and were thus removed from the record in the Grand Canyon. Some rock types were particularly resistant to erosion, such as the Shinumo Quartzite in the Unkar Group, and

photo 2: *View from the Tonto Platform looking west along the Colorado River into the Upper Granite Gorge, with dark-colored Vishnu Schist intruded by pink Zoroaster Granite. This package of mid-Proterozoic crystalline rocks formed about 1,750 Ma (million years ago) by the collision of island arcs with the proto-North American continent (photo : W. Ranney).* ►

photo 3: *A spectacular diabase dike cuts across the red Hakatai Shale, a rock unit within the mid-Proterozoic Grand Canyon Supergroup (Unkar Group). These dikes are thought to be the source for the Cardenas Basalt, located out of view and higher up in the section (photo : W. Ranney).*

photo 4: *The Great Unconformity, with Cambrian Tapeats Sandstone capping the Vishnu Schist and Zoroaster Granite in Blacktail Canyon, Grand Canyon. The time gap represented at this unconformity is 1,225 Ma (photo : W. Ranney).*

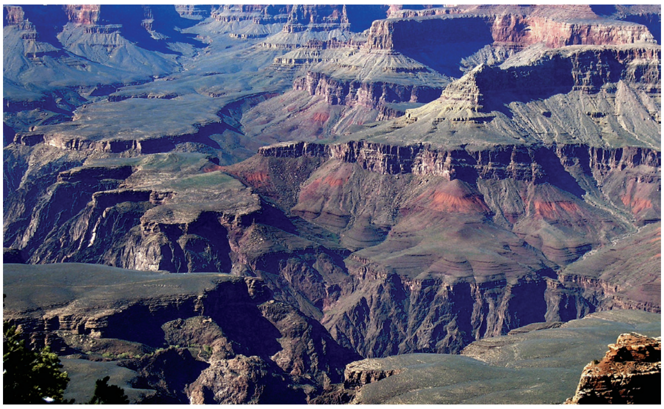

photo 5: *View from Grand Canyon's South Rim toward a paleo-monadnock. This feature is located in the center of the photo, and is composed of brightly colored and slightly tilted Supergroup rocks, which were block-faulted in the Late Proterozoic and left as erosional remnants in the Cambrian. The Tapeats Sandstone (brown layer to the left of the Supergroup outcrop) was then deposited against the rising cliff. Such paleo-topography is often well exposed near the margins of Supergroup outcrops in Grand Canyon (photo : W. Ranney).*

stood as residual hills in the ancient environment that were only buried after significant Cambrian-age deposition **(photo 5)**.

C- Paleozoic Rocks

A 1200 m (4000 ft) section of nearly flat-lying Paleozoic strata compose the upper 80% of the walls of Grand Canyon. These account for the easily recognizable stratified profile of the canyon **(photo 6)**. These rocks record deposition over a 250 million year time period spanning the entire Paleozoic Era (Blakey and Middleton, 2012). However, rocks of Ordovician and Silurian age are completely absent in Grand Canyon, and Devonian and some Mississippian-Pennsylvanian rocks are found only in discontinuous channels.

Cambrian rocks belonging to the Tonto Group include the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone, a marine sequence showing a gradual onlap of the sea onto the continental margin. Differential erosion on the easily weathered Bright Angel Shale has formed the Tonto Platform in eastern Grand Canyon. A hiatus of no less than 135 million years separates the Tonto Group from the Devonian Temple Butte Formation, which in eastern Grand Canyon is located in discontinuous channels that thicken and converge into a 120 m (400 ft) continuous deposit in the western part of the canyon. All of these deposits reflect the passive continental shelf conditions in western North America during the early Paleozoic, after the opening of the proto-Pacific Ocean with the breakup of the Rodinian supercontinent.

Another 30-million-year unconformity separates Devonian rocks from the overlying Redwall Limestone, a durable Mississippian (Lower Carboniferous) carbonate that everywhere forms an obvious 150 m (500 ft) cliff midway in the canyon. The Redwall formed in an open marine setting and contains abundant fossils of crinoids, bryozoans, brachiopods and corals. The Redwall has numerous correlatives throughout the western USA, suggesting an extensive shallow shelf. It is overlain by discontinuous channel deposits of the Surprise Canyon Formation, a heterogeneous mix of plant-bearing conglomerate and sandstone, and marine limestone and siltstone. It is interpreted to be an estuarine deposit which, like the Temple Butte Limestone, converges and thickens considerably to the west.

Upper Carboniferous rocks known as the Supai Group document the gradual replacement of marine conditions, prevalent in the early Paleozoic, by more continental conditions in the late Paleozoic. Mixed limestone and red siltstone near the base gives way to dominant mudstone, siltstone and sandstone at the top, recording this major shift in the depositional environment. The Supai rocks are interpreted to be, in ascending order, near-shore, coastal floodplain, and eolian deposits. Some fossil vertebrate tracks have been found. The overlying brick-red Hermit Formation (Permian) consists of sandstone, mudstone and local sedimentary

photo 6: *The entire Permian section at Grand Canyon is exposed west of the South Kaibab Trail, showing the familiar profile resulting from differential erosion of resistant cliff-forming strata alternating with softer slope-forming shale and mudstone (photo : W. Ranney).*

pebble conglomerate. It formed on a broad coastal plain in mostly fluvial settings but also in eolian settings (loess and dunes). Recession of the easily eroded Hermit Formation has created the Esplanade Platform in the central and western portions of Grand Canyon.

The next deposit is the Coconino Sandstone, a pale-yellow, cross-stratified unit that everywhere forms cliffs within the canyon. It originated in an arid, inland dune environment. Some cross-beds, especially at its base, contain numerous and well-preserved reptile trackways. The overlying Toroweap Formation is often overlooked in Grand Canyon because it forms slopes of easily eroded siltstone and gypsum (as well as some limestone). It was likely deposited along the shore of a sea that encroached from the west. The gypsum and siltstone were probably deposited in a sabkha environment (evaporative and just above tidal range). Capping the Grand Canyon and completing the entire Paleozoic section is the Kaibab Limestone. It represents a final transgression of the late Paleozoic sea into the area. Numerous chert horizons help to solidify the Kaibab and make it the durable rock that "holds up" the strata in the canyon. Many of the chert bodies are diagenetic in origin, formed by the dissolution of sponge spicules on the ocean floor soon after the rock was deposited. The region was an erosion surface in the latter half of the Permian, as no rocks of this age are known there.

D- Mesozoic Rocks

A voluminous stack of Mesozoic-age rocks (250–65 Ma) once covered the Grand Canyon area, but most of it was removed by erosion. Only two places near the Grand Canyon preserve the lowest units of this once great stack, Cedar Mountain east of Desert View, and Red Butte about 24 km (15 mi) south of Grand Canyon Village. At both localities, the Moenkopi Formation rests unconformably on the Kaibab Limestone. A gap of about 30 million years separates the two units. The Moenkopi records river and near-shore environments and is known for its well-developed ripple marks and amphibian fossils. The Shinarump Member of the Chinle Formation overlies the Moenkopi and is a durable conglomerate that holds up Cedar Mountain. (At Red Butte the Shinarump is overlain by a more recent basalt lava cap). The Shinarump is a river deposit with a source area to the south of Grand Canyon and is quite extensive across the Colorado Plateau.

Additional strata, on the order of 1500 to 3000 m thick (5,000 to 10,000 ft) once covered the Grand Canyon area and are still preserved to the north, forming the Grand Staircase in southern Utah (where north-dipping strata are progressively eroded to create a stair-step topography). Erosional stripping may have begun in the Early Cretaceous, but considerable lateral erosion occurred during the Laramide Orogeny, when uplift in southwestern Arizona occurred. This produced a regional northeast dip in much of northern Arizona. Details about the removal of the Mesozoic section from Grand Canyon are just now being revealed with the use of temperature-reconstruction methods such as apatite fission track dating and ([U-Th]/He) techniques (Karlstrom et.al., 2012, and Flowers et.al., 2008).

E- Cenozoic Rocks

Rocks of Cenozoic age (less than 65 Ma) are relatively scarce at Grand Canyon. It was a time of regional uplift and erosion leading to the removal of

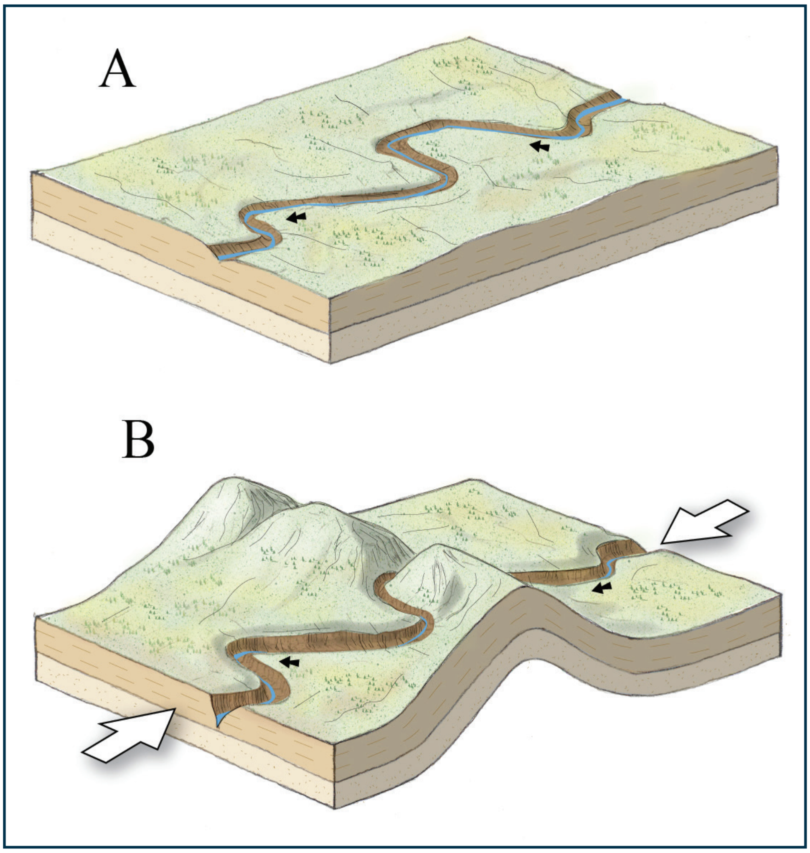

figure 3: John Wesley Powell proposed the theory of antecedence for the development of drainage along the Colorado River system. Later work showed that the folded structures were older than the river courses. Nevertheless, Powell mentored successive generations of geologists in the southwestern USA.

most evidence. During the Laramide Orogeny, north-directed river gravels, called the Music Mountain Formation, were delivered from highlands south of Grand Canyon. They are exposed in paleocanyons cut down into Cambrian-age strata and document significant Laramide incision near modern Grand Canyon (Young, 2011). A second gravel package, the Buck and Doe Conglomerate, is late Oligocene in age (roughly 24 Ma) and records sluggish rivers that may have ultimately buried and overtopped ancient drainage divides and other landforms in western Grand Canyon. Additional sedimentary deposits of Miocene age and younger are discussed in the next section, which deals with the history of canyon incision.

Grand Canyon also contains a spectacular record of Quaternary volcanism (< 2 Ma) in its western section, where basalt lava, ranging in age from 830,000 to 1,000 years ago, erupted along a 16 km (10 mi) stretch of the Colorado River between the Toroweap and Hurricane faults (which likely served as conduits for the eruptions). Today many flows and cones are perched above and within the canyon walls. These flows blocked and filled side canyons and the channel of the Colorado River. Remnants of one flow traveled 135 km (84 mi) down the river channel, while others lie up to 330 m (1,100 ft) above the channel. As many as seventeen lava dams blocked the Colorado River, and on at least five occasions huge outburst floods resulted from catastrophic failure of these dams. The deposits from these floods are found from 45 to 200 m (150 to 650 ft) above the modern river channel, with boulder sizes up to 30 m (100 ft) in diameter.

II- Carving of Grand Canyon – Historical Perspectives and New Ideas

As well known as the rock record is in Grand Canyon, details about the canyon's excavation and formation are not as clear. The last 70 million years, in which the region has been subjected to significant erosion, has removed much of the evidence for how the canyon could have formed. Certain details are known: the Colorado River and its tributaries excavated this great space; it could not have happened prior to about 80 to 70 Ma; and it is likely that much of what we see today has formed in just the last 5 or 6 million years.

A- The 19th Century

It is unknown when the first human being saw the Grand Canyon, but evidence from nearby areas suggests that it occurred between 12,000 to 13,000 years ago, when migrants from Siberia arrived, perhaps inadvertently, in the New World. Although these people preceded a scientific understanding of the Earth, they were likely impressed with Grand Canyon. People of European descent arrived in the mid-16th century but were apparently disinterested in the canyon as a landform. In fact, of all the explorers and pioneers who happened upon the canyon in the 318 years between AD 1541 and 1858, not one of them returned for a second visit and most referred to it in journals as worthless, profitless, and to be avoided (Ranney, 2013).

In April 1858, however, the first geologist laid eyes on the canyon and changed forever our relationship to it. John Strong Newberry came west as the scientist assigned to the Ives Expedition and made the first geologic interpretation of the gorge. He observed that strata on either side of the river were found in perfect correspondence, suggesting that no fault or fissure opened the ground and only later became occupied by the river. Rather, Newberry proposed that the canyon formed by "the exclusive action of water" (Newberry, 1861). This concept, known as **fluvialism**, describes how landscape formation is facilitated and shaped by running water. This single concept remains the most basic fact about the canyon's formation.

John Wesley Powell made his pioneering river trips through Grand Canyon in 1869 and 1871 but suffered from weariness and a shortage of food by the time he reached the Grand Canyon. Thus, he could only surmise the geologic history of the great gorge by inference from what he observed further upstream on the Green River, and proposed **antecedence** as the cause of the specific placement of the river (Powell, 1875). He envisioned the river system to be old, and that the uplifts adjacent to it came later and did not deflect the river's course **(figure 3)**. Although later discoveries proved that the river courses are young compared to regional uplift, Powell laid a foundation of Colorado River studies and was a mentor to the next generation of canyon geologists.

Following his footsteps was Clarence Dutton, a Yale-educated Army officer who sought to further explain how the Green River was placed on Powell's antecedent landscape. He postulated that a precise course for the river was established on Eocene-age lake sediments (the modern-day Green River Formation) in the Uintah Basin. According to Dutton, when the lake water drained away the river found a course through the shallow irregular depressions on top of the lake sediments. Later uplift of the Uintah Mountains then caused the river to carve the Canyon of Lodore, while the dissection of the landscape kept pace with the slowly uplifting terrain (Dutton, 1882). This process is known as **superposition**.

Powell then selected Charles Walcott to work in eastern Grand Canyon, where he identified and named the Butte fault (Walcott, 1890). This fault is a more deep-seated expression of the East Kaibab monocline, a fault and fold system that has experienced a complex history, and is now known to have had at least 3200 m (10,500 ft) of late Proterozoic normal offset, overprinted by 300 m (1,000 ft) of Laramide reverse movement. Folding along the fault was the evidence that caught Walcott's attention, and he reasoned that this must have occurred when a considerable thickness of strata still covered the area. This showed that the uplift was older than the river's course. Walcott showed that uplift of the area might be older than previously thought. The 19th century ended with most geologists committed to ideas for an old Colorado River, but with some uncertainties beginning to emerge.

B- The 20th Century

It became apparent that no one could address the age or formation of the Grand Canyon without also understanding the history of the Colorado River. Newberry had initially shown the relationship between the Colorado River and Grand Canyon, but no one had yet argued for a young Colorado River. After studying the lower river, Eliot Blackwelder forever changed this viewpoint by asking why, if the Colorado River were an old river system, it had not yet captured interior-drained basins that lie only a few kilometers distant (Blackwelder, 1934). He noted how the river flowed through various open basins in its course from the Rocky Mountains to the sea, separated by drainage through narrow canyons. Blackwelder laid the groundwork for a grand assault on the perceived antiquity of the river by proposing that **basin spillover** might be the process that integrated the river. He opened the door to a new way of thinking about the evolution of the Grand Canyon.

Following on Blackwelder's heels was Chester Longwell, who studied the geology of an area that became flooded by the water behind Hoover Dam, located where the Grand Canyon exits the Grand Wash Cliffs at the southwestern edge of the Colorado Plateau. Longwell mapped basin-fill deposits called the Muddy Creek Formation in the Grand Wash trough, a mid- to late Miocene fault-block basin. These rocks are exposed on both sides of the Colorado River, but they contain no detritus that originated from bedrock in the Grand Canyon or upstream (Longwell, 1946). He concluded that the Muddy Creek Formation was deposited before the modern Colorado River came into existence. This curious relationship became known as the "Muddy Creek problem." Uppermost deposits of the Muddy Creek Formation (Hualapai Limestone Member) yield radiometric ages of 6 Ma, and this is the source of the widely cited age for the Grand Canyon. This was definitive proof for a "young" Colorado River.

By the 1960s a solution was needed to the conflicting evidence of an "old" or "young" river and canyon. Eddie McKee, a pre-eminent Grand Canyon geologist, convened a special symposium in August 1964 attended by 20 geologists. Two significant results were the establishment of a timeline that gave a plausible sequence of landscape-forming events, and the introduction of a theory for how the Colorado River (and by extension Grand Canyon) formed from the integration of two separate and distinct river systems. The authors outlined a five-stage evolutionary sequence: (1) initial northeast drainage across a low-relief but uplifted surface; (2) slight deviation of this pattern around local upwarps; (3) development of two separate and distinct drainage systems on either side of the Kaibab upwarp, with the younger, steeper, west-directed Hualapai drainage going to the Gulf of California, and the older more sluggish ancestral upper Colorado River going southeast along the present course of the Little Colorado River; (4) growth of interior basins to the west and east of Grand Canyon (the Muddy Creek basin and the Bidahochi basin); and (5) integration of the two drainages by renewed uplift, headward erosion, and stream capture (McKee et al., 1967). This idea stated that the western Hualapai drainage gradually lengthened its channel eastward, in the upstream direction, to intersect and capture the older, more sluggish ancestral upper Colorado River **(figure 4)**.

The ideas generated at the symposium received much exposure and support in the years immediately following. But by the early to mid-1980s it became apparent that the proposed ancestral upper Colorado River could not have gone southeast along the course of the Little Colorado River. Nevertheless, the concepts of headward erosion and stream piracy would be the lasting legacy of this pivotal meeting, and they still influence thinking about the evolution of the river.

C- New Ideas in the 21st Century

A recent surge in interest in the evolution of the Colorado River and Grand Canyon has commenced since the dawn of the new millennium. With advancements in laboratory techniques such as detrital zircon studies, apatite fission-track dating, thermochronology, and cosmogenic helium studies, geologists have more tools to tease out information from Grand Canyon's stubborn rocks. This surge in interest began in June 2000, when a second Colorado River symposium was convened at Grand Canyon, with 73 geologists in attendance and the publication of a symposium volume (Young and Spamer, 2004). The key

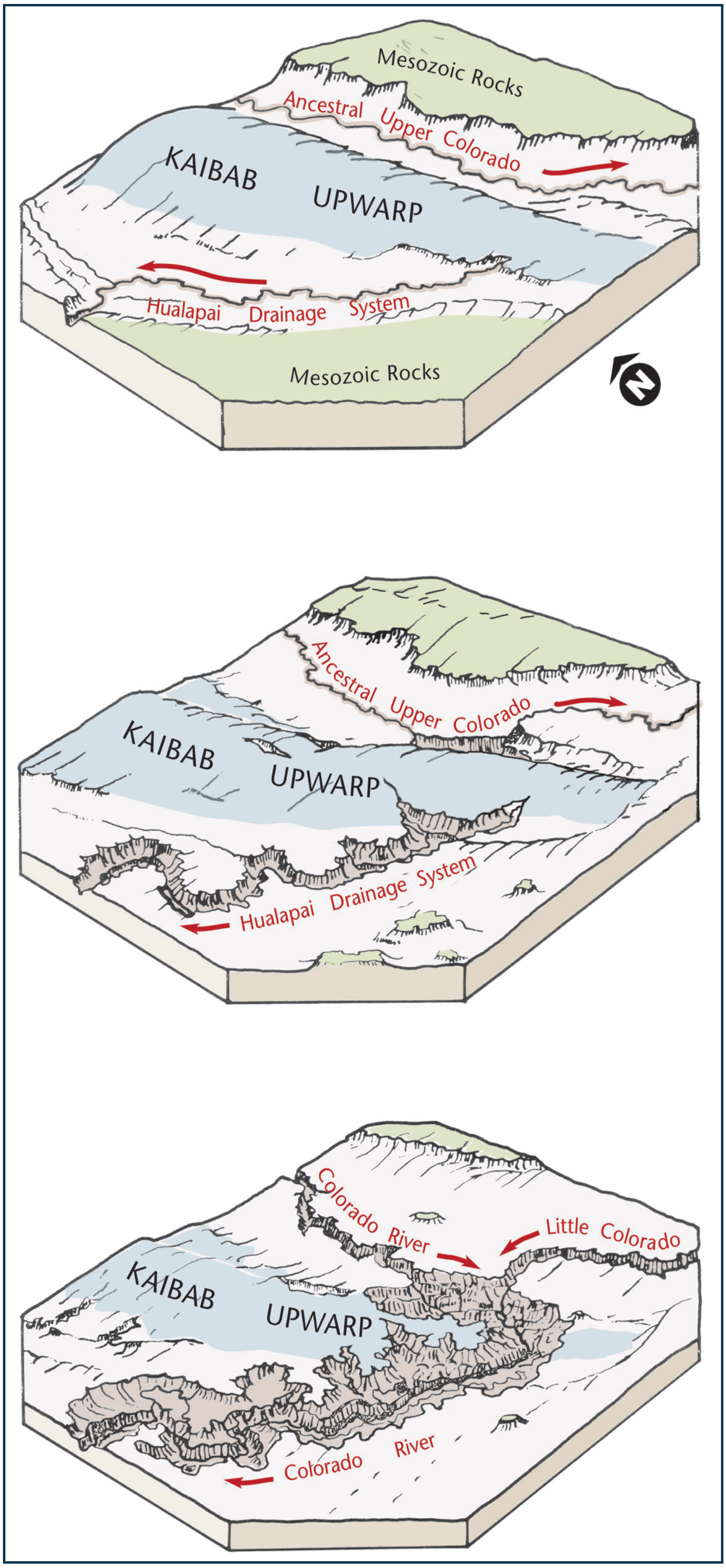

figure 4: Diagram of how headward erosion and stream piracy may have led to the development of the modern Colorado River. Top: the ancestral Upper Colorado River and the Hualapai drainage flowed away from the Kaibab upwarp. Middle: the Hualapai drainage lengthened its channel across the upwarp. Bottom: complete integration of the two systems. Some aspects of this model were later shown to be untenable, but the concept of a multi-phase history for the river still influences modern thinking. (Diagram modified from Museum of Northern Arizona Bulletin 44, 1967).

concepts addressed were: (1) support for and attacks upon headward erosion and stream piracy, (2) alternatives to basin-spillover for integrating the river, (3) evidence for reversal of drainage in all or parts of the Grand Canyon, and (4) support for recent deepening of the canyon.

The surge in interest was advanced again with a professional workshop held in May 2010 in Flagstaff, Arizona, with 59 geologists in attendance and numerous papers published in two volumes (Beard et al., 2011; and Karlstrom et al., 2012). A summary of the ideas presented are: (1) possible uplift mechanisms for the southwestern Colorado Plateau; (2) evidence for possible early ancestors of the Colorado River, including ideas for an "old" (Paleogene) Grand Canyon; (3) recognition of the lack of evidence for mid-Cenozoic drainage across the region; (4) possibility of integration of the river by groundwater and an underground karst connection; and (5) robust evidence for a young lower Colorado River.

1- Possible Uplift Mechanisms

The uplift history of the Grand Canyon region and Colorado Plateau has been viewed historically as having occurred in three pulses, early, middle and late Cenozoic, with the relative importance of each being debated. Much speculation involves the difficulty in dating an uplift event, as opposed to a deposit on the ground. New and leading-edge techniques, however, are providing geologists with new information and a possible uplift history of the plateau.

Support for plateau uplift in the last six million years comes from studies showing that hot, upwelling material from the Earth's mantle might be driving the surface uplift and volcanism at the southern edge of the Colorado Plateau in western Grand Canyon (Crow et al., 2011). These studies used computer tomography to provide images of the variable compositions and temperatures within the Earth's interior. They detected the presence of shallow, hot material beneath the western Grand Canyon and inferred a correlation with recent uplift. The researchers explained that the hot material might have become detached from the overlying more solid crust beneath western Grand Canyon, gradually "dripping" into layers below (in the Earth's mantle). When this happened, the hot material invaded the area beneath the more solid crust, heating it and driving the uplift of the plateau's edge, as well as supplying the Quaternary volcanism.

Recent movement along the Toroweap and Hurricane faults might be the surface expression of this buoyant rise of hot material beneath the western Grand Canyon. The more rigid overlying crust would have become elevated and stressed, and faults would have been activated. The authors proposed a possible connection between this and the observed high gradient of the Colorado River in the western Grand Canyon (relative to other portions of the river) – an actively uplifting terrain would produce an obstacle across the river's path and force it to slice more forcefully through it.

New evidence for multi-stage erosion intervals (and perhaps uplift events) during the early, middle, and late Cenozoic uses fission-track dating techniques in the phosphate mineral apatite (Beard et al., 2011). The study showed that deeply buried rocks on the Colorado Plateau cooled when uplift and erosion removed overlying material. It also reported that the area of the Mogollon Highlands in southwestern Arizona had 4 km (2.5 mi) of sedimentary rock removed during the Laramide uplift. In the eastern Grand Canyon, up to 1.6 km (one mile) of rock strata covered the Kaibab Limestone until mid-Cenozoic time. Finally, the central Colorado Plateau was exhumed within only the last 6 to 7 million years. Thermal cooling techniques have been a windfall in resolving the uplift history of the region and additional surprising results are expected from this area in the future.

2- Early Ancestors of the Colorado River, and an "Old" Grand Canyon

Geologists recognize that the Colorado River can be no older than about 80 Ma, because this is the age of nearby marine deposits. This date is not controversial and provides a maximum age for the Colorado River and Grand Canyon. A nascent drainage system developed after withdrawal of the sea and flowed toward the northeast. Aspects of this drainage system have been known about for decades. They show that a mountain range, similar in a tectonic sense to the modern Andes Mountains, existed to the southwest of the Grand Canyon. These mountains formed in a line that connects the modern-day cities of Las Vegas, Nevada; Needles, California; and Kingman, Prescott, Phoenix, and Tucson, Arizona.

Evidence obtained from tiny crystals of zircon (zirconium silicate) show that a large trunk river with dimensions comparable to the modern Colorado River flowed north from the Mojave Desert region in southern California to the Uintah basin in Utah (Davis et al., 2010). They named this 700-mile long river the *California River*, after the source area where it originated (likewise, the modern Colorado River received its name for the same reason). The researchers suggest that this river was located in some unspecified portion of the Grand Canyon region, but did not say whether the California River was involved in the carving of the Grand Canyon or the placement of the modern Colorado River – they merely showed that zircon grains found in deposits on the northern Colorado plateau were derived from a bedrock source in the Mojave Desert region of southern California.

Using two state-of-the-art laboratory techniques – apatite fission-track dating (AFT) and uranium-thorium/helium dating (U-Th)/He) – other researchers claimed that a large-scale river might have carved the Grand Canyon about 70 Ma (Flowers et al. 2008, and Wernicke, 2011). This approach revealed the unroofing history of rocks in the canyon, with the result that the western Grand Canyon was cut to within *a few hundred meters* of its present depth by about 70 Ma, and that the eastern Grand Canyon was the site of a canyon *of similar proportions* to the modern gorge cut into now-eroded Mesozoic rocks by 16 Ma **(figure 5)** Zircon crystals were obtained in eastern Grand Canyon from the Coconino Sandstone, the Esplanade Sandstone, and Vishnu Schist, showing that each was located *beneath equal thicknesses of rock* during the Laramide. Since these layers are exposed at different elevations within the modern canyon, the observed burial depths suggest that a canyon of roughly the same proportions as today's gorge may once have been present here. These are surprising results that fuel the controversy about the age of the Grand Canyon.

Three Laramide-age paleocanyons have been documented on the Hualapai Plateau on the southwestern edge of the Colorado Plateau. Drainage in these paleocanyons came from the Kingman arch, a Laramide-age high area that was likely positioned on the eastern edge of the Mogollon Highlands. These canyons contain deposits that are bracketed between 55 and 18 Ma, with the largest deposit being

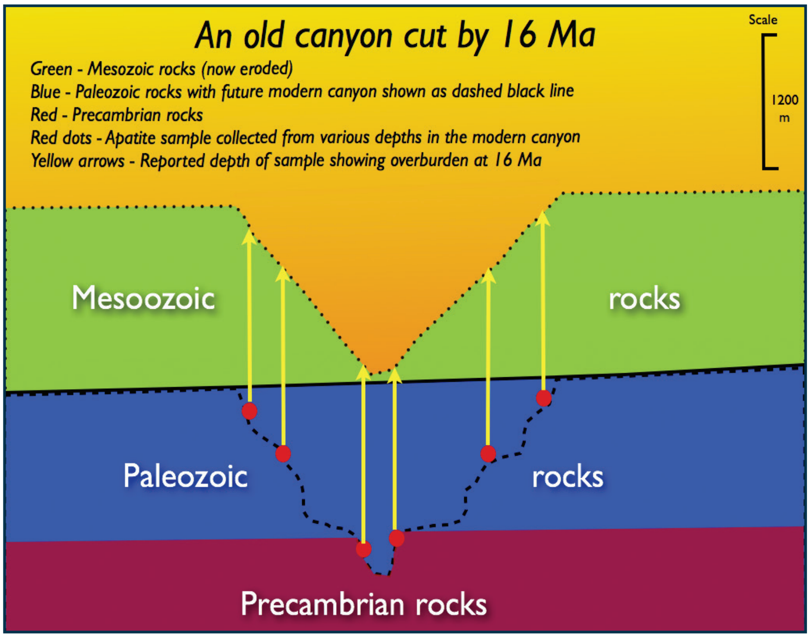

figure 5: *Sketch showing the proposal by Wernicke (2011) for how the modern Grand Canyon (eastern half) may have been the location of an ancestral canyon cut into Mesozoic rocks, but now eroded away (figure by W. Ranney).*

Grand Canyon National Park, Arizona. Photo by Wayne Ranney.
Zoroaster Temple, seen from the Inner Gorge of Grand Canyon. The foreground rocks are composed of the Precambrian Vishnu Schist and Zoroaster Granite, capped by a ledge of sedimentary Tapeats Sandstone (Cambrian). This contact is known as the Great Unconformity and represents a 1200 million year gap in the rock record. The “temple” itself is composed of Permian Coconino Sandstone with a 20m cap of the Toroweap Formation.

about 1200 m (4,000 ft) deep and 5 km (3 mi) wide (Beard et al., 2011). Whether these canyons acted as tributary channels to the Laramide-age Grand Canyon mentioned above is unknown, but a connection might be possible. The recognition of these paleocanyons gives geologists a fantastic view of the erosional and depositional history of the southern plateau area during the Laramide Orogeny.

Hill and Ranney (2008) have also proposed a proto-Grand Canyon that may have formed during the period of northeast drainage. This paleocanyon went north through Peach Springs Wash along the Hurricane fault zone; then jogged northeast along the present course of the Colorado River, but with flow in the opposite direction following a recognized fracture pattern in bedrock. The river likely continued north into the Claron basin in southern Utah, paralleling the present-day route of Kanab Creek. This setting is too far west to accommodate the California River of Davis et al., but is in general agreement with other paleocanyon hypotheses. All of these paleocanyon studies acknowledge that older drainages cut significant gorges in the Grand Canyon region as early as the Laramide. Whether these old canyons have a direct link with the modern canyons is unknown, because virtually no deposits remain that can unequivocally connect the older drainage system with the present one.

3- Paucity of Evidence for Mid-Cenozoic Drainage

Northeast-directed flow on the southern Colorado Plateau lasted for at least 50 million years from about 80 to 30 Ma. The rock record is sparse for the next 10 to 18 million years. In the Grand Canyon there is no rock record from about 24 to 6 Ma. This gap may result from the collapse and/or erosion of the Mogollon Highlands during mid-Cenozoic mountain uplift, or it may reflect the gradual change in climate from humid conditions in the early Cenozoic to arid conditions by the mid-Cenozoic. Rivers in northern Arizona either lost their highland source area in the south through faulting, or suffered diminished precipitation in a global climate shift, or both.

One deposit from outside the Grand Canyon suggests that aridity may be the cause of diminished rivers at that time. The Chuska Sandstone, located in the Chuska Mountains of northeast Arizona, is more than 500 m (1,700 ft) thick but may have been thicker before volcanic rocks covered them about 25 Ma, aiding their fortuitous preservation. The Chuska Sandstone was deposited between 33 and 25 Ma in eolian settings (Cather, 2008). Estimates propose that the Chuska sand sea may have extended across 140,000 km^2 (54,000 mi^2) including the southern half of the modern Colorado Plateau, although it is unlikely to have reached as far west as the Grand Canyon. Sand may have been brought initially onto the plateau surface by northeast-directed rivers from the Mogollon Highlands, but this drainage was blocked by volcanic eruptions in the southern Rocky Mountains between 38 and 28 Ma. The volcanic highlands likely caused the sand to accumulate west of the volcanoes (a smaller version of this setting is found today at Great Sand Dunes National Park near Alamosa, Colorado). The age of the Chuska Sandstone is significant from a global climate time perspective – this is when Antarctic glaciation began, signaling a global change to much cooler and dryer conditions on Earth. Significant evidence for aridity is also preserved on the Great Plains at this time. The onset of aridity likely caused older deposits to become reworked into wind-blown sand that became trapped against the rising volcanoes to the east. The end of Chuska deposition at 25 Ma correlates with other worldwide evidence for more humid conditions.

4- Karst Connection Model

A different process to integrate the Colorado River involves the presence of karst, which can collapse to create or enlarge surface drainage. Current karst connection models have been proposed by Hill et.al. (2008) and suggest that a subsurface karst aquifer system was channeled beneath the Kaibab upwarp and discharged into a west-flowing ancestor of the downstream part of the river. After this subsurface connection was made through the upwarp, karst collapse and fluvial incision created the modern Colorado River and the eastern Grand Canyon after 6 Ma. This hypothesis proposes that the Little Colorado River and Marble Canyon previously drained north into a proposed basin in southeast Utah. A series of sinkholes then developed into Redwall Limestone caves near the present confluence of the Colorado and Little Colorado rivers **(figure 6)**. These sinkholes captured surface water and directed it beneath the Kaibab upwarp, discharging into the west–directed drainage. Collapse of the karst system integrated these two drainages to form the modern river. The karst connection model is a "subterranean to surface" process – an alternative to headward erosion (a

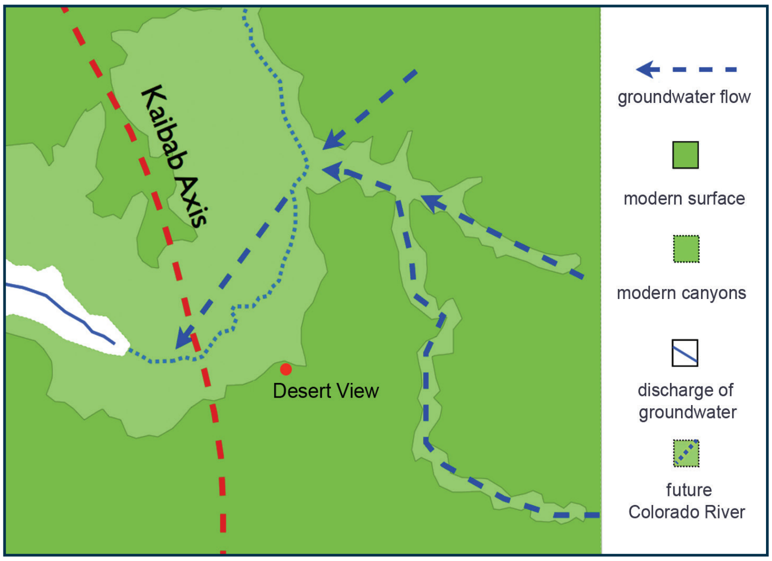

***figure 6:** The karst model for the integration of the Colorado River and the formation of the Grand Canyon involves subterranean flow of water beneath the Kaibab upwarp (labeled Kaibab Axis). Underground karst drainage developed within the Redwall Limestone beneath eastern Grand Canyon and then collapsed to form the surface drainage for the river (figure by W. Ranney).*

"bottom-up" process) and basin spillover (a "top-down" process).

In another study, Polyak et al. (2008), working in western Grand Canyon, obtained uranium-lead dates on distinctive cave deposits called mammillaries, which form at and just below the water table. These deposits revealed that the regional water table was progressively lowered between 17 and 6 Ma. They interpreted the lowering of the water table to be the result of incision in western Grand Canyon by headward erosion. Other geologists challenged their interpretation and suggested instead that the lowering of the water table was better explained by the advent of the Basin and Range structures to the west. Polyak et al. agreed with them and added that the formation of the Basin and Range lowered base level and was the mechanism driving canyon incision.

5- Basin Spillover on the Lower Colorado River

In spite of ideas for old ancestors of the Colorado River, other geologists provide evidence for a relatively young river. Studying deposits along the lower river near Laughlin, Nevada and Bullhead City, Arizona, House et al. (2007) show that closed, disconnected basins became sequentially filled with water, overtopped their bedrock divides, and created a course for the river **(figure 7)**. The results show that this "fill and spill" episode spanned the period between 5.6 and 4.1 Ma. The study showed that four distinct basins contain a similar sequence of deposits that grade from bottom to top: (1) material derived only from the enclosing mountains; (2) coarse debris derived from bedrock exposures upstream of the basin edge; (3) fine-grained lake deposits; and (4) unmistakable deposits of the Colorado River. Their interpretation is that water rapidly arrived (geologically speaking) in the Las Vegas basin and eventually overtopped a bedrock divide in Black Canyon. The spillover from Las Vegas basin created the river through Black Canyon (Hoover Dam area) and filled the Cottonwood Valley to the south. Eventually the Cottonwood basin overtopped a bedrock divide in the Pyramid Hills (Davis Dam area) and spilled water into the Mojave Valley. When the Mojave Valley filled, it overtopped another bedrock divide near Topock Gorge and filled the Chemehuevi Valley downstream (Lake Havasu City and Blythe area). The lake deposits in this sequence are called the Bouse Formation.

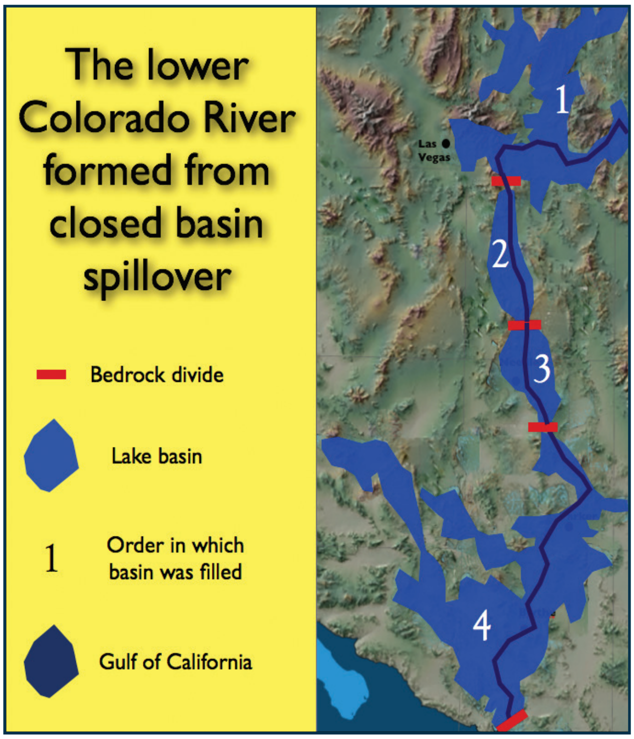

figure 7: Work along the lower Colorado River from near Hoover Dam to Yuma, Arizona, has revealed four paleo-basins that were likely connected from the spillover of the lakes. Each basin contains a similar set of deposits bracketed between 5.6 and 4.1 Ma (figure by W. Ranney).

Overlying the Bouse remnants are unmistakable Colorado River sand and gravel deposits that culminated in the southernmost basin about 4.1 Ma. The workers wondered what might have brought the rapid arrival of river water to the Las Vegas basin, and turned their gaze upstream toward the Grand Canyon and beyond. Did basin spillover provide this rapid arrival of river water? Or was it perhaps stream capture related to headward erosion, or karst collapse? The results from the lower Colorado River only intensify the questions about how the upper Colorado River became integrated. But the origin of the lower Colorado River now seems rather certain.

Support for the age of the Colorado River east of Grand Canyon is so far inconclusive. Geologists have long proposed that the Bidahochi Formation (exposed near Holbrook, Arizona) may document the existence of a large freshwater lake (known as Lake Bidahochi or Hopi Lake), that might have "filled and spilled" about 6 Ma, establishing a course for the Colorado River through Grand Canyon (Douglass et al., 2009). However, the existence of a large Lake Bidahochi has been challenged and appears tenuous at this time (Dickinson, 2013).

Conclusions

The picture that is emerging for Grand Canyon is that one of three processes (or a combination of processes) helped to integrate the Colorado River and create the great gorge. The processes are headward erosion and stream piracy, closed-basin spillover, and karst collapse. Most geologists agree that the canyon we see today is the result of deep incision only within the last 5 to 6 million years. However, parts of this "modern" landscape may have overprinted, concealed or incorporated some sections of older canyons. A broad outline of the major events is now possible: (1) Laramide uplift caused the withdrawal of the Cretaceous Interior Seaway; (2) an initial river system with drainage to the northeast was formed, with possible early segments of Grand Canyon being carved; (3) drainage in the region became disrupted in the mid-Cenozoic, resulting in few deposits; (4) opening of the Gulf of California lowered base level south and west of the Grand Canyon; (5) integration of the Colorado River began, with basin spillover, to create the lower river, and some as-yet unknown process took place to integrate the whole system from the Rockies to the sea.

The Grand Canyon continues to inspire geologists and the public as one of the most impressive outdoor laboratories for the study of Earth history. In the almost 160 years that it has been studied scientifically, much has been learned about river processes acting on an uplifted, arid landscape, and the canyon will continue to reveal more of its secrets.

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