CHAPTER 3: THE TECTONIC EVOLUTION OF THE COLORADO PLATEAU AND GRAND CANYON REGION

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INTRODUCTION

Do not allow the epic, flat-lying rocks of the Grand Canyon to deceive you. Following the period of marine deposition that formed the classic Grand Canyon Paleozoic strata (see Kercher, this volume), the Grand Canyon, embedded into the Colorado Plateau, has undergone a dynamic and evolving tectonic history. During the past ~70 million years, compressional, extensional, and transtensional geologic forces related to far-field tectonic plate interactions have deformed the regions surrounding the Colorado Plateau. However, this large, stable plateau of continental crust has remained relatively undeformed, and lacks significant internal faulting, folding, and tilting that characterizes the surrounding regions. This chapter discusses the evolution of the Grand Canyon in the context of plate tectonic theory and how the tectonic history of southwestern North America has uplifted Paleozoic sedimentary rocks once deposited near sea level to Colorado Plateau elevations of >2 kilometers. This tectonic evolution has controlled the flow direction of major rivers, led to the incision of the Canyon, and eventually connected the Colorado River to the Gulf of California (Fig. 3.1).

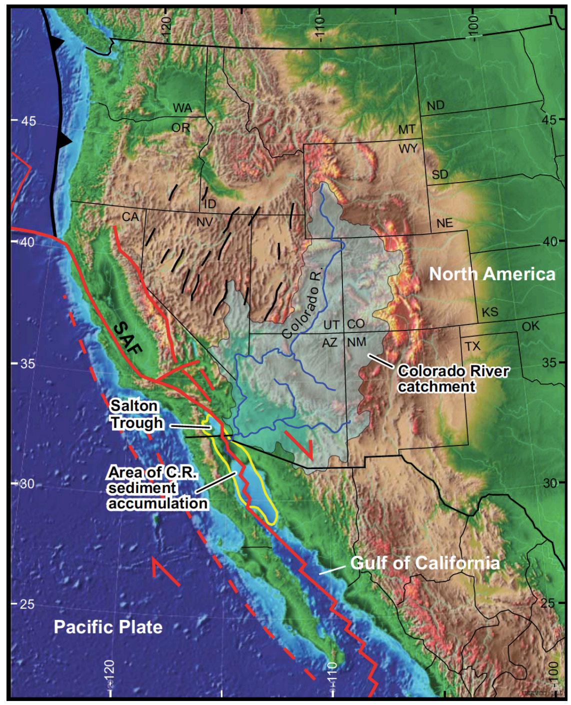

Figure 3.1 Topographic-tectonic map of SW North America highlighting the upstream catchment of the Colorado River and downstream sediment accumulation area. From Dorsey, (2010)

UPLIFT OF THE COLORADO PLATEAU

At the beginning of the Mesozoic Era (250-65 Ma), Pangea began to break up, separating eastern North America from northwestern Africa. As part of this global plate reorganization, subduction later initiated along the western margin of North America. The oceanic crust of the Farallon plate began to subduct beneath the continental crust of the North American plate. Early subduction-related deformation due to this convergence was concentrated along the western edge of the continent. Around 70 Ma, the angle of the downgoing Farallon plate is thought to have significantly shallowed (Fig. 3.2), causing the deformation related to plate convergence to migrate eastward (Coney and Reynolds, 1977). Widespread uplift and deformation occurred across the interior western North American continent (Fig. 3.3A). Uplifted regions and belts of thrust faulting and folding related to this 'Laramide' phase of compressional deformation are found today in southern Canada, from

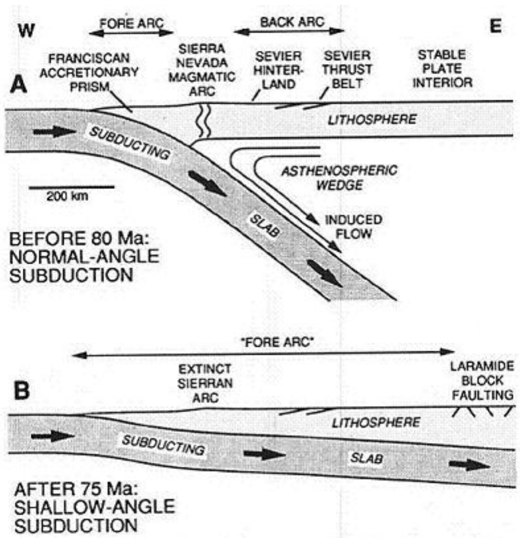

Figure 3.2 (A) Typical Mesozoic subduction angle. (B) Shallow, or 'flat-slab' Laramide-age subduction. (Dimutru et al., 1991)

Montana to Arizona, and throughout Mexico. The Colorado Plateau is a large (~500,000 km^2) block of continental crust that eluded much of this deformation, and was uplifted as a relatively undeformed block.

The precise timing and magnitude of Plateau uplift is central to many debates about the evolution of the Plateau and to the incision of the Grand Canyon. Many models of Colorado Plateau uplift describe the tectonic removal of thick portions of the mantle lithosphere, resulting in the isostatic uplift of the Plateau region (e.g. Spencer, 1996). Some researchers argue that the majority of this 2-3 km of vertical uplift is Laramide-age and related to the shallow subduction angle (Spencer, 1996). Similar (U-Th)/He thermochronologic ages from both the top and bottom of the Canyon suggests that the Grand Canyon was incised as early as 80-70 Ma (Flowers et al., 2008), broadly coincident with Laramide uplift. However, Late Miocene and Pliocene U/Pb ages on speleothems in perched groundwater caves suggest that the majority of the Canyon incision occurred in the past 6 Myr (Karlstrom et al., 2008). The following chapter (Longinotti, this volume) provides a more comprehensive discussion of the timing of Grand Canyon incision and the evolution of various paleo-river systems that possibly flowed in the proto-Grand Canyon. Regardless, it is important to appreciate that sedimentary rocks exposed in the Grand Canyon were deposited within tens to hundreds of meters either below or above sea level and are now found at elevations 2-3 km above sea level.

Laramide Deformation in the Grand Canyon

The Paleozoic and Precambrian rocks of the Grand Canyon were not entirely immune to Laramide deformation. Structures related to Laramide-age compression are visible throughout the Grand Canyon. Pre-existing normal faults that tilted Precambrian rocks (see Garber, this

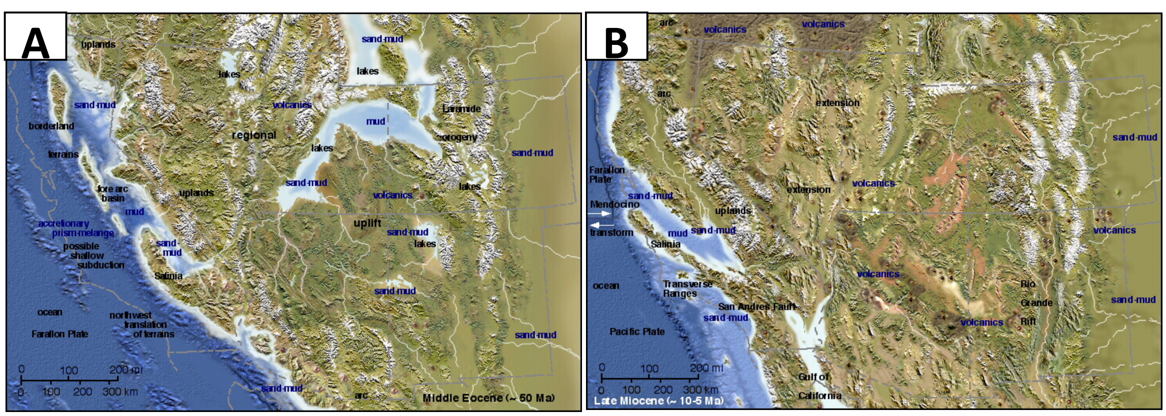

Figure 3.3 Paleo-physiographic maps of southwestern North America. (A) At ca. 50 Ma, the Farallon plate is depicted subducting beneath North America, forming highlands in southeastern California. This Laramide-age compression uplifted the Colorado Plateau and Grand Canyon region. (B) At ca. 10-5 Ma, Basin and Range extension and oblique-rifting across much of western North America has drastically altered regional topography. By 5.3 Ma, the modern-day Colorado River is established, draining the highlands of the Rocky Mountains into marine waters of the Gulf of California. Maps from Blakely, 2012)

volume) were commonly reactivated as reverse faults. These reverse faults accommodated moderate amounts of shortening, with typical offsets limited to a few hundred meters or less. These brittle faults also coincide with many of the monoclinal folds in the Colorado Plateau. One such example of a reverse fault-monocline pair is the East Kaibab monocline that flanks the eastern edge of the Kaibab Plateau (River Mile 52-82), and formed above the Butte reverse fault (River Mile 68.5). Later chapters in this book go into further detail about how the locations and orientations of these faults control tributary formation (see Elliott, this volume), and funnel debris flows that coincide with large river rapids (see Selander, this volume).

BASIN AND RANGE EXTENSION

Following the late Mesozoic and early Cenozoic Laramide deformation, many regions of extension initiated adjacent to the Colorado Plateau and Grand Canyon region (Fig. 3.3B). By ca. 40 Ma, the angle of the subducting Farallon slab began to steepen again, and compressional deformation migrated back to the western edge of the continent (Coney and Reynolds, 1977). By ~30 Ma, in the wake of the steepening slab, extensional regions were established west, south, and east of the Plateau (Fig. 3.4). A narrow belt of extension formed the Rio Grande Rift, east and southeast of the Plateau, where modest extension (10-50%) initiated at ~32 Ma and is still active today (Aldrich et al., 1986). West and southwest of the Plateau, Basin and Range extension has formed multiple topographic ranges and valleys in response to normal faulting and block tilting (Fig. 3.4). The Basin and Range province has been extended by over 100% (e.g. Surpless et al., 2002) across a province now hundreds of kilometers wide (Fig. 3.1).

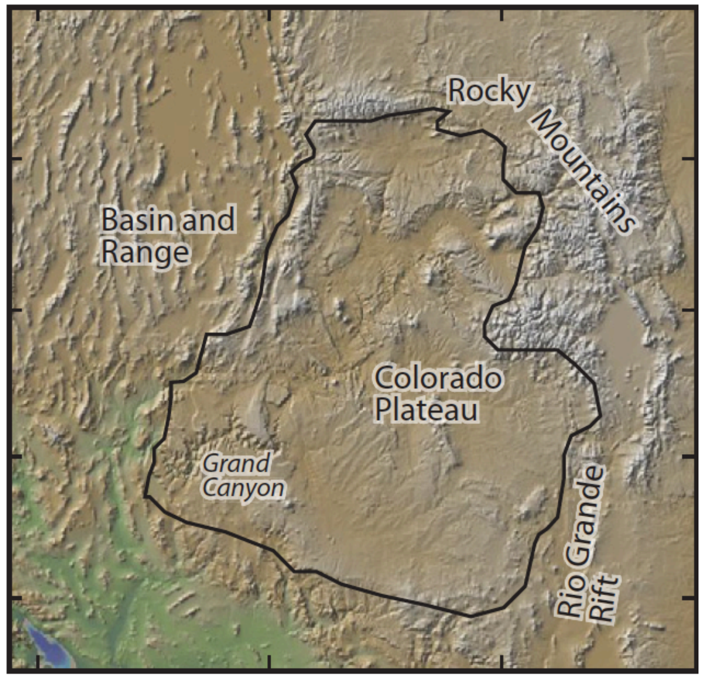

Figure 3.4 Physiographic map depicting the Colorado Plateau, the Grand Canyon, and the surrounding regions of Laramide-age compression (Rocky Mtns.) and ongoing crustal stretching (Basin and Range, Rio Grande Rift). From Flowers (2010).

The eastern limit of significant Basin and Range extension coincides with the western edge of the Colorado Plateau and the western end of the deeply incised Grand Canyon (see Elliott, this volume). This abrupt tectonic transition from flat-lying, relatively undeformed strata of the Colorado Plateau to the highly-extended and variably titled rocks of the Basin and Range province coincides with the Grand Wash fault zone. Normal faulting on the Grand Wash fault zone is marked by the impressive Grand Wash Cliffs topographic escarpment (River Mile 278). Vertical structural relief across this fault zone exceeds 5 km (Faulds et al., 2008). The Colorado River exits the Canyon at this escarpment, where it enters the topographically less impressive Colorado River extensional corridor, a subdivision of the Basin and Range Province, and immediately enters the upstream extent of the Lake Mead reservoir. Within the Canyon, the

Colorado River has not yet established an equilibrium stream profile, and river gradients are steeper than those in the upstream (high Plateau) and downstream (Basin and Range) regions.

Basin and Range Faulting in the Grand Canyon

Although the majority of Basin and Range normal faulting has occurred west of the Grand Wash cliffs, where the Grand Canyon ends, minor normal faults are present within the Grand Canyon. These N- to NW-striking faults are located near the western margin of the Colorado Plateau (Fig. 5.1) and all show down-to-the-west vertical offsets of tens to a few hundred meters (Table 3.1). Elliott (this volume) discusses Quaternary and historic seismic activity on many of these faults.

Table 3.1 Significant normal faults exposed in the Grand Canyon.

Fault	Approx. Vertical Offset (m)	Location (miles from Lees Ferry)
Eminence fault	30	49-50
Bright Angel fault	145	88.5
Toroweap fault	180	179.5
Hurricane fault	400	191 and 221-224
Grand Wash fault	>5,000	278
Wheeler fault*	unknown	284.5

*** downriver of Grand Wash cliffs, at upper end of Lake Mead reservoir**

Cenozoic Watershed Evolution

Because plate tectonic forces place strong controls on the topography and absolute elevation of Earth's surface, these forces also exhibit controls on the shape and extent of watersheds and the direction of flowing rivers. Prior to and during Laramide compressional deformation, highlands were being constructed west of the Grand Canyon region, inboard of the Farallon-North American subduction zone. A paleoriver, coined the California River, likely flowed northeastward from these topographic highlands near present-day southeastern California towards large intracontinental lakes within a large internally drained region of Utah and Colorado (Fig. 3.3A; Davis et al., 2010; Wernicke, 2011). During subsequent Basin and Range extension, these California River highlands were gradually destroyed (Fig. 3.3B). High magnitude extension and crustal thinning due to normal faulting west of the Grand Wash cliffs led to the tectonic collapse of this region. As a result, watersheds and paths of large paleorivers traversing the southwestern United States were drastically altered, possibly more than once (see Longinotti, this volume).

REGIONAL VOLCANISM

Regional volcanism occurred sporadically across the Colorado Plateau over the past 30 Myr, with much of the recent volcanism focused near the Plateau margin (Fig. 3.3B). Remnants of volcanic centers are evident today, protruding up through the Plateau strata. Well-known volcanic centers include Shiprock in northwestern New Mexico (27 Ma), the La Sal Mountains in southeastern Utah (25-28 Ma), and San Francisco Peaks just north of Flagstaff, Arizona (0-6 Ma).

Volcanism in the Grand Canyon

Local volcanic activity related to the Uinkaret volcanic field has produced scores of lava flows over the past 3 million years. Many of these flows have cascaded into the Grand Canyon and formed lava dams, temporarily blocking Colorado River sediment and water from continuing to the Gulf of California for tens to thousands of years. These transient, natural dams are strikingly similar to the anthropogenic affects of the large concrete dams and human water consumption that plagues management of the modern Colorado River. Details of the location, size, and destruction of these past lava dams are discussed in further detail in Chapter 7 (see Clark, this volume).

THE MODERN COLORADO RIVER

The present-day Colorado River drains a large subcontinental-scale drainage system with headwaters in western Wyoming, Colorado, and New Mexico (Fig. 3.1). The River system continues across the Colorado Plateau, through the Grand Canyon, and meanders along the California-Arizona and Baja California Norte-Sonora borders before meeting the marine waters of the northern Gulf of California. This continuous modern drainage system, from the continental divide of the Rocky Mountains to sea level, has existed only since early Pliocene time (Dorsey et al., 2007). Marine sedimentary basins of the Salton Trough and northern Gulf of California showed no evidence of the diagnostic, red, quartzose Colorado River sand until ~5.3 Ma. Prior to this period, these basins received only locally-derived sediment.

Transtensional Pacific-North America Plate Boundary

Beginning ca. 30 Ma, while extension was initiating in the Basin and Range Province, complicated plate boundary reorganization was occurring offshore southern California. The East Pacific Rise, the mid-ocean ridge between the Farallon and Pacific oceanic plates, was approaching the subduction zone. Subsequent subduction of a protrusion of the East Pacific Rise spreading center resulted in the contact of and incipient right-lateral relative motion between the Pacific and North American plates (Atwater and Stock, 1998). This early right-lateral relative plate motion was accommodated along NW-striking strike-slip faults and via large magnitude clockwise block rotations in the California borderlands. As subduction continued, a progressively larger portion of the Pacific plate came in contact with the North American plate. The Mendocino and Rivera triple junctions migrated to the north and south, respectively, effectively lengthening the Pacific-North American plate boundary. Not until ~7-8 Ma (Fig. 3.3B), did the Pacific-North American plate boundary eventually organize itself into the Salton Trough and northern Gulf of California (Bennett et al., in review; Dorsey et al., 2007).

Since Late Miocene time, the Salton Trough-Gulf of California has been a transtensional releasing bend along the Pacific-North America plate boundary, immediately south of the restraining bend of the San Andreas fault system of southern California (Fig. 3.1). This releasing bend geometry, or oblique rift, forms a series of right-stepping, en-echelon, dextral strike-slip faults (Lonsdale, 1989). Extensional pull-apart basins connect these strike-slip faults, such as the Miocene-Pliocene deposits at Split Mountain Gorge (Dorsey et al., 2007), the Pliocene-Pleistocene Fish Creek-Vallecitos basin (Winker, 1987), and the modern non-marine and marine pull-apart basins of the Salton Tough and northern Gulf of California, respectively (Dorsey, 2010). These rhombochasm-shaped basins are the locations of extreme crustal thinning and significant basin sedimentation. Crustal thinning in these basins initiated ca. ~8 Ma, receiving only locally-derived sediments. By ca. 6.5 -6.3 Ma, many of these basins had been flooded by a synchronous marine incursion (Oskin and Stock, 2003; Bennett and Oskin, in prep; Dorsey et al., 2007). Thus, extreme crustal thinning in transtensional basins along the Pacific-North American plate boundary set the stage for the Colorado River to reach the ultimate base level, sea level.

This final connection of the Colorado River from the Grand Canyon to the Gulf of California (Fig. 3.3B) could have occurred by either headward erosion and capture of Colorado Plateau rivers (Lucchitta et al., 2001) or by multiple down-river lake spillover events (Meek and Douglas, 2001).

Sediment Flux Through the Grand Canyon

Since ca. 5.3 Ma, large volumes of sediment have eroded off the Colorado Plateau, been funneled through the Grand Canyon, and deposited in the Salton Trough-Gulf of California. Dorsey (2010) estimates that 2.2 - 3.4 x 10^5 km^3 of Colorado River sediments are stored in these subsurface basins. Maybe unsurprisingly, this value is strikingly similar to the 2.5 - 3.1 x 10^5 km^3 volume of eroded rock from the Colorado Plateau during this same period, estimated from projecting pre-dam sediment discharge (Meade and Parker, 1985) back to 5.3 Ma. This phenomenon illustrates how the Grand Canyon has played an important role in funneling continental detritus to an active plate boundary where it is recycled into new, hybrid continental crust (Dorsey, 2010).

RIVER MANAGEMENT IN THE CONTEXT OF REGIONAL PLATE TECTONICS

The tectonic history of the stable Colorado Plateau-Grand Canyon region illustrates how major river systems, such as the Colorado River, respond to evolving tectonic regimes. The Grand Canyon and Colorado River have been intimately controlled by protracted histories of compression, extension, and transtension along the western edge of the North American tectonic plate. Watersheds and river paths have been transient features, lasting for tens of millions of years, followed by abrupt tectonic reorganization and modification. This puts the longevity of the modern-day Colorado River watershed into perspective. One can compare the effects of the last century of river management practices to the prolonged geologic events required to alter the Colorado River at a similar scale. Future river management plans can incorporate future geologic projections of the current Colorado River system, including lack of sediment and fresh water input to the Gulf of California and rising base level (sea level) due to climate change.

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