Model for tectonically driven incision of the younger than 6 Ma Grand Canyon

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ABSTRACT

Accurate models for the incision of the Grand Canyon must include characterization of tectonic influences on incision dynamics such as active faulting and mantle to surface fluid interconnections. These young tectonic features support other geologic data that indicate that the Grand Canyon has been carved in the past 6 Ma. New U-Pb dates on speleothems are reinterpreted here in terms of improved geologic constraints and understanding of the modern aquifer. The combined data suggest that Grand Canyon incision rates have been relatively steady since 3–4 Ma. Differences in rates in the eastern (175–250 m/Ma) and western (50–80 m/Ma) Grand Canyon are explained by Neogene fault block uplift across the Toroweap-Hurricane system. Mantle tomography shows an abrupt step in mantle velocities near the Colorado Plateau edge, and geodynamic modeling suggests that upwelling asthenosphere is driving uplift of the Colorado Plateau margin relative to the Basin and Range. Our model for dynamic surface uplift in the past 6 Ma contrasts with the notion of passive incision of the Grand Canyon due solely to river integration and geomorphic response to base-level fall.

INTRODUCTION

After over a century of controversy there is a growing consensus that the Grand Canyon has formed in the past 6 Ma (Young and Spamer, 2001). In this consensus, the term Grand Canyon is used for the canyon system carved by a west-flowing Colorado River, not for local precursor canyons (Young, 2008), or for northeast-flowing Tertiary drainages that may have existed in the now-eroded Mesozoic strata (Flowers et al., 2008). This paper formulates an incision model that integrates tectonic influences and driving forces such as Neogene faulting (Pederson et al., 2002; Karlstrom et al., 2007), mantle to surface fluid interconnections (Crossey et al., 2006), and mantle-driven dynamic uplift of the western edge of the Colorado Plateau (Ni et al., 2007).

Evidence for inception of carving of the Grand Canyon after 6 Ma is strong. (1) The sedimentary record shows that there are no Colorado River sediments in the 13–6 Ma Muddy Creek Formation that now blankets the Grand Wash trough at the mouth of the Grand Canyon (Lucchitta, 1972; Faulds et al., 2001). (2) The first sediments containing distinctive sand composition and detrital zircons that can be traced to Rocky Mountain sources reached the newly opened Gulf of California at 5.3 Ma (Dorsey et al., 2007; Kimbrough et al., 2007). (3) Gravels on top of the 6 Ma Hualapai Limestone and beneath the 4.4 Ma Sandy Point basalt show that the river became established in its present course between 6 and 4.4 Ma (Howard and Bohannan, 2001).

A recent challenge to the 6 Ma "young canyon" model is based on U-Pb dates from speleothems, one of which is interpreted to indicate that the Grand Canyon is older than 17 Ma (Polyak et al., 2008). First, we demonstrate that available geologic and geochronologic data overwhelmingly support the young canyon model. Second, we propose an incision model involving steady incision from 3–4 Ma to the Quaternary that incorporates neotectonic influences and explains U-Pb dates on speleothems (Polyak et al., 2008).

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WATER-TABLE CONSTRAINTS—GRAND CANYON AS AN INCISED AQUIFER SYSTEM

The key assumption for interpreting U-Pb dates on speleothems is that "groundwater table decline rates are equivalent to incision rates" (Polyak et al., 2008, p. 1377). We test this assumption by analysis of the modern aquifer system. Recharge from the San Francisco Peaks flows north and discharges in the Grand Canyon, mainly in Blue and Havasu springs (Crossey et al., 2006). These springs are locations where the gently north sloping water table is breached by tributaries of the Colorado River (Fig. 1). Other springs are widely distributed (Fig. 2; Table DR1 in the GSA Data Repository[1]) and are associated with various perched aquifer units. Instead of defining a single water table, the distribution of springs indicates that the walls of the Grand Canyon are a seepage face (Rulon et al., 1985) and that groundwater is hydrologically and geochemically distinct from the river. Only in one section of the eastern Grand Canyon (Fence Spring and Vasey's Paradise) is the river currently incising through the confined Redwall-Muav aquifer and intersecting the water table. Elsewhere, the position of the Redwall-Muav equipotential surface is controlled stratigraphically by the lower confining layer (Fig. 2; Bright Angel Shale) and by the relationships between aquifer recharge and discharge. Therefore, the assumption that "groundwater table decline rates are equivalent to incision rates" (Polyak et al., 2008, p. 1377) is falsified by the modern hydrologic system. Nevertheless, speleothem dates could have incision rate significance for locations (1) where the water table is not perched, and (2) for caves within the main river corridor (not up a sidestream). Unless both 1 and 2 can be demonstrated, ages from cave mammilary coatings should be considered to give maximum incision rates.

[1]GSA Data Repository item 2008218, Table DR1 (Colorado Plateau hydrochemistry), Table DR2 (incision rate constraints), and an incision animation, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TECTONIC INFLUENCES ON KARST WATERS, TRAVERTINES, AND SPELEOTHEMS

Mammilary calcite in caves was interpreted by Polyak et al. (2008) to be related to changes in water level during the time of transition from below to above the water table. However, this is not a unique interpretation and other processes need to be considered. Modern aquifer waters are supersaturated with CO_2 and contain $^3He/^4He$ ratios indicating direct inputs from mantle fluids (Crossey et al., 2006). Similar to travertine deposits at springs and sidestreams (e.g., Blue and Havasu springs), mammilaries form when high pCO_2 groundwaters encounter lower pCO_2, degas CO_2, and precipitate calcite. In addition to water-table lowering, processes that can change groundwater flow path, water-table elevation, and/or hydrogeochemistry and hence cause calcite growth in the roof of caves include cave breaching by cliff retreat, enhanced turbulent flow, mixing with low pCO_2 surface water or air, and/or influx of CO_2 during seismic events and/or climatic changes. Thus, given the complex geologic evolution of the region, interpreting the significance of dates on mammilary calcite growths requires a better geologic context than is currently available.

INCISION RATE DATA

A careful evaluation of all available incision rate data and their geologic context (Fig. 2; Table DR2) provides support for a younger than

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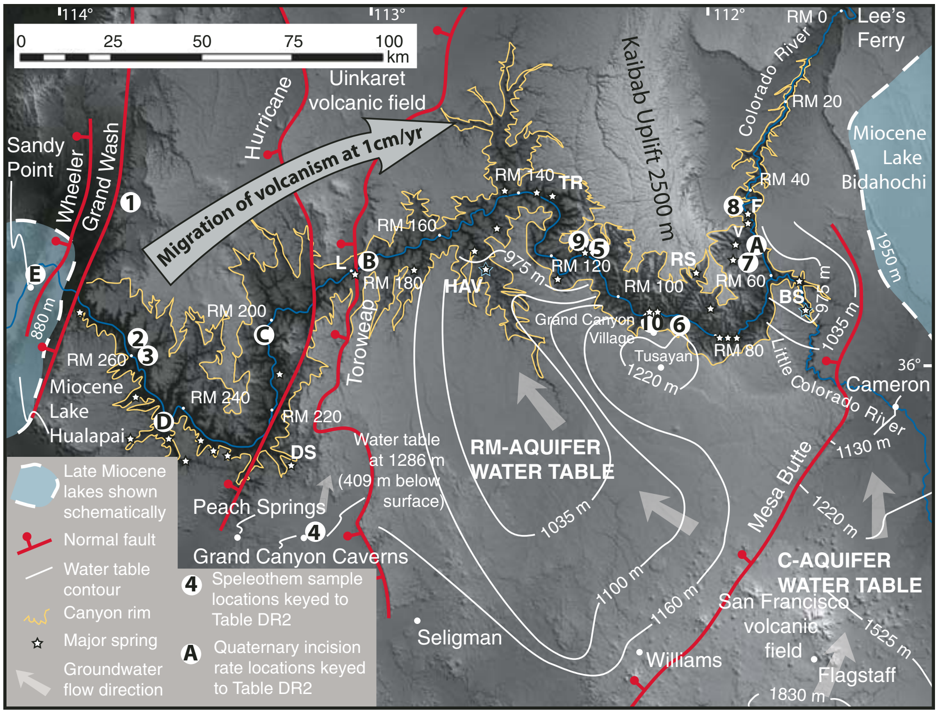

Figure 1. Map showing modern hydrologic system in Grand Canyon region, including water-table contours, major springs, major faults, and incision points discussed in text. RM—River Mile downstream from Lees Ferry. Labeled springs: BS—Blue, DS—Diamond, F—Fence, HAV—Havasu, L—Lava Warm Springs, RS—Roaring, TR—Thunder River, V—Vasey's Paradise. RM-AQUIFER is Redwall-Muav aquifer; C-aquifer is Coconino aquifer; circled letters and numbers refer to incision rate points listed in Table DR2 (see footnote 1).

6 Ma Grand Canyon. This treatment argues that the 17 Ma date on calcite from Grand Canyon caverns is not evidence for a 17 Ma Grand Canyon (Polyak et al., 2008). This cave is in the Redwall Limestone, 30 km south of the river (Fig. 1) in an area where the present water table is at an elevation of 410 m below the surface (Arizona Department of Water Resources, 2007) and hence only 150–250 m below the dated sample, and about 1 km above the modern river. The 17 Ma calcite may date a time of water-table drop, but there is nothing that relates such an event to Grand Canyon incision. Furthermore, 150–250 m of water-table lowering in 17 Ma would give an average rate of 10–15 m/Ma (not the 68 m/Ma reported). The 17 Ma age is interpreted here as due to initiation of large-magnitude Basin and Range extension in this region and associated changes in cave hydrology or hydrogeochemistry. Similarly, the next oldest U-Pb age (7.1 Ma; Site 1 of Polyak et al., 2008) is at great distance north of the Grand Canyon (38.6 km) and cannot confidently be related to canyon incision (Pearthree et al., 2008).

The remaining U-Pb dates are from caves within the Grand Canyon and are all younger than 4 Ma, consistent with models for a younger than 6 Ma Grand Canyon. The best measure of the internal consistency of the combined data is to plot height versus age for all proposed incision points (Fig. 3). Two caves (points 2 and 3)

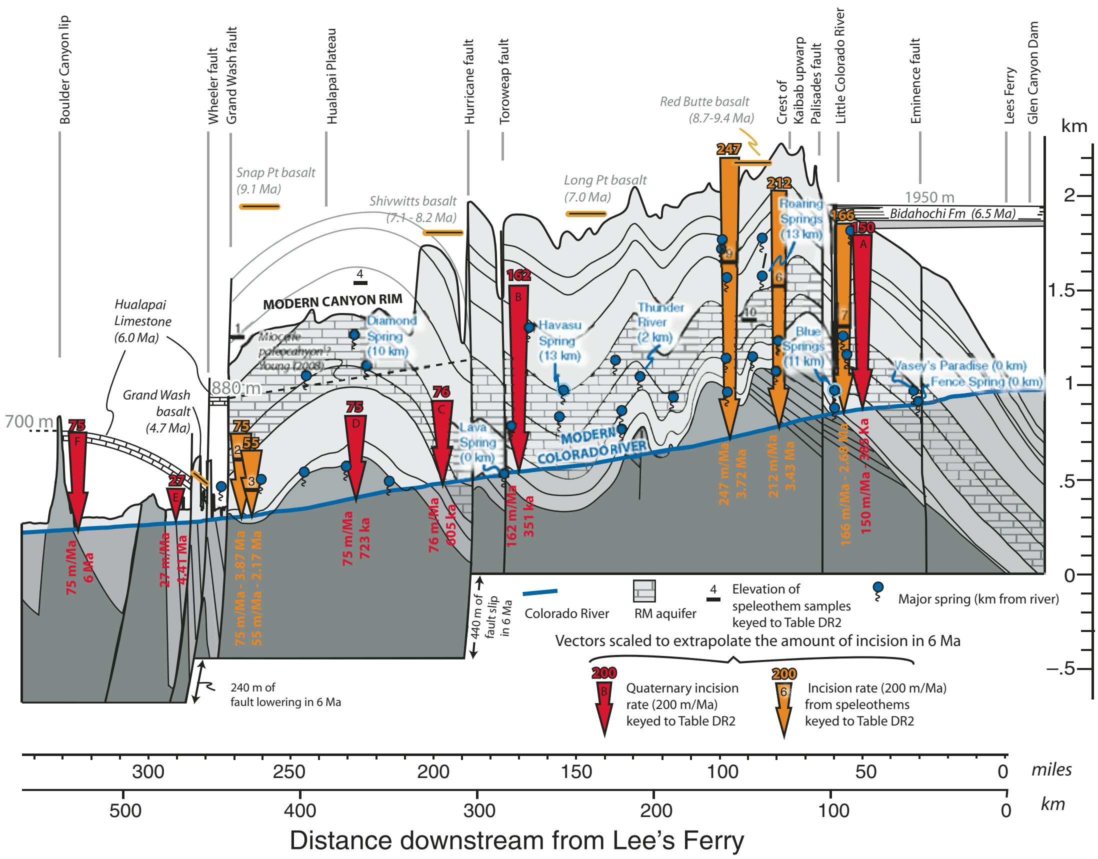

Figure 2. Longitudinal river profile, modern canyon rim, stratigraphic units, spring elevations (Table DR1; see footnote 1), and incision points (Table DR2).

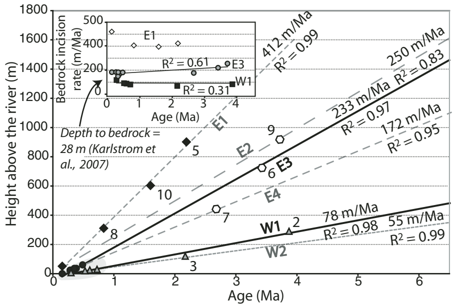

Figure 3. Age-height plots for proposed incision rate points showing near-steady incision of Grand Canyon over past 3–4 Ma Regression lines for eastern Grand Canyon rates: E1—highest rates, E2—all rates, E3—best rates, E4—Quaternary rates. Western Grand Canyon rates: W1—best rates, W2—Quaternary rates. A: Inset shows age–incision rate plot indicating steady, but differing, incision since 4 Ma for both eastern (E3) and western (W1) Grand Canyon.

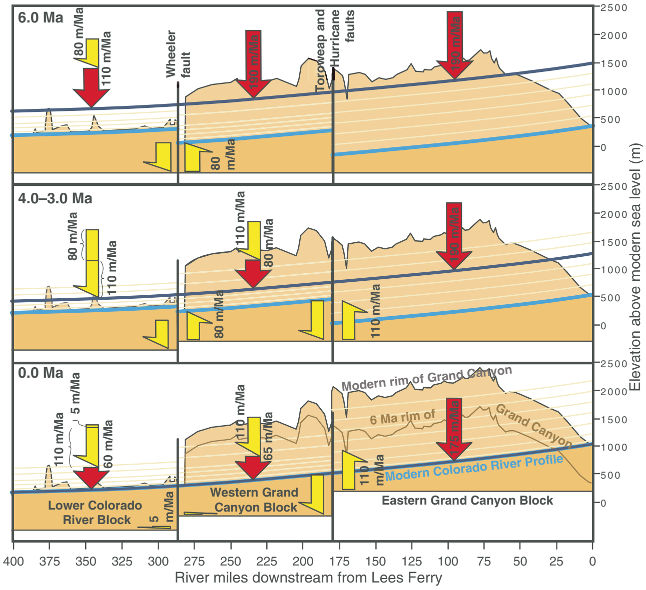

Figure 4. Sequential restoration and model constraints for interplay between Grand Canyon incision rates (red arrows) and normal faulting (yellow arrows) in past 6 Ma. Shown here are 3 panels of a 12-panel animation in the Data Repository (see footnote 1).

in the western Grand Canyon are within the river corridor and may date the time of river incision through the Redwall-Muav karst system. If so, they yield incision rates of 75 and 55 m/Ma over 3.87 Ma and 2.17 Ma, respectively. When combined with Quaternary incision rates, line W1 (Fig. 3) suggests a long-term (4 Ma) steady incision rate of 78 m/Ma and an estimated depth to bedrock below the river surface of 25 m (Y intercept of Fig. 3), in general agreement with Quaternary rates (55 m/Ma; line W2 of Fig. 3) and drilling depths to bedrock beneath the river (15–28 m; Karlstrom et al., 2007).

Eastern Grand Canyon dates (points 5–10) are from caves high in the seepage face and 2–7 km away from the river corridor and therefore are less reliable as incision points. When combined with Quaternary rates, the complete data set suggests an overall steady average bedrock incision rate of 250 m/Ma, the rate needed to carve the deepest part of the eastern Grand Canyon (1.6 km) in ~6 Ma (line E2 of Fig. 3). Problematically, caves giving similar ages occur at different heights (samples 5 and 7) and caves of similar height give different ages (samples 5 and 9), both of which negate the assumption of a strict incision rate significance for the dates. However, because all rates are considered here as maximum rates, we select the samples that give the lowest rates (samples 6, 7, and 9; Table DR2), yielding an apparent incision rate of 233 m/Ma relative to the mainstem over 3.72 Ma (line E3 of Fig. 3). We interpret samples 5, 8 (both surface features), and 10 to record carbonate precipitation events that took place high in the landscape due to hydrologic or geochemical changes. An analog for breaching of caves at multiple elevations in today's hydrologic system would be Roaring (highest), Havasu, and Blue Springs (Fig. 2). Thus, Figure 3 suggests steady rates for the past 4 Ma rather than "accelerated headward erosion in the eastern Grand Canyon" (Polyak et al., 2008, p. 1379). Within tectonic blocks, we see no systematic west to east changes in incision ages or incision rates (Fig. 2) as would be predicted in a headward erosion model.

Instead, steady incision and the difference in eastern-versus-western Grand Canyon incision rates (inset to Fig. 3) are well explained by the fault-dampened incision model (Pederson et al., 2002), acting over 6 Ma (Karlstrom et al., 2007), and reusing preexisting Tertiary paleocanyons in the western Grand Canyon (Young, 2008). Our sequential model (Fig. 4, and the incision animation in the Data Repository) explains key assumptions and makes numerous predictions that can be tested in future research. At 6 Ma, Lake Bidahochi became integrated through paleochannels in the western Grand Canyon (Young, 2008) to the top of the Hualapai Limestone. Eastern and western Grand Canyon fault blocks are restored to their 6 Ma position by pinning the Lake Mead block at its current elevation; movement on the Wheeler fault initiates differential incision. At 4–3 Ma, slip on the Wheeler fault waned and slip on the Hurricane-Toroweap system increased, initiating differential incision between eastern and western Grand Canyon blocks; aggradation of ~250 m of Bullhead gravels between 5.5 and 3.3 Ma in the Lake Mojave area (House et al., 2005) was facilitated by combined slip on the Wheeler and Hurricane-Toroweap system. At 0 Ma, the eastern Grand Canyon block has been uplifted 440 m (110 m/Ma × 4 Ma) relative to the western Grand Canyon block and an additional 240 m relative to the Lake Mead block.

TECTONIC UPLIFT VERSUS STATIC EROSIONAL MODELS

A static framework for incision of the Grand Canyon envisions a previously elevated Colorado Plateau region that was passively incised by a deepening canyon system (and progressive water-table lowering) in response to base-level fall. However, analyses of modern mantle velocity structure beneath the region (Sine et al., 2008) and the geoid (Coblentz and van Wijk, 2007) provide compelling evidence for a more dynamic framework involving mantle tectonism due to small-scale asthenospheric convection beneath the western edge of the Colorado Plateau. In particular, edge-driven convection associated with a migrating step in the lithosphere (Fig. 5) is proposed as a mechanism to produce a dynamically supported ~400-m-high topographic welt and a 2–4 m geoid high near the edge of the Colorado Plateau (Ni et al., 2007; Coblentz and van Wijk, 2007). This, combined with the now-strengthened differential incision model, suggests links among dynamic mantle upwelling, faulting, surface uplift (similar but smaller magnitude than Lucchitta, 1979), migration of volcanism (Fig. 4; Nelson and Tingey, 1997), and flux of mantle volatiles (Crossey et al., 2006).

CONCLUSIONS

Our hypothesis is that active faulting and broadly distributed epeirogenic uplift have influenced differential incision of the Grand Canyon in the past 6 Ma. Recent interpretations of new U-Pb dates on speleothems as providing evidence for a 17 Ma Grand Canyon (Polyak et al., 2008) are geologically unsupported. The assumption that water-table lowering rate is a proxy for canyon incision rates is invalidated by an analysis of the modern Redwall-Muav aquifer system, although apparent rates may be used as maximum rates. A combination of the lowest rates based on new U-Pb data, Quaternary incision rate data, and geologic constraints indicates that incision rates have been semisteady back to 3–4 Ma, with persistently different rates in the western (50–80 m/Ma) versus eastern

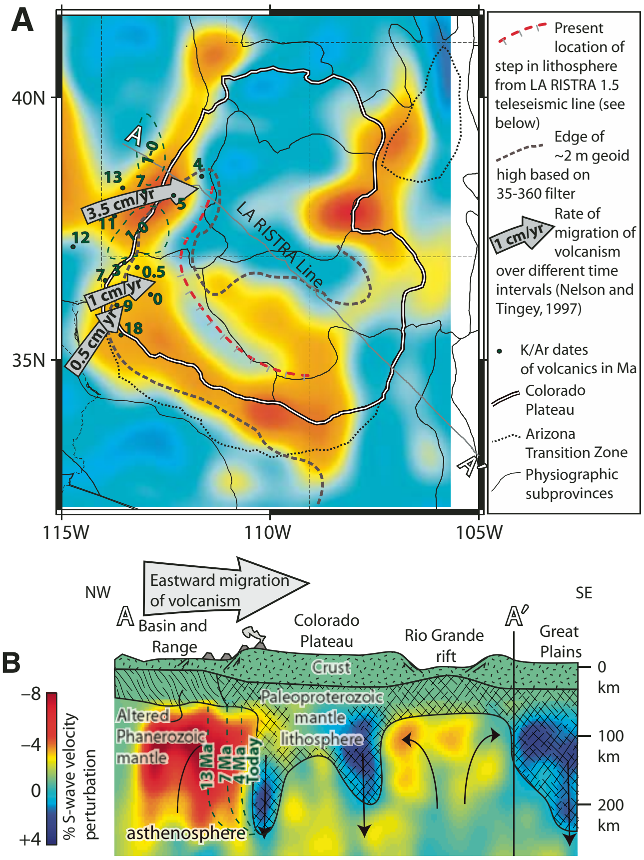

Figure 5. Long-wavelength (>200 km) topography showing 400 m elevated rim of Colorado Plateau and coincident 4 m geoid anomaly. Cross section (topography vertically exaggerated) shows mantle tomography (Sine et al., 2008) with large velocity contrast hypothesized to image edge-driven convection across migrating step in Colorado Plateau lithosphere, and resulting eastward sweep of surface magmatism since late Miocene. LA RISTRA line from Sine et al. (2008).

(175–250 m/Ma) Grand Canyon. This difference is due to ~700 m of east-side-up Neogene block uplift of the Colorado Plateau relative to the Basin and Range in the past 6 Ma driven by asthenospheric flow. We favor a “young canyon” model and show here that fault evolution and neotectonic driving forces are components that must be included in any viable model for the incision history of the Grand Canyon.

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