Thompson FIELD FORUMS | THE GEOLOGICAL SOCIETY OF AMERICA

REPORT

Age and Carving of Grand Canyon: Toward a Resolution of 150 Years of Debate

14–21 September 2019 | Grand Canyon, Arizona, USA

CONVENERS

Karl E. Karlstrom, *University of New Mexico, Albuquerque, New Mexico 87131, USA; kek1@unm.edu*
Laura J. Crossey, *University of New Mexico, Albuquerque, New Mexico 87131, USA*
Eugene Humphreys, *University of Oregon, Eugene, Oregon 97403, USA*
David Shuster, *University California Berkeley, Berkeley, California 94720, USA*
Kelin Whipple, *Arizona State University, Tempe, Arizona 85287, USA*
Ryan Crow, *U.S. Geological Survey, 2255 N. Gemini Road, Flagstaff, Arizona 86001, USA*

PARTICIPANTS

Andres Aslan (AA); Thorsten Becker (TB); Whitney Behr (WB); Jeanne Calhoun (JC); Kristen Cook (KC); Laurie Crossey (LC); Ryan Crow (RC); Andy Darling (AD); Rebecca Dorsey (RD); Madison Douglas (MD); Claudio Faccenna (CF); Anke Friedrich (AF); Arjun Heimsath (AH); Gene Humphreys (GH); Karl Karlstrom (KK); Eric Kirby (EK); Alan Levander (AL); M. Qasim Mahmood (MQM); Juliet McKenna (JM); Peter Reiners (PR); Marisa Repasch (MR); David Rowley (DR); Leah Sabbeth (LS); Taylor Schildgen (TS); David Shuster (DS); Peter van der Beek (PvdB); Brian Wernicke (BW); Kelin Whipple (KW).*

This GSA Thompson Field Forum involved 28 researchers and young scientists who discussed the evidence for the age, geomorphic evolution, and incision history of Grand Canyon. The field forum was centered around an eight-day, 280-mile field conference by raft through the Grand Canyon. Each of the participants gave a field seminar presentation.

Water in Grand Canyon's dissected aquifer system includes the Colorado River plus indigenous groundwaters that emerge as springs. John Wesley Powell, in an 1893 address to irrigation advocates in Los Angeles, foresaw: "… a heritage of conflict and litigation over water rights for there is not enough water to supply the land." As we face a hotter and drier future, our task is to figure out how to make do with less water and more people while preserving our quality of life, lands, groundwater resources, and groundwater-dependent ecosystems (JM). Grand Canyon's incised aquifer system shows mixing of meteoric, karst, and CO_2-rich "lower world" waters, and complex water pathways (LC). Grand Canyon National Park, in its 100th anniversary and beyond, is working to establish a better baseline for understanding water quantity and quality as well as complex groundwater flow paths in order to continue to provide water for the park's more than six-million annual visitors (JC).

Regional uplift of the Rocky Mountain–Colorado Plateau region took place in three episodes (Laramide, mid-Tertiary, and past 10 Ma), each related to a phase of carving of paleocanyons, but the relative uplift amounts have yet to be well quantified; ~thirds for each is one estimate (KK, GH). These lithospheric modifications started with flat slab subduction of the buoyant conjugate of the Shatsky Rise (GH). Middle Tertiary removal of the slab initiated the ignimbrite flare-up volcanism with uplift and heating consequences that still need to be deconvolved (PR). Young and ongoing uplift of the Rockies relative to the Colorado Plateau (EK, AA) and of western Colorado Plateau relative to sea level (KK, RC) may be driven by mantle convection at global scales (DR) but is probably dominated by changes in lithospheric density structure (GH), for example, by lithosphere delamination and asthenospheric return flow (AL) that is driving inboard migration of basaltic volcanism (RC). Mantle xenoliths were seen near Lava Falls that show deformation features and give pressure and temperature information about mantle tectonism (WB).

Geodynamics of uplift involved both isostatic and dynamic forces. We used the term "dynamic topography" for the components of topography not explained by crustal isostasy (DR). The western U.S. upper mantle contains very large gradients in seismic velocity that likely reflect marked buoyancy variations that affect topography. Estimates of dynamic topography for the region in recent papers range from several kilometers (TB) to near zero. Empirical estimates of differential uplift over the past 5–10 Ma of ~1 km are based on differential incision studies of rivers, which is observed where rivers cross sharp mantle velocity gradients (KK, RC, AA, EK).

Age of the Colorado River: The oldest known deposits of a major river draining the western Rockies are the 11 Ma gravels below the Grand Mesa basalt (AA). Downward integration of the system is suggested by onset of rapid cooling near Rifle, Colorado,

GSA Today, v. 30, no. 2, https://doi.org/10.1130/GSAT-TFF-GC.1.

*Participant initials are referenced throughout this report based on contributions to discussions during the forum.

Group picture at the Little Colorado River. Photo by Laurie Crossey. Front row, from left: Marisa Repasch; M. Qasim Mahmood; Taylor Schildgen; Andy Darling; Arjun Heimsath; Karl Karlstrom; Laurie Crossey; Peter Reiners; Juliet McKenna. Standing, from left: Thorsten Becker; Kristen Cook; Kelin Whipple; Jeanne Calhoun; Whitney Behr; Eric Kirby; Andres Aslan; David Rowley; Gene Humphreys; Alan Levander; Peter van der Beek; Madison Douglas; David Shuster; Ryan Crow; Leah Sabbeth; Anke Friedrich; Brian Wernicke; Becky Dorsey; and Claudio Faccenna.

(MWX well) at 6–8 Ma, before the Colorado River was integrated through Grand Canyon (EK). The Green River was integrated with the Colorado between 8 and 2 Ma, but the lack of terraces older than 2–3 Ma and steady incision documented by detrital sanidine dating data suggest a young 2–3 Ma Green River integration (AA). New detrital sanidine dating combined with magnetostratigraphy show that the oldest Colorado River sediment was first delivered to the Gulf of California between 4.8 and 4.63 Ma (RC). Recent studies provide new evidence for a multistage history of punctuated sediment discharge and complex marine-river interactions during integration of the Colorado River to the ocean (RD).

Thermochronology allows us to reconstruct past, now-eroded, landscapes. Lees Ferry and Marble Canyon rocks were >60 °C until after 5 Ma, indicating that this area was beneath ~2 km of Jurassic and Cretaceous strata (Vermillion cliffs) and hence was not carved until the past 5 Ma (KK). All thermochronology models for the eastern Grand Canyon segment show rim- and river-level samples at 50–80 °C until 25–15 Ma, indicating this segment of Grand Canyon was also not carved in its present location and depth. Rim- and river-level samples that are now separated vertically by 1.5 km show different rim (~55 °C) and river (~85 °C) temperatures until their temperatures converged 25–15 Ma, indicating that an East Kaibab paleocanyon was carved across the Kaibab uplift at this time (KK). Best time-temperature histories need to account for the long radiation damage history and that lattice damage by alpha particle decay has different annealing characteristics than fissioning of radioactive nuclei (DS).

Age of Grand Canyon: Endmember “Young Canyon” models (all post–6 Ma) and “Old Canyon” models (70–50 Ma) were not strongly supported on the trip. A “paleocanyon solution” is that integration of the Colorado River at 5–6 Ma deepened older paleocanyon segments as it carved Grand Canyon (KK). Marble Canyon is a young (post–5 Ma) canyon segment based on thermochronology. Eastern Grand Canyon may have been partially carved 25–15 Ma by a paleo–Little Colorado River. Muav Gorge “looks young” like Marble Canyon but has little incision rate data. A 65–50 Ma north-flowing Hualapai paleoriver (Music Mountain Formation) and Hindu paleovalley have been long recognized; these may have followed the Hurricane fault segment. Westernmost Grand Canyon has recent thermochronologic data that are most consistent with it being carved below the Esplanade surface in the past 5 Ma (DS, KK). A Wheeler Ridge ca. 20 Ma paleocanyon and a ca. 20 Ma paleoriver that supplied clasts from Grand Canyon’s Shinumo Sandstone to the Sespe Formation of California were presented and debated (BW, LS).

Bedrock incision rates in the northern Colorado River basin have been 100–160 m/Ma over the past 10 Ma and somewhat faster (200–300 m/Ma) over the past 0.3 to 1 Ma. Short-term (100 ka) incision rates are variable, reflecting complexities of fluvial processes at glacial-interglacial scales. Incision rates in Grand Canyon show semi-steady incision at 160 m/Ma over the past 1.2 Ma in the east; 100–110 m/Ma over 1.2 Ma in central Grand Canyon; and 90–100 m/Ma over 3–4 Ma in the west (RC). Steady incision in a given reach at the million-year timescale suggests steady forcings, the absence of major knickpoint passage, and a tectonic uplift driver (RC, KK, AA, EK). Differences reach-to-reach have been interpreted by some researchers to reflect active differential uplift (RC, KK, AA, EK), although geomorphic dampening from landslides, such as the three-million-year history of landsliding near Surprise Valley (KK), may have dampened bedrock incision in central Grand Canyon. Seventeen lava damming events from ca. 800 to 100 ka are recorded in western Grand Canyon; these dams quickly failed by overtopping, then the system returned to semi-steady bedrock incision rates (RC).

Incision history may be affected by ongoing uplift, but this is debated. Absent strong spatial gradients in rock strength or rock uplift rate relative to base level, rivers evolve toward smoothly concave-up profiles. In contrast, major slope-break knickpoints or convexities in the river profile existing on the Colorado River at Lees Ferry and on the Little Colorado River near Cameron give rise to “double concave” river profiles. These knickpoints coincide with the top of the Kaibab Limestone surface, suggesting a controlling influence of rock strength. These and other profile convexities are at least partly controlled by rock strength (KW, KC) and may be “hung up” in harder rocks, complicating interpretation (AD, KC). Projection of the restored level of the pre–6 Ma Little Colorado paleoriver profile through the proposed East Kaibab paleocanyon suggests that the Esplanade bedrock bench of western Grand Canyon could have been cut at this time (KW), although a new date of 3.3 Ma of basalt on Whitmore Hill that rests on Hermit Shale shows that the entire Esplanade surface had not yet been exposed at this time (KK).

Landscape evolution of the region has been influenced by pronounced differences in rock erodibility (rock strength) that give rise to the characteristic cliff and bench morphology of canyon walls and the Grand Staircase. Erosion rates can be quantified by measuring the concentration of cosmogenic ^{10}Be in sands deposited by river tributaries (AH). These data show significant scatter but with averages in eastern and central Grand Canyon generally similar to independently measured incision rates (KW). In western Grand Canyon, tributary profiles are suggestive of sustained quasi-steady river incision since integration (AD). However, it is also possible that incision on these tributaries has ceased, but their form is preserved by an armoring of large boulders that inhibits further incision and topographic relaxation, potentially consistent with a longer history of western Grand Canyon (MD). Contrary to this idea, cliff and tributary river profiles along the <17 Ma Grand Wash Cliffs are considerably less steep than those in western Grand Canyon despite similar geology and climate, implying that the final ~1 km of relief generation in westernmost Grand Canyon is <10 Ma (AD).

Regional and global analogs were also discussed. Mantle-driven uplift at a rising plume head can be modeled to leave predictable stratigraphic patterns in the sedimentary record of many continents (AF). The Rio Grande, on the other side of the continental divide, extended its length in a downward direction about six million years ago at the same time Grand Canyon was becoming integrated, which may implicate climatic changes near the end of the Miocene (MR). River incision and profile analysis in the central Anatolian region of the eastern Mediterranean supports very young tectonic uplift caused by slab breakoff (TS). Himalayan and Andean rivers show double-concave profiles with major knickzones, a delay between uplift and incision in knickzones, fault-control on knickzones, and tectonic rather than climate controls on incision (PvdB). Along the Nile River, the change in base level during the Messinian drawdown, and the uplifting Ethiopian Plateau headwaters provide possible direct comparisons to Colorado Plateau evolution with similar multi-stage uplift and potential ongoing mantle-driven dynamic uplift (CF).

Geoscience outreach is needed to improve global science literacy. Challenges include language barriers, validating tested from pseudoscience, citing and crediting sources, and outreach to developing countries. The “Learning Geology” Facebook page (headed by MQM) reaches 137,000 geoscience learners internationally and provides an ongoing successful example of geoscience outreach through social media. Informal science education at Grand Canyon in partnership with Grand Canyon National Park offers continued opportunities.