William Henry Holmes lithograph; part of Atlas Sheet XVI, Panorama from Point Sublime, looking south, from Dutton, 1882, Tertiary History of Grand Canon District. Public Domain.

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

THOMPSON FIELD FORUM REPORT

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

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Grand Canyon, Arizona, USA

CONVENERS

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ABSTRACT

The age and evolution of the Grand Canyon, in the western USA, have been debated since J.W. Powell's exploration of the Colorado River in 1869. This paper reports results of a 2019 GSA Thompson Field Forum that honored the 150th anniversary of Powell's first trip.

INTRODUCTION

The 2019 GSA Thompson Field Forum, "Age and Carving of Grand Canyon: Toward a Resolution of 150 Years of Debate" involved 28 researchers and young scientists (Table 1) who discussed the evidence for the age, geomorphic evolution, and incision history of Grand Canyon in the context of recent advances and ongoing debates. The objective was to emphasize the power of

integration of multiple disciplines in research on the evolution of the Colorado River, the uplift of the Colorado Plateau region, and the development of iconic western U.S. landscapes, and to inspire similar integrative approaches elsewhere. The field forum was centered around an eight-day, 280-mile field conference by raft through the Grand Canyon. We started and ended in Las Vegas, Nevada, USA, and covered 280 miles from Lees Ferry to Pearce Ferry under a charter with Grand Canyon Expeditions. Each of the participants gave a field seminar presentation via: (1) presentations on the outcrop; (2) “plenary” presentations at morning and evening seminars on the beach; and (3) short talks and discussions on boats and at key locations. Each participant prepared ahead of time some reference figures that were compiled into a companion booklet that facilitated the presentations and discussions. The goal of this paper is to summarize data presented and emerging consensus on ongoing debates and future research directions. The forum discussed the entire Rocky Mountain–Colorado Plateau region extending from Wyoming and Colorado to the Gulf of California. To minimize semantic misunderstandings, we found it important to distinguish the modern form of the Grand Canyon and the Colorado River drainage network from the history of paleorivers and paleocanyons that evolved into the modern landscape.

RESULTS

The following topics were energetically discussed, with the initials of the primary presenters keyed to Table 1. Consensus hovered in the background of many discussions, but the main goal of this paper is to summarize what was presented. Continued debates and future challenges are summarized in the attached selected references section.

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 due 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 CO₂-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 >6 million annual visitors (JC).

Figure 1. Map of the Grand Canyon showing river miles below Lees Ferry, canyon segments (in purple), and Quaternary faults.

Regional uplift of the Rocky Mountain–Colorado Plateau region provided the elevation difference needed for rivers to incise landscapes such that uplift history debates are entwined with canyon incision debates. Three episodes of uplift (Laramide, mid-Tertiary, and past 10 Ma) may have driven three stages of drainage reorganization and carving of paleocanyons, but the relative uplift amounts have yet to be well quantified; ~thirds for each is one estimate (KK, GH). Laramide uplift involved hydration of North American lithosphere and erosion of basal North America. These lithospheric modifications were driven by flat slab subduction of the Farallon ocean lithosphere, which occurred with the 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). Xenoliths from the Earth’s mantle were seen in the Uinkaret basalts near Lava Falls; such samples show deformation features and give pressure and temperature information about mantle tectonism beneath the region (WB).

Geodynamics of how deep crustal and mantle processes may drive changes in surface elevation involves both isostatic (changes in buoyancy) and dynamic (mantle flow) forces. We used the term “dynamic topography” to mean all components of topography not explained by (instantaneous) crustal isostasy (DR). The western U.S. upper mantle contains very large gradients in seismic velocity (e.g., exceeding 4% in V_p) that likely reflect marked buoyancy variations that affect topography. Modeled dynamic topography for the Colorado Plateau–Rocky Mountain region in recent papers ranges from several kilometers in some models (TB) to near zero in others. 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 near Grand Junction Colorado (AA). Downward integration of the system is suggested by onset of rapid cooling near Rifle Colorado (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 seen since then based on detrital sanidine dating suggests a young 2–3 Ma Green River integration across the Uinta Mountains (AA). New detrital sanidine dating combined with magnetostratigraphy shows that the oldest Colorado River sediment was first delivered to the Gulf of California between 4.8 and 4.63 Ma (RC), reinforcing the “young” river model. Recent studies of sedimentology, stratigraphy, and paleontology 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, though the controls on this behavior remain poorly understood (RD).

Thermochronology tracks how minerals cooled as they were exhumed to Earth’s surface; this tool 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 Marble Canyon 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 beneath ~2 km of rock and had not been carved in its present location and depth. Models for 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, suggesting an East Kaibab paleocanyon was carved across the Kaibab uplift at this time (KK). Grand Canyon samples present a challenge for thermochronology techniques because of long term residence which allows radiation damage to build up in crystals that

effects helium (daughter product) diffusion, and thermal histories that demonstrably include both cooling and reheating episodes. Developing better time-temperature histories should involve recognition of the long radiation damage history plus understanding that lattice damage by alpha particle decay versus fissioning of radioactive nuclei produce different types of damage, with different annealing characteristics (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” suggested that integration of the Colorado River at 5–6 Ma deepened older paleocanyon segments as it carved Grand Canyon such that five segments need to be analyzed independently (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 relics of the Hindu paleovalley on the Hualapai Plateau have been long recognized. These drain northward into Grand Canyon along the Hurricane fault, but its northward exit is debated. Westernmost Grand Canyon received the most debate; recent thermochronologic data presented in 2014–2017 papers are most consistent with it being carved below the Esplanade surface in the past 5 Ma (DS). But a Wheeler Ridge ca. 20 Ma paleocanyon, 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 of a canyon are obtained by dating past river levels (e.g., strath terraces and basalts that flowed into rivers) and calculating incision rates from strath-to-strath and relative to the bedrock beneath the modern river. In the upper Colorado River basin, incision rates have been 100–160 m/Ma over the past 10 Ma and somewhat faster (200–300 m/Ma) over the past 0.3–1 Ma. Short-term (100 ka) incision rates are variable reflecting complexities of fluvial processes at glacial-interglacial scales. The proposed “bulls eye” of incision in Glen Canyon is not evident at intermediate or long time scales, but recent acceleration of incision was debated. Regressed Grand Canyon incision rates 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 time scale suggests steady forcings, absence of major knickpoint passage, and a tectonic uplift driver (RC, KK, AA, EK). Differences reach-to-reach are interpreted in terms of (equated with) differential uplift (RC, KK, AA, EK) although geomorphic dampening from landslides, such as the three-million-year history of landsliding we saw near Surprise Valley (KK), may provide another

explanation for bedrock incision dampening in central Grand Canyon. Seventeen lava damming events are recorded in western Grand Canyon. These dams quickly failed by overtopping at their upstream ends, the river became established atop and continued to dismantle the dams as evidenced by basalt-rich gravels, then the system returned to semi-steady bedrock incision rates as calculated from now well-dated intra-canyon lava dam remnants ranging in age from ca. 800–100 ka (RC).

Incision history of the Colorado River trunk drainage and its tributaries since integration may be affected by ongoing base level change (base-level fall and/or headwater uplift), but whether this is required 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 exist 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 as the river steepens to erode hard rock and shallows in weak strata above the knickpoints (KC). However, slope-break knickpoints can also record an increase in river incision rate triggered by a change in base level (e.g., integration across the Grand Wash Cliffs). A challenge in Grand Canyon is sorting out the relative contributions of rock-strength and incision rate history in establishing the profile of the Colorado River and its tributaries. Part of the challenge is that both knickpoints controlled by rock strength contrasts in gently dipping rock layers and those resulting from base level change are transient features, migrating slowly upstream. Profile evolution models illustrate that base-level driven transient knickpoints often get “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). Much work is needed to resolve the timing and history of the formation of the Esplanade surface.

Landscape evolution of the greater Colorado Plateau 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. This implies that the final ~1km of relief generation in westernmost Grand Canyon is “young” (<10 Ma) rather than “old” (>17 Ma) (AD). Field investigation of comparable tributary rivers in both settings and consideration of differences in boundary conditions is required to fully resolve this debate.

Regional and global analogs were also discussed. For example, at continental scale and long time scales, mantle-driven uplift at a rising plume head can be modeled to leave predictable stratigraphic patterns such that mantle-driven uplift may be recognized in the sedimentary record of many continents (AF). At regional scales, the Rio Grande, on the other side of the continental divide, extended its length in a downward direction ~6 million years ago at the same time Grand Canyon was being established as a continental scale river; this may implicate climatic changes that affected the region near the end of the Pliocene (MR). Application of river incision and profile analysis in the tectonically active areas like the central Anatolian region of the eastern Mediterranean is useful to support very young tectonic uplift caused by slab breakoff (TS). Examples from tectonically active regions in the Himalayan and Andean orogens using integration of river and thermochronology studies showed double concave profiles with major knickzones, a delay between uplift and incision in knickzones, and 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, including potential ongoing mantle-driven dynamic uplift (CF). A next Thompson Field Forum to this region was discussed enthusiastically.

Geoscience outreach, defined as any activity that promotes science and communicates its purpose and values to the community, is needed to improve global science literacy. Challenges include language barriers, validating tested from pseudo-science, 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 (KK, LC).

RESULTS

Summaries of pre-2012 ideas about the age and carving of Grand Canyon are in Karlstrom et al. (2012) and Wernicke (2012). Early papers that proposed mantle-driven uplift of the Colorado Plateau–Rocky Mountain region are Karlstrom et al. (2008), Karlstrom et al. (2011), and Levander et al. (2011). These concepts and many of the debates from the 2010 CRevolution meeting in Flagstaff (Karlstrom et al., 2012) are still under discussion. Continued research is informed by the selected 2012–2019 research papers listed below from meeting participants as well as other papers from the Geosphere Colorado River Evolution themed issue (<https://pubs.geoscienceworld.org/geosphere/pages/revolution>). Continued interdisciplinary research needed to resolve uncertainties about the evolution of the region’s river and canyon systems may include several subdisciplines, such as detrital grain geochronology of detrital zircon and detrital sanidine of paleoriver deposits; geophysical modeling of dynamic topography to test hypothesis for young and ongoing mantle-driven uplift; geomorphic modeling of the effects of rock strength; thermochronometric analyses of rim and river-level samples using multiple methods to image now-eroded landscapes; and empirical data to evaluate steady versus non-steady bedrock incision in different reaches of river systems.

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Figure 2. 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; Anka Friedrich; Brian Wernicke; Becky Dorsey; and Claudio Faccenna.

Figure 3. “Piano Hike” at the Surprise Valley Landslide. Photo by Laurie Crossey.

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