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Notes

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ABSTRACT

A 2010 Colorado River symposium held in Flagstaff, Arizona, in May 2010, had 70 participants who engaged in intense debate about the origin and evolution of the Colorado River system. This symposium, built on two previous decadal scientific meetings, focused on forging scientific consensus where possible, while also articulating continued controversies regarding the Cenozoic evolution of the Colorado River System and the landscapes of the Colorado Plateau–Rocky Mountain region that it drains. New developments involved hypotheses that Neogene mantle flow is driving plateau tilting and differential uplift, with consensus that multidisciplinary studies involving differential incision studies and additional geochronology and thermochronology are needed to test the relative importance of tectonic and geomorphic forcings in shaping the spectacular landscapes of the Colorado Plateau region. In addition to the scientific goals, the meeting participants emphasized the iconic status of Grand Canyon for geosciences, and the importance of good communication between the research community, the geoscience education/interpretation community, the public, and the media. Building on a century-long tradition, this region still provides a globally important natural laboratory for studies of the interactions of erosion and tectonism in the shaping landscape of elevated plateaus.

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BACKGROUND

Studies of the origin and evolution of the Colorado River System are central to understanding the Cenozoic tectonic and geomorphic evolution of the western U.S. orogenic plateau. This region was uplifted from sea level in the late Cretaceous, to present elevations that exceed 4 km in the Rocky Mountains and 1.5 km over large regions of the Colorado Plateau. The Colorado River is the trunk river of the single river system that drains the western slope of the Rockies and the entire Colorado Plateau, and hence is central to understanding the uplift and erosion history of the region.

The timing of the initial development of the Colorado River, and its evolution into the drainage network seen today, have been the focus of over a century of research, since the early scientific trips of J.W. Powell down the Green and Colorado river systems. This field laboratory, because of its spectacular exposure, has been at the forefront of scientific breakthroughs in geomorphology, stratigraphy, paleontology, and tectonics for over a century (Dutton, 1882).

In early syntheses (Powell, 1875, 1879; Dutton, 1882), the Colorado River system was presumed to be ancient and antecedent, following the path of today's west-flowing river system that carries snowmelt from the Rocky Mountains to the Pacific. Longwell (1928, p. 143) noted the problem ("Muddy Creek problem") that the Colorado River did not exit the western edge of the Colorado Plateau during the Pliocene, the lower boundary of which was placed at ~11 Ma until the early 1970s. Blackwelder (1934) proposed that the regional river and canyon system did not exist until the Pleistocene, before which time there was a general lack of integrated river systems. Hunt (1956) outlined the evolution of the entire region since Cretaceous time, and his Colorado River synthesis (Hunt, 1969) involved discussions of interacting geomorphic and structural controls on Colorado Plateau drainages through time.

In summary of the continuing debate, Hunt (1969, p. 63) stated, "The view that the Colorado River is an ancient river considers the river as a whole from the time of first uplift of the present Rocky Mountains; the view that the river is young is based on particular segments." This was a glimpse of subsequent controversies that attempt to reconstruct the regional picture by study of both regional uplift history and individual segments of the river system. Additional advances in our understanding of the complexities of the river system have been punctuated by three collaborative meetings in northern Arizona, in 1964, 2000, and 2010. This paper provides brief reflections on the first two meetings and a summary of the 2010 meeting. Our goal is to foster continued research on western U.S. landscape evolution at all scales.

1964 MEETING: MUSEUM OF NORTHERN ARIZONA COLORADO RIVER SYMPOSIUM

The first meeting had 21 participants. It was an outgrowth of discussions between Eddie McKee and Dick Young during visits to McKee's U.S. Geological Survey office in Denver, Colorado, related to Young's PhD (Young, 1966), funded in part by the Museum of Northern Arizona (MNA awards were $1000 each for the summers of 1962–1965). Young's fieldwork on the Hualapai Reservation and Ivo Lucchitta's work in the Lake Mead region (Lucchitta, 1966, 1972) evolved with close interaction. Contrary to the account in Ranney (2005), the new data

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and participation of the two PhD students were a major focus of the 1964 meeting. The symposium began with a 3-day field trip to the Lake Mead country, then to Milkweed and Peach Springs canyons. This was followed by formal group discussions at the MNA for the better part of a week. No formal talks, and very few slides, were allowed. Most of the data provided by participants, other than Young and Lucchitta, had been previously published, and all the information from the symposium was ultimately integrated into McKee et al. (1967). Gene Shoemaker attended sporadically due to his urgent Apollo Project commitments, but he was a dynamic and influential force during the formal discussions and the field trips. Charlie Hunt, in spite of his influential works (Hunt, 1956, 1969), did not attend the 1964 symposium.

In retrospect, two things stand out about the overall events at the 1964 symposium. First, some senior geologists (especially McKee, Shoemaker, and Koons) refused to readily accept the idea that the paleodrainage channels on the Hualapai Plateau that converge on Peach Springs Canyon actually flowed northeast and exited to the north across the course of the modern Grand Canyon. This was in spite of the undeniable field data from gravel imbrication and clast lithologies. The conceptual problem was that these deep Tertiary canyons seemed to them to be heading into a "deep hole" from which there was no obvious outlet at appropriate elevations on the other side of Grand Canyon. The concept of NE tilting of the Plateau during Laramide uplift to solve this issue of gradients (Young, 1982) was not strongly argued until after McKee et al. (1967). There was also hesitancy to accept the idea that the oldest basal arkosic Rim gravels could be older than Miocene (now known to be Paleogene or late Cretaceous by Young and Hartman, this themed issue). The subsequent McKee and McKee (1972) article on "Pliocene Uplift" of the Colorado Plateau to explain the "Rim gravels" attests to the difficulty of changing minds about that history, despite the 18.5 Ma age of the Peach Springs Tuff that caps the gravels in the Hualapai sections (Young and Brennan, 1974) and even given that the Pliocene-Miocene boundary at that time had recently been moved from 11 Ma to 5 Ma.

Second, there were few individuals at the meeting who knew factual details of the little-studied Cenozoic history of the Little Colorado River Valley and environs. Therefore, despite the perceived young age of the Bidahochi deposits (~6–4 Ma age at the time; McKee et al., 1967), it was decided to "send" the Colorado off to the south (by default), presumably accompanying ponding of the drainage in Bidahochi time. There seemed to be no other place for the ancestral river to go. Bidahochi ages have been revised since then (16–6 Ma), and an alternate southern escape route through the ancestral Salt River Canyon has been resurrected by Potochnik (this themed issue). Much of the uncertainty concerning the timing of events as perceived in 1964 needs to be put in the context of the relative lack of precise geochronology on key Cenozoic units.

Nevertheless, the main accomplishment of the 1964 symposium discussions was to more clearly focus the state of knowledge for different parts of the plateau and to combine the ideas of major researchers, other than those of Charlie Hunt. McKee et al. (1967) re-articulated some of the main questions about the Colorado River evolution: (1) time of initiation, (2) processes of integration, and (3) early paleodrainage courses. There was continued emphasis on river segments that may have had different earlier histories and been integrated into the Colorado River system that we see today in post–Muddy Creek time. Then, as now, there was little consensus about pre–6 Ma river geometries, but the stage was set for continued debate.

2000 GRAND CANYON MEETING: COLORADO RIVER, ORIGIN AND EVOLUTION

This summary is modified from Young and Spammer (2001, p. 1–3). This meeting had 73 formal registrants and was held at Grand Canyon National Park in June 2000. By the time of the 2000 meeting, the maturation and practical application of plate tectonics concepts, much more fieldwork, and many more K-Ar ages had improved the chronology and order of events dramatically. Yet, the central problems of where to send a postulated Miocene river, and how Colorado River integration occurred, remained unresolved.

The meeting and resulting collection of papers was an outgrowth of informal conversations among Colorado Plateau geologists during the 1990s. The purpose of the symposium was to update the status of current knowledge of the geologic issues, controversies, and progress surrounding the geologic evolution of the Colorado Plateau and the Colorado River during Cenozoic time. The meeting (5–11 June 2000) was coordinated by R.A. Young, with significant input from George Billingsley and field trips led by Michael Ort to view the Bidahochi Formation stratigraphy and Andre Potochnik to view Mogollon Rim geology, and with a postmeeting field trip to view the Tertiary geology of the Hualapai Indian Reservation and Lake Mead areas led by Richard Young, James Faulds, Sue Beard, Keith Howard, and Ivo Lucchitta. Grand Canyon National Park superintendent Robert L. Arnberger underwrote the major expenses for the meeting, with other financial and informal donations of materials and personnel time provided by the USGS Flagstaff, Arizona, office (George Billingsley, Sue Beard, Sue Priest), Grand Canyon Association (Greer Price), SUNY Geneseo Department of Geological Sciences (R.A. Young), NAU Departments of Geology and Geography (Michael Ort, Lee Dexter), the Arizona Geological Survey (Jon Spencer), and the Nevada Bureau of Mines (James Faulds). The meeting was coordinated by Greer Price, with assistance from Tom Pittinger of the National Park Service for accommodations, meals, and meeting facilities.

Among other specific advances, many papers used relatively new dating techniques applied to high level terraces of the river system to infer incision rate data. The emerging picture was a river with both spatially and temporally varying incision rates along its course, with differential incision rates related to both geomorphic and structural controls. The existence of a well-integrated ancestral upper Colorado River drainage system in Colorado and southern Utah, as postulated by Hunt (1969), was not strongly supported, with continued debate about where ancestral upper Colorado River water and sediment loads would have been stored before integration at the mouth of Grand Canyon between 4 and 5 Ma. The Bidahochi Formation in eastern Arizona as evidence for such a Miocene lake seemed more acceptable from a chronologic perspective, but not necessarily from a sedimentological viewpoint. Timing of Colorado Plateau uplift(s) remained controversial with both late Tertiary uplift and older Laramide uplift proponents. Late Pleistocene incision rates were reported to be rapid enough to carve Grand Canyon within the last 10 Ma, but this raised the significant issue of why rapid incision of the entire basin did not begin and progress rapidly more immediately following Miocene Basin and Range extension, when appreciable relief developed between the Colorado Plateau and the extended terrane to the west. There was still no consensus about mechanisms by which different river segments may have been integrated. Both lake spillover and headward erosion models were advanced again, and other controversies were aired: (1) when did canyon cutting first begin, (2) which way rivers were flowing in the early Tertiary, (3) how much Mesozoic rock and Cenozoic sediment overlay the Kaibab surface in different areas and how fast was erosion denuding the landscape, and (4) how the 5–6 Ma Bidahochi, Hualapai and Bouse lake systems were related to a through-going Colorado River.

Overall, the 2000 meeting marked renewed progress on all aspects of the Cenozoic evolution of the Colorado River system. At the same time that a plethora of models were discussed, this meeting seemed to mark an attempt to compile all objective criteria for the timing of various surfaces and paleosurfaces, the timing of cooling of rocks as they were unroofed toward today's surface, and rates of river incision through time. The meeting and resulting volume catalyzed renewed research and the integration of diverse scientific approaches all aimed at resolving the landscape evolution of the Colorado Plateau/Grand Canyon region. It also spawned more popular treatments of long-standing controversies about evolution of Grand Canyon (Ranney, 2005; Powell, 2005).

Continued challenges and questions were identified at the meeting: (1) What were the causes and precise timing of plateau uplift(s)? (2) How much Mesozoic and Cenozoic sediment covered the Grand Canyon region and when did it get stripped off? (3) Could a western Grand Canyon precursor stream have existed without leaving a preserved sedimentary record near the present mouth of Grand Canyon? (4) Did integration across the Kaibab uplift take place by headward erosion or "basin spillover"? (5) What potential role did local or global climate change play either in enhancing or delaying the incision and integration of the Colorado River system?

2010 FLAGSTAFF MEETING: CREVOLUTION 2: ORIGIN AND EVOLUTION OF THE COLORADO RIVER SYSTEM II

The 2010 meeting, reported on herein, follows in the footsteps of prior meetings in several important respects. It represented an assembly of many of the key scientists and their students researching the evolution of the Colorado River system. There were 70 registered participants. This meeting followed a comprehensive regional approach (e.g., Hunt, 1956) that involves detailed studies from the Gulf of California to the high Rockies, including application of the latest geochronologic and analytical techniques to quantify rates and to model processes of landscape evolution. New aspects of this meeting were: (1) the examination of links between mantle processes and their potential surface effects, (2) discussion and quantification of the isostatic response to denudation that affects landscapes, (3) increased emphasis and emerging syntheses of low-T thermochronology (apatite fission-track and apatite helium studies), (4) discussion of groundwater sapping as an important river integration mechanism, and (5) greater emphasis on process-oriented studies, all aimed at understanding driving mechanisms, timing, and magnitudes of differential river incision and landscape denudation and their tectonic connections in this classic landscape.

Table 1 lists the abstracts presented at the meeting; see Beard et al. (2010), for the text and figures of these extended abstracts. The agenda of the meeting (Beard et al., 2010) preceded from the Gulf of Mexico, up the Lower Colorado River system, through Grand Canyon, across the central Colorado Plateau, to the Rocky Mountain headwaters. Like the 2000 workshop, the 2010 workshop reinvigorated research on the Colorado River region in the context of regional and global questions about tectonic and geomorphic processes that shape landscapes.

Invitees submitted extended online abstracts to an Internet site (https://sites.google.com/site/crevolution2/home) so that all participants could access and read these informal contributions before the meeting. The format of the workshop was designed to encourage discussion and data compilation in a format that differed from the formal talks presented at most professional meetings. Oral remarks were limited to 5 minutes and were followed by extensive plenary discussion among the participants. Products of the workshop include this summary report, developed, in part, at the workshop. Electronic databases and resources on geochronology and incision data, as well as useful maps and images of the Colorado River system developed for this meeting (see website) will also be submitted as separate contributions to this *Geosphere* themed issue.

Toward Consensus

The meeting moved toward consensus on several topics. The references in this section refer to abstracts listed in Table 1 (also in Beard et al., 2010), and many of these papers are elaborated on and updated in this themed issue.

Multiple episodes of erosion and uplift. Punctuated episodes of erosion, and inferred uplift, took place in the Laramide (Wernicke; Lee et al.; Young and Hartman), in the middle Tertiary (Cather; Lee et al.), and in the last 10 million years (Karlstrom et al.; Hoffman et al.), as supported by regional geologic and thermochronologic data (Kelley et al.; Lee et al.). There is continued debate regarding durations and nature of tectonic and/or climatic forcings, and which episode was dominant in a given region or reach of the river system.

Drainage reversal(s). The concept of drainage reversal seems well established. Rivers flowed north (Davis et al.; Hill et al.), or northeast and east (Wernicke; Potochnik), during the late Cretaceous (Wernicke), and Paleocene–Eocene (Davis et al.; Young and Hartman; Young et al.; Beard and Faulds), whereas the post–6 Ma Colorado River flows southwest. Debate continues about the timing and drainage geometry of most of the pre–6 Ma paleorivers and the mechanisms driving drainage reversals.

Mid-Tertiary erosion. Middle Tertiary time, after the Chuska erg (Cather), represented a time of regional deep erosion on parts of the Colorado Plateau that is documented by ~25 Ma cooling based on thermochronology data in Grand Canyon and the Colorado Rockies (Kelley et al.; Lee et al.). Tectonic influences on this denudation are debated.

Age of the upper Colorado River system. Gravels exist beneath 25 Ma basalts (Aslan et al.) and there are west-draining Oligocene paleocanyons in the Gunnison region (Sandoval et al.). By 10 Ma, evidence of a paleo–Colorado River in the Colorado Rockies is seen in gravels beneath the 10–11 Ma Grand Mesa basalt (Aslan et al.; Cole) and several other ~10 Ma basalts (Lazear et al.). Onset of rapid incision and denudation in the upper Colorado River paleodrainages took place between 10 and 6 Ma, as documented by thermochronology from the MWX well (Karlstrom et al.).

Age of the Lower Colorado system. The 5–6 Ma age of integration of the Colorado River system as we know it today, across the Kaibab uplift to the Gulf of California, continues to be supported based on data from the 5.3 Ma age of the first sediments arriving in the Gulf (Dorsey; Kimbrough et al.), lack of Colorado River sediments in the Grand Wash trough (Muddy Creek constraint; Lucchitta), and geometry of late Miocene alluvial fans that are now dissected by the Colorado River and Grand Canyon (Luchitta et al.). Comparison of sedimentary budgets suggests that the volume of sediment in sedimentary basins of southern California is roughly compatible with estimates for erosion of material off the Colorado Plateau in the last 6 Ma (Dorsey), compatible with post–6 Ma integration. Debate continues about pre–6 Ma paleocanyons that may have become reused and linked to evolve into the modern Grand Canyon (Young, 2008).

Lake spillover along the lower Colorado. Lake spillover models for the lower Colorado River (House et al.; Howard) are increasingly well documented by mapping of Pliocene deposits for Mojave Basin, and there was continued support for a lacustrine origin for the Bouse Formation in the Mojave-Parker reaches (House et al.; Malmon et al.). Contrary to some older models for marine origin, Sr, O, and C isotopes support a lacustrine origin for the upper Bouse (Mojave Basin) and Hualapai Limestone (Spencer et al.; Crossey et al.; Lopez Pearce et al.).

Bullhead aggradation. Major aggradation in the lower Colorado River at ~5.5–3.3 Ma is well

TABLE 1. ABSTRACTS PRESENTED AT THE 2010 MEETING—ALL CAN BE REFERENCED AS, 2010, *IN* BEARD ET AL., 2010, CREVOLUTION 2—ORIGIN AND EVOLUTION OF THE COLORADO RIVER SYSTEM, WORKSHOP ABSTRACTS: USGS OPEN-FILE REPORT OF-2011-1210

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documented by the Bullhead and related gravels (House et al.; Howard et al.), although explanations for this event and for the steep profile at the top of the aggradational sequence (Howard) are debated.

Integration processes. In general, river integration processes of lake spillover, headward erosion, and groundwater sapping (Crossey et al.; Pederson; Hill et al.) were all considered viable processes (Douglass), and may have operated in combination. Although the 5–6 Ma timing is generally agreed upon, the dominant mechanisms for integration of the Colorado River system remain controversial.

Differential incision. There is increasing evidence for different incision rates through time and space in the river system and patterns of differential incision are becoming better resolved by combined geochronologic and geomorphic data (Crow et al.; Marchetti et al.). Where differential incision can be shown to be related to fault dampening of incision, as in western Grand Canyon (Crow et al.), this is indicative of a dynamically changing river system that is adjusting to tectonic forcings. The relative importance of geomorphic, climatic, and tectonic controls on drainage evolution are important issues being debated.

Rapid onset of denudation 6–10 Ma. There is also improved evidence from apatite helium measurements as well as geologic studies for regional acceleration of exhumation and incision in the Neogene. This occurred after ~5–7 Ma in the upper Grand Canyon (Lee et al.), Little Colorado River (Embid et al.), Monument Uplift, Canyonlands, and Roan Cliffs (Hoffman et al.). Incision accelerated starting 6–10 Ma in the Grand Mesa area (Aslan et al.; Cole; Karlstrom et al.). Debates continue about the extent to which this was driven by tectonic uplift (Karlstrom et al.) or combinations of drainage integration (Pederson), enhanced Pleistocene runoff, the southwest monsoon climate, and the opening of the Gulf of California (Hoffman et al.).

Isostatic response to denudation. Isostatic consequences of erosion involve rebound of buried rocks to balance the load removed (Pederson; Lazear et al.). Faulting and differential erosion during possible tilting also have isostatic responses. Quantification of this component of landscape evolution is important and is being studied by several groups.

Paleogeography reconstructions. Because of any tectonic and isostatic adjustments to surface elevation, we cannot rely solely on modern elevations to reconstruct past elevations and geometries of paleolake shorelines, spillover points, and paleoriver gradients.

Mantle-driven uplift. There is strong evidence for Neogene mantle flow and tectonism in the western U.S., based on new geophysical images that show large contrasts in mantle velocity (and inferentially, temperature and rheology) over <100 km spatial scales. In addition, petrology of volcanic rocks shows both asthenospheric and lithospheric sources for Neogene basalts (Karlstrom et al.). Geodynamic models suggest that observed mantle velocity variation should drive surface uplift and subsidence (Karlstrom et al.; Robert et al.), but there is continued debate about timing and nature of mantle flow. Several geodynamic models suggest that the magnitude of predicted effects on surface topography are on the order of 400–800 m of surface uplift.

Continued Controversies

Many of the same controversies raised during the 1964 and 2000 symposia persist.

Opening of the Gulf of California. While most published data support a latest Miocene age (~6.5 Ma) for initial marine incursion (Dorsey), paleontological data support marine conditions starting in middle Miocene time (McDougall). A middle Miocene age for opening of the Gulf would suggest that it did not play a major role in the integration of the Colorado River at ca. 5.5–6 Ma. Top-down (e.g., lake spillover) integration models also do not rely on opening of the Gulf of California to lower base level and directly facilitate integration, although Gulf opening may have intensified summer monsoons and erosion rates (Wernicke).

The Bouse Formation. A marine versus nonmarine origin for the "lowermost" Bouse Formation along the Colorado River in the southern Yuma and Blythe Basins was debated again in 2010 (McDougall). Some workers suggested that the Bouse Formation records a change from a marine environment in the Yuma Basin to nonmarine conditions in the northern Mojave paleolake. Sr, O, and C isotopes from "lower" Bouse carbonates are consistent with mixing trends between river, marine, and deep bedrock sources of water for parts of the Yuma Basin such that Sr isotopes alone do not provide sufficient evidence for nonmarine origin (Crossey et al.). In contrast, other workers point toward the similar character of the basal Bouse limestone in all areas, and nonmarine isotopic signatures (Spencer et al.), to support a nonmarine origin in all of the sub-basins.

Comparisons between the Green and Colorado Rivers. Two great rivers converge in Canyonlands to form the Colorado River system. The Colorado River is steeper and has higher incision rates over the last few million years than the Green River (Aslan et al.). Controversies involve when the Green became established as a south-flowing river (Pederson) and became integrated with drainage from the Colorado Rockies, and whether the different gradients reflect differential uplift of the Colorado Rockies relative to the central Colorado Plateau (Karlstrom et al.). However, if the Green River switched its flow direction from north- to south-flowing in the latest Miocene (Ferguson), that may allow the uplift rates to be roughly equivalent.

Where to "send" Miocene paleorivers. The longstanding question of where Miocene upper Colorado paleorivers may have exited, or terminated within, the Colorado Plateau is unresolved. One model is for internal drainage in the western Rockies until 6 Ma, separated by the Kaibab uplift from west-flowing Miocene paleorivers in western Grand Canyon (Wernicke; Hill et al.; but cf. Lopez Pearce et al.). In contrast, evidence from gravels in Wyoming suggests a possible north-flowing system in the Miocene (Ferguson). Alternatively, a south exit, along the Salt River system, was revived (Potochnik).

Pre–6 Ma paleocanyons and paleorivers. Numerous workers have proposed models by which pre–6 Ma paleocanyons on the southern Colorado Plateau may have become re-occupied and linked to evolve into the modern Grand Canyon. A possible west-flowing Miocene river is preserved along Crooked Ridge (Lucchitta et al.), and it may have fed into a system occupying the present location of eastern Grand Canyon (Lee et al.; Pederson) or the entire Grand Canyon (Wernicke), but the latter model, especially, is in conflict with the Muddy Creek constraint (Lucchitta). Geologic evidence argues against the existence of at least some of the proposed paleocanyons; for example, a precursor western Grand Canyon drainage (Hill et al.; Wernicke; Young, 2008) seems to be negated by the absence of Paleozoic detritus in detrital zircon populations in 13–6 Ma rocks of the Muddy Creek Formation near Pearce Ferry, suggesting these deposits could not have had detrital input from the Paleozoic strata of western Grand Canyon to the east (Lopez Pearce et al.).

An old Grand Canyon. The possibility of a Late Cretaceous (70 Ma) paleocanyon coincident with both the eastern and westernmost segments of the modern Grand Canyon, and cut to within 400 m of its present depth, was supported by a new interpretation of published thermochronology data (Wernicke). This was hotly debated by both thermochronologists (Kelley et al.; Lee et al.) and geologists (Karlstrom et al.), and provides a hypothesis that challenges other existing models and needs to be tested by more comprehensive thermochronologic and geologic datasets.

Integration mechanisms. Possible mechanisms of integration of the upper and lower

Colorado River basins across the Kaibab uplift include lake spillover (Douglass), piracy, headward erosion, and groundwater sapping involving karst connections. Different types of proposed groundwater and karst connections included: (1) ~6 Ma karst-piping of river waters from the upper basin, under the Kaibab uplift (Hill et al.); (2) upper basin drainage through paleocanyons to a seepage-integration point in central-western Grand Canyon region (Pederson); and (3) groundwater sapping from locally sourced groundwater (not upper basin river water) where hydrologic head facilitated incision and integration, while geochemical signals of local groundwater were preserved (Crossey et al.). Simple headward erosion as a dominant integration mechanism was supported by some (Hill et al.) as was piracy and integration of existing drainage systems by a top-down process (Douglass). The striking similarity of detrital zircon populations in the modern river delta to 5.3 and 4.4 Ma Colorado River deposits (Kimbrough et al.) suggests a top-down integration because headward erosion would be predicted to show progressive changes in detrital populations through time in the river's lower reaches and delta, which are not observed. In addition, thermochronology data for rapid onset of denudation at about the same time in several places across the region (Hoffman et al.) are hard to reconcile with headward erosion models.

Lake Bidahochi. The size and significance of a paleo "Hopi Lake," or "Lake Bidahochi" and the depositional setting for the Bidahochi Formation were debated and several models were presented. (1) This Miocene basin was a terminal, internally drained depression for southward flowing river waters from the Rockies. (2) This lake system may have been a headwater lake for a regional northward flowing river that carried Rocky Mountain drainage into Wyoming (Ferguson), or drained into other hypothetical lakes near Lees Ferry (Hill et al.). Models for integration of the Colorado River driven by spillover from Lake Bidahochi were not strongly supported by facies analysis of the Bidahochi Formation, which suggests low sediment accumulation rates in a small lake (Pederson) where fluvial beds aggraded across a more limited lacustrine facies (Dickinson).

Drainage reversal. The concept of drainage reversal from the Paleocene to Eocene N- to E-flowing systems (including the paleo Salt River), to the post–6 Ma SW-flowing Colorado River system is now better constrained (Young and Hartman), but there was much discussion on the timing and mechanisms for this reversal. Tilting due to mantle-driven epeirogeny (Robert et al.; Karlstrom et al.) was discussed as a mechanism of drainage reversal as well as a possible driving force for river integration and propagation of knickpoints (Darling et al.).

Nature of knickpoints. The cause and significance of knickpoints and convexities seen in the longitudinal profiles of the Colorado River and its tributaries were discussed. (1) These features may be relatively fixed and pinned at less erodible rock layers or reaches, as documented by studies of bedrock strength properties along the river profile (Tressler et al.). (2) Alternatively (or in addition), they may be incision transients propagating upstream in response to downstream tectonic and/or geomorphic (e.g., piracy) events (Darling et al.). A process of diffuse knickpoint migration to bypass a bedrock obstruction (Cook et al., 2009) may help explain high incision rates above Lees Ferry (Hanks et al.; Marchetti et al.; Pederson). Mantle tomographic images suggest the possibility that the Lees Ferry knickpoint is caused by dynamic forcings due to mantle flow associated with a pronounced mantle velocity gradient (Karlstrom et al.; Karlsrom et al., 2012) that may help explain differential incision rates above and below Lees Ferry (Darling et al.).

Isostatic response to denudation. The relative roles of tectonic uplift and isostatic responses to denudation to drive rock uplift were discussed to explain differences in incision rates. By one model (Pederson et al.), calculated magnitudes of isostatic response to erosion were correlated with the pattern of faster Pleistocene incision rates in the central Colorado Plateau, suggesting that the isostatic feedback accounts for much of those amplified rates. A second model (Lazear et al.) suggested that the difference between river incision rates and calculated isostatic response to denudation over the last 10 Ma in the Grand Canyon and Rocky Mountains requires Neogene tectonic uplift components at both ends of the river system.

Timing and mechanisms of uplift. The timing and process of uplift of the surface of the Colorado Plateau and southern Rocky Mountains, from sea level in the late Cretaceous to modern high elevations, and the interactions of uplift, drainage development, and erosion (incision/denudation), remain the underlying questions. Paleoelevation data from clumped isotopes suggest that most uplift in the southwestern plateau was accomplished in the Laramide, and this model is paired with "old canyon" models (Wernicke). Thermochronology indicates Miocene cooling in eastern Grand Canyon (Lee et al.) about the same time as broad denudation across the southern plateau (Cather). This is consistent with various proposed mechanisms, including lithosphere delamination, conductive mantle heating, Farallon slab removal, and whole mantle flow (Robert et al.). Evidence for Neogene and ongoing mantle flow and resulting uplift can be paired with young canyon models (Karlstrom et al.). If onset of rapid denudation on the Colorado Plateau predated Colorado River integration at ~6 Ma, recent surface uplift and tilting seem required (Karlstrom et al.). Alternatively, if rapid onset postdated integration, then tectonic uplift would not be required to create a young Grand Canyon (Hoffman et al.).

New Developments and Future Research Directions

Directions for productive further research involve application of new methodologies and better integration of diverse datasets.

Detrital zircons. Further detrital zircon studies of all tributaries, and of paleo–Colorado River deposits in different places along the mainstem and tributaries may help resolve processes of integration and evolution of the Colorado River system.

Paleoaltimetry. There is continued need to develop and test paleobarometers to estimate absolute elevation changes through time and thus demonstrate any links between topographic changes and surface uplift events.

Drainage reversals. Geologic work is needed to evaluate the timing and locations of drainage reversals by studies of ages of terrace gravels and lake deposits.

Dates on old, high terraces. Additional work on the highest terraces of the Green and Colorado Rivers, southern Wyoming, and the Browns Park Formation offer potential to better document how and when the Colorado and Green Rivers became integrated and whether the steeper gradients in the Colorado River are due to rock uplift of the Rocky Mountains.

Thermochronology. Additional studies are needed to reconcile apatite fission-track ages and U-Th-He ages with each other and with other geologic constraints. Application of both techniques to the same samples needs to be done routinely. Additional discussion and cross-lab comparisons should be done to try to produce protocols and reduce uncertainty in how to interpret variable-age apatites from the same sample. It is important to apply thermal models to reduce uncertainty in estimating timing of onset of rapid denudation (the kink) in diffuse kinked age-elevation plots. For example, it is critical to resolve whether onset of rapid denudation in the Colorado Plateau areas was pre–6 Ma, in which case river integration is not the causative explanation, versus syn– to post–6 Ma, in which case a river integration explanation predicts an upstream younging of onset of rapid denudation (so far not observed).

Sediment budgets. Studies of sediment budgets should continue to be integrated with thermochronology to establish links between upland denudation events and downstream sediment volumes and major aggradation events.

Differential incision rates through time. Incision rate studies at all temporal and spatial scales are needed to evaluate evolution of river profiles through time. Precise dates, firm strath heights, and, ideally, depth to bedrock are needed to calculate reliable bedrock incision points. Strath-to-strath comparisons for a given reach are especially valuable to calculate bedrock incision rates independent of depth to bedrock in the river channel. Strath-to-strath age data are also needed to test changes in rates through time versus steady incision models.

Tectonic influences. Improved structural studies and models (e.g., Resor) are needed to provide better understanding of fault slip history, monoclinal fold formation, and possible eperiogenic doming or tilting. Structural studies need to be better integrated with incision and cooling/denudation (thermochronology) interpretations. Locations need to be sought (e.g., Lees Ferry and Grand Mesa regions) to integrate long-term incision rate data with age-elevation low T thermochronology data to merge denudation and incision rate data (in m/Ma).

Geodynamic models. Geodynamic models of mantle flow need to be tested against improved differential incision and differential denudation models.

Knickpoint migration. Geomorphic models of knickpoint migration also need to be tested against improved differential incision and differential denudation data.

Community database. A community effort is developing to produce improved databases on geochronologic, incision rate, and thermochronologic constraints for evolution of the Colorado River system. These need to be continually updated from new research.

3-D visualizations and animations. For visualization, building on graphic methods that evolved between the 1964, 2000, and 2010 meetings, portrayal of models should involve improved GIS-based paleogeographic maps, be tied to a detailed timeline, and be spatially referenced to updated comprehensive databases. This will lead to "movie(s)" of the evolving landscape tied to evolving lithospheric structure.

Outreach

In addition to the scientific goals, the meeting participants emphasized the iconic status of Grand Canyon for geosciences, and the importance of good communication between the research community, the geoscience education/interpretation community, the public, and the media. About 5 million visitors come to Grand Canyon each year, and most want to know how old it is and the processes that shaped it. The meeting promoted the awareness of the importance of our evolving research understanding in the eyes of the world. There is an important obligation to convey new research advances and educational resources involving the spectacular landscapes and field laboratories of the Colorado Plateau–Rocky Mountain region. We conclude that informal research meetings of the type conducted here provide exceptional research and public relations value for the geosciences.

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