

PALEORIVERS

Late Miocene Colorado River arrival in the Bidahochi basin supports spillover origin of Grand Canyon

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The timing and mechanism of the integration of the Colorado River and incision of the Grand Canyon remain among geology's enduring controversies. A key question is the configuration of the upper Colorado River watershed between 11 and 6 million years ago. In this study, we present new evidence from zircon uranium-lead geochronology for the arrival of distinctive Colorado–Green River sediment in the Bidahochi basin by 6.6 million years ago derived from the Browns Park Formation. This is coeval with an order-of-magnitude increase in depositional rate, an increase in carbonate strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios, the appearance of large fish species characteristic of fast-flowing waters, and other sedimentological changes. This evidence is consistent with the Colorado River supplying water and sediment to the Bidahochi basin before spillover integration of the river through the Grand Canyon.

Well-established constraints indicate that the Colorado River (CR) existed in western Colorado at 11 million years ago (Ma) (1) and first exited the Grand Canyon after 5.6 Ma (2–5). This begs the question, where was the CR in the intervening 5 million years? Thermochronology (6–9) suggests a multiphased Grand Canyon incision history. Older paleocanyons in the Grand Canyon region may have been carved by other river systems, but the CR must have crossed the Kaibab arch and at least partially carved the Grand Canyon at the time of integration. Hypotheses abound to explain how the river crossed the arch, including karst piping (10), groundwater connection or sapping (11–13), headward erosion (14–16), and lake spillover (17–19). Linked to these possible integration processes are a series of previously proposed pathways for the early CR, including courses in the subsurface subparallel to the modern CR and to the northwest (NW) and southeast (SE) (Fig. 1). Integration happened in a region that was likely experiencing post-6-Ma epeirogenic uplift (20, 21).

Lake spillover is well established as the process by which the lower CR integrated through a series of closed basins downstream from modern Lake Mead, reaching the sea (22) between 4.8 and 4.6 Ma (3). A similar process was proposed in the 1930s (19) for the CR as a whole: the linking of initially closed basins from the headwaters to the sea. The stratigraphic record for the paleolake upstream of modern Lake Mead is the late Miocene (7 to 6 Ma) upper member of the Bidahochi Formation (UBF), east of the Kaibab arch. Various depositional settings for the UBF have been proposed and include a playa-like environment

(23), a shallow lake that aggraded with alluvial deposits (24), or a fluctuating lake fed by the CR (17). Similarly elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in freshwater carbonates from the UBF and downstream CR-derived Bouse Formation suggest that the upper CR could have drained into the Bidahochi basin (17). However, other studies have rejected the overflow hypothesis, arguing that the sedimentation rate in the UBF was too low (25), that the lake was not high enough to overtop the Kaibab arch, and most critically, that its provenance is inconsistent with CR derivation (26, 27). We present evidence that contradicts previous arguments against the spillover hypothesis, based on new detrital zircon (DZ) provenance data, new U-Pb ages for volcanic ash beds in the UBF, and comparisons with known ancestral CR deposits.

New U-Pb ages for volcanic and detrital zircon in the UBF

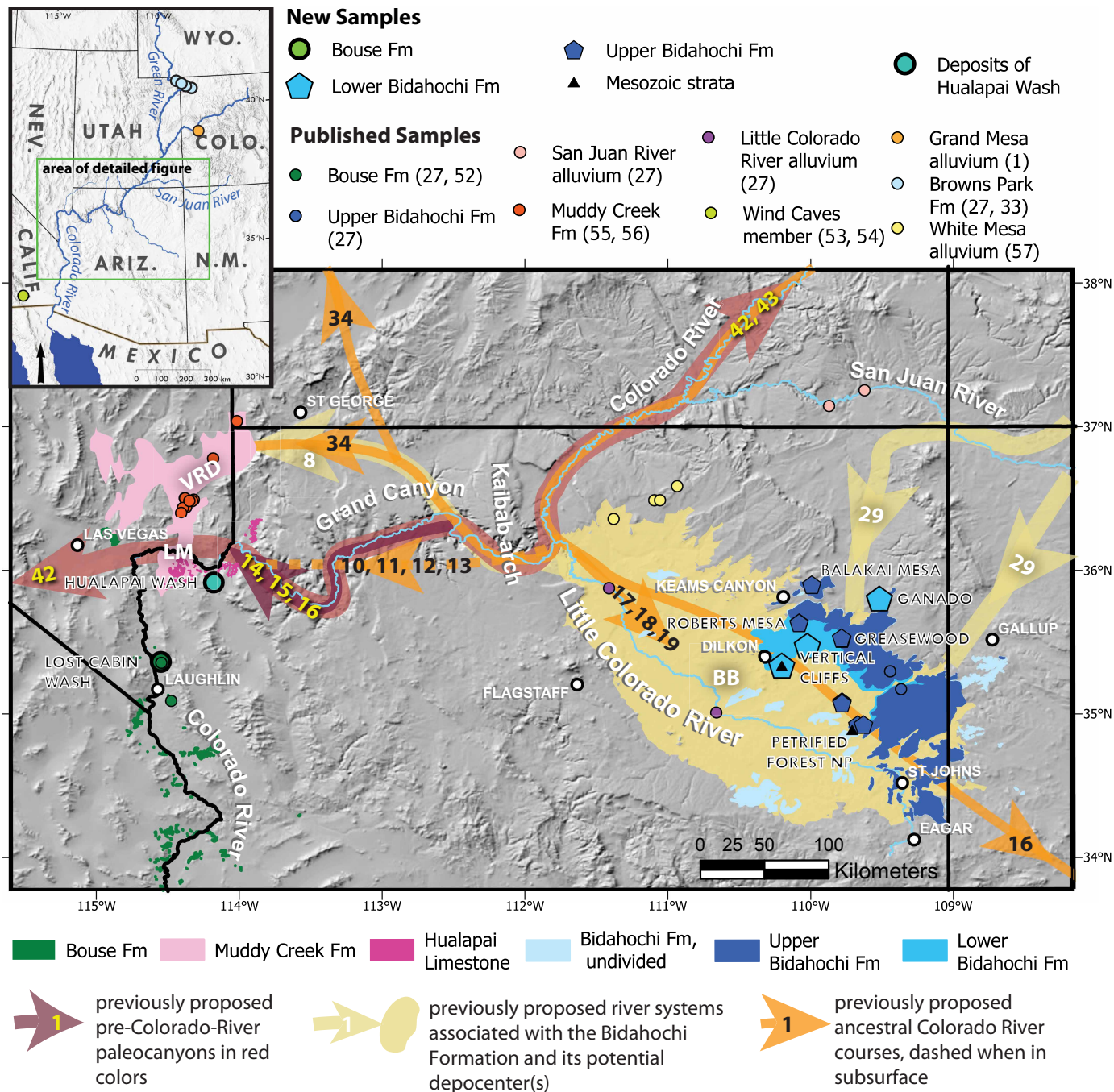
U-Pb dating of zircons from interbedded, silicic volcanic ash beds in the UBF (see materials and methods) was performed with an ion microprobe (fig. S1 and tables S2 to S4). At Roberts mesa (28) (Figs. 1 and 2), the youngest populations of $^{206}\text{Pb}/^{238}\text{U}$ dates in two variably reworked ash beds indicate depositional ages from stratigraphically lowest to highest of 6.53 ± 0.09 Ma (2 σ and hereafter) and 6.46 ± 0.15 Ma. At Greasewood mesa, the lowest ash bed in the UBF is correlated to the 6.62-Ma Blacktail Creek eruption on the basis of geochemical similarities (25), whereas a stratigraphically higher ash bed yields a $^{206}\text{Pb}/^{238}\text{U}$ date of 6.42 ± 0.08 Ma. At Ganado Mesa, the stratigraphically highest ash bed yields a date of 10.95 ± 0.10 Ma, indicating that at least a portion of the Ganado Mesa site is lower Bidahochi Formation (LBF), which was deposited between 16 and >7 Ma (25).

U-Pb dating of DZ grains ($N = 3596$) in 19 sandstone samples of the LBF, the UBF, the Bouse Formation, the deposits of Hualapai Wash, and underlying Mesozoic units (Figs. 1 and 2 and table S2) was performed by laser-ablation mass spectrometry. These $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ dates are reported in Fig. 3 (data S2 to S4). The youngest DZ grains in the UBF are 6.2 to 6.5 Ma, which is consistent with slightly younger maximum depositional ages of 6.07 ± 0.07 Ma from detrital sanidine dating (29). Detrital spectra show notable changes between the LBF and UBF. In particular, the large group of 40- to 25-Ma (Oligocene) DZ grains in the UBF is almost entirely absent in the LBF. In addition, the UBF and ancestral lower CR samples [e.g., Pliocene (~5.2 to 4.6 Ma) deposits of Hualapai Wash, Bouse Formation, and Wind Caves member of the Latrania formation (30, 31)] have prominent peaks in common at ~95, 170, 1100, 1450, and 1700 Ma. They also show more subtle similarities, including a small number of late Neoproterozoic (~650 to 550 Ma) and early Paleozoic (~450 to 400 Ma) grains, as well as a small number of 1900- and 2680-Ma grains (fig. S2). Lastly, both LBF and UBF samples generally share prominent 200-Ma peaks with the underlying Mesozoic units (32) that are less pronounced in ancestral CR units. Consistent with the above observations, a multidimensional scaling analysis of the DZ data with bootstrap resampling of compiled sample groups shows the pairwise dissimilarity between each group and the extent to which any dissimilarity may arise from sampling uncertainty alone (Fig. 4).

Colorado River source for the UBF

The occurrence of 40- to 25-Ma DZ grains in the UBF reflects the introduction of detritus from the upper CR watershed into the Bidahochi basin by ~6.6 Ma. This change in provenance is underscored by statistical comparison of UBF DZ spectra (Fig. 3A) with known ancestral lower CR deposits (Fig. 3, B and C), indicating that the UBF is far more like the lower CR deposits than the underlying LBF (Fig. 4). Previous regional compilations have demonstrated a DZ age distribution typified by Oligocene grains as being diagnostic of CR derivation (27). Oligocene grains were likely eroded from widespread ash deposits related to the San Juan volcanic field, such as those in the Browns Park Formation (33). This distinctive CR signature cannot be explained by other nearby 40- to 25-Ma volcanic sources such as the Mogollon-Datil

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Fig. 1. Map of the study area. Sample locations, pre-dam river courses, outcrops of key stratigraphic units, landforms such as the Kaibab arch, previously proposed courses of the ancestral CR, and previously proposed paleo canyons are shown. Previously proposed river pathways are labeled by the proposing reference (1, 27, 33, 52–57). See table S1 for more information on previously published samples. VRD, Virgin River depression; LM, Lake Mead; BB, modeled Bidahochi basin; Fm, formation (see supplementary materials). Shaded relief is from (58). Outcrop patterns are from (12, 17, 59).

volcanic field (fig. S3). Indeed, the paucity or absence of 40- to 25-Ma grains in both the present-day Little Colorado River DZ spectra and in the LBF precludes any proximal ash bed or volcanic rocks in the Bidahochi basin as likely sources of this peak in the UBF.

DZ evidence for the arrival of the CR at the Bidahochi basin by 6.6 Ma is corroborated by other stratigraphic and sedimentological evidence. Linear extrapolation of newly dated ash beds in the upper Bidahochi Formation (fig. S1) constrains depositional rates of 100 to 400 m/Ma, a dramatic increase from 10 to 20 m/Ma for most of the LBF (17, 25)

(Fig. 2) and consistent with the arrival of a major new sediment source. Elevated $^{87}\text{Sr}/^{86}\text{Sr}$ isotope values in carbonates of both the UBF (Fig. 2) and downstream Bouse Formation also suggests that CR water drained into the Bidahochi basin by the late Miocene (17). Strata in the UBF transitions from dominantly green-gray silt-claystones at the base of the unit to laterally continuous, tabular sandstones at the top (Fig. 2), as occurs in the deltaic sequences of the Bouse Formation. This and other features (fig. S4) further support the existence of a CR-fed lake in the Bidahochi basin.

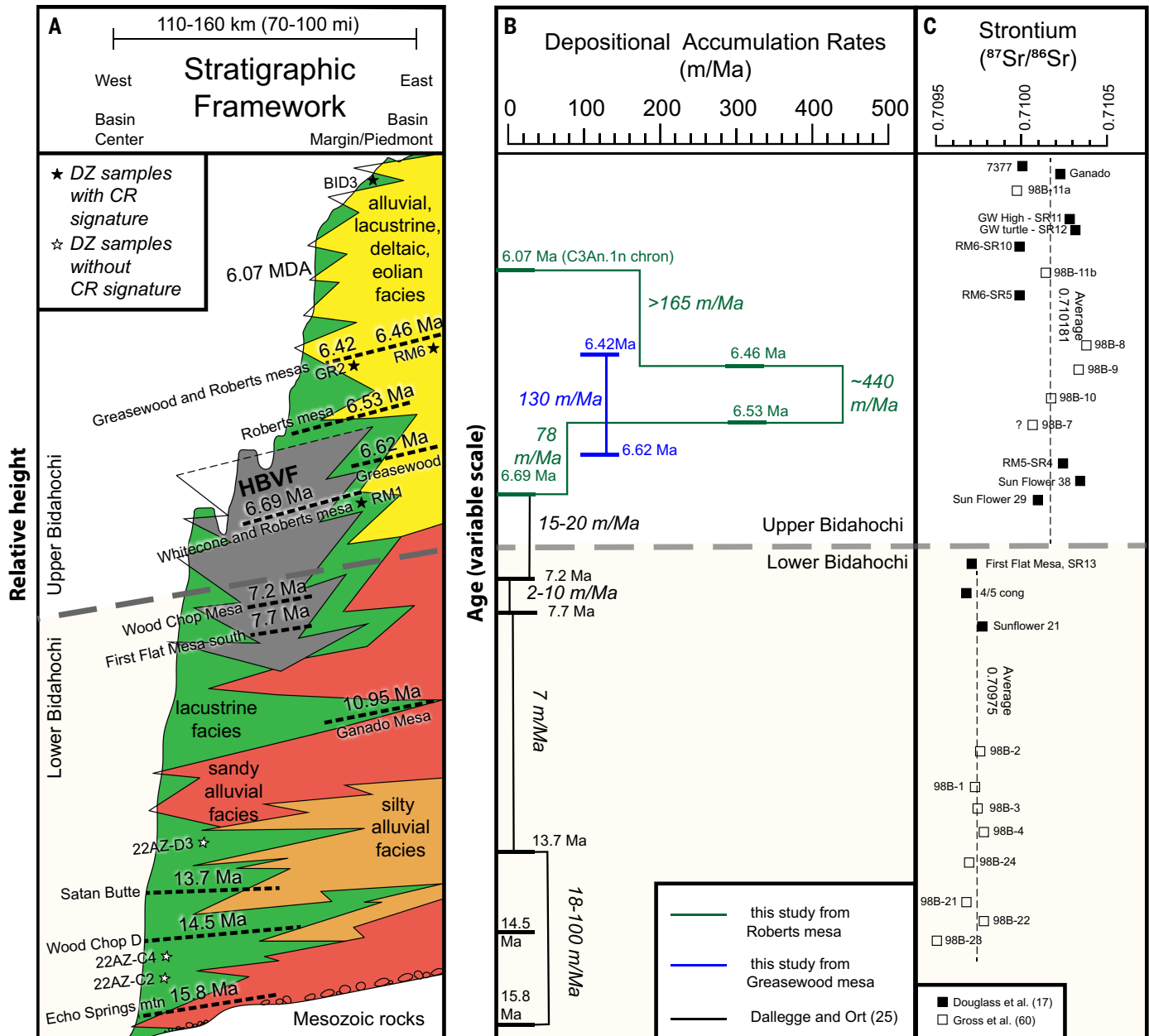


Fig. 2. Schematic stratigraphic column for the Bidahochi Formation. This figure was adapted from Douglass *et al.* (17). (A) Facies variation from the basin margin to the center and the stratigraphic position of dated ashes are shown as bold dashed lines. Detrital zircon (DZ) samples with and without CR signatures (i.e., presence of 40- to 25-Ma grains) are shown as filled and open stars, respectively. Southern samples (from Petrified Forest National Park) are not shown on this stratigraphic framework; some sample numbers are abbreviated. (B) Depositional rates from this study and from (25). (C) Summary of past work, showing changes in $^{87}\text{Sr}/^{86}\text{Sr}$ isotope values (17,60) within the Bidahochi Formation. HBVF, Hope Buttes volcanic field; MDA, maximum depositional age.

Implications for the broader CR paleodrainage network:

We also compared the UBF to (i) upstream deposits and sources (Fig. 5), including the ~11-Ma CR alluvium at Grand Mesa in Colorado, the 25- to 8-Ma Browns Park Formation and the San Juan River (29), as well as (ii) other proposed potential Miocene CR depocenters such as the Virgin River depression (34) (Fig. 1). DZ analyses of Pliocene ancestral San Juan River deposits are not available, but comparison to Holocene deposits shows considerable discrepancies, including a much larger proportion of late Neoproterozoic, early Paleozoic, and Archean grains and no DZ peak at 35 Ma, despite the presence of ~35-Ma detrital sanidine grains (29), as expected.

Notably, a striking similarity between the DZ signature of the Browns Park Formation and the UBF (Figs. 3 and 4) raises the possibility of a Green River connection and connections to the late Miocene Yellowstone–Snake River Plain magmatic centers, which formed a transient northeast-to-southwest trending topographic high and a likely drainage divide (35) (Fig. 5). Identical late Miocene detrital signatures are present in graben-filling strata both southeast and north of late Miocene volcanic centers [Browns Park and Sixmile Creek Formations (33, 36)]. If the isotopically juvenile population of late Miocene zircons in the UBF (with ϵHf up to +7; mantle-like oxygen fugacity estimates near the fayalite-magnetite-quartz buffer; U/Yb ~1)

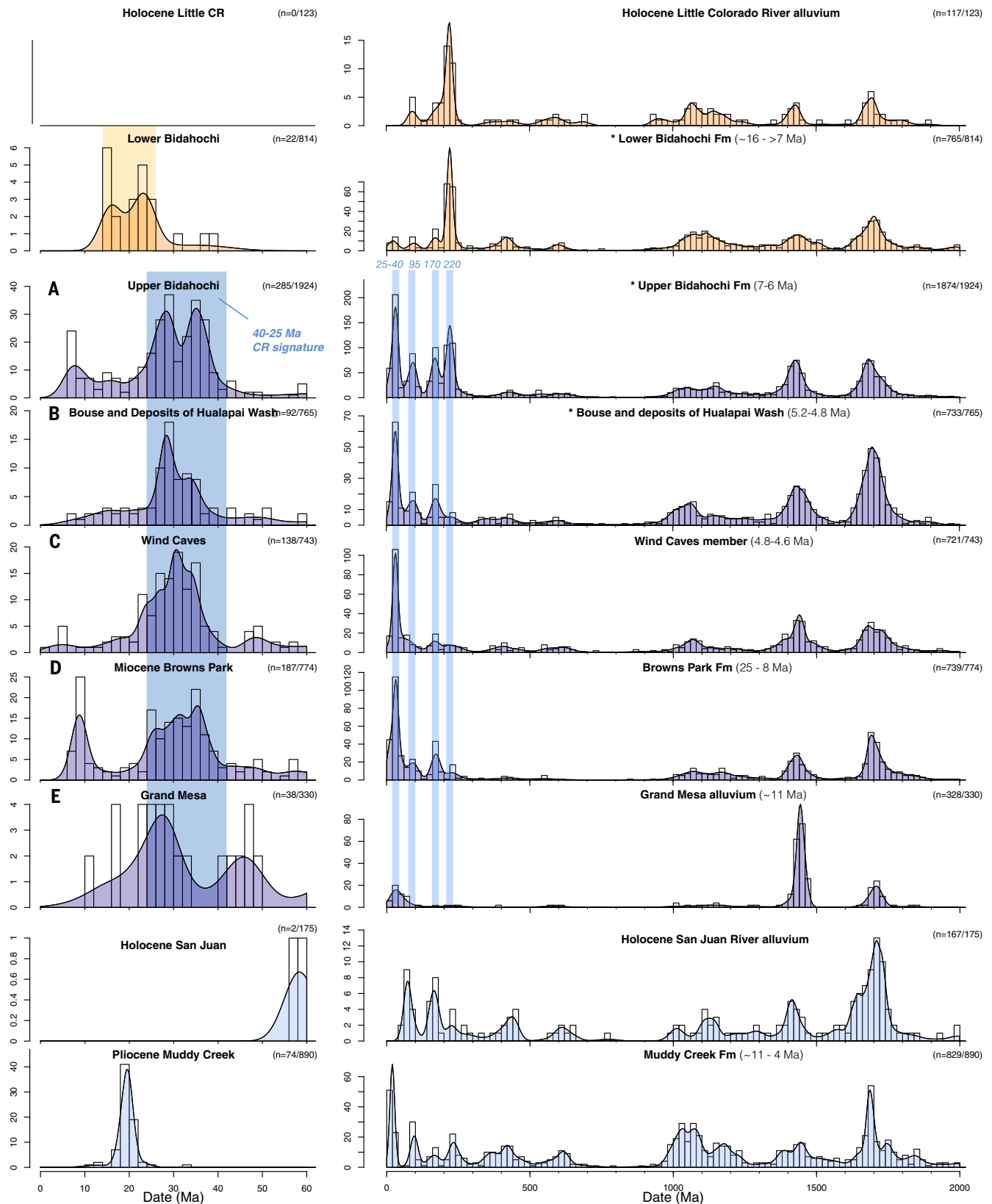


Fig. 3. Histograms and adaptive kernel density estimates of compiled DZ U-Pb age spectra. Compilations including new data from this study are indicated with *. An aggregate of DZ analyses from the Bidahochi Fm is shown with early Pliocene ancestral CR deposits from the lower CR (i.e., Bouse Fm and the deposits of Hualapai Wash) and other proposed CR depocenters. Histograms bins are 2 and 20 Ma (left and right panel, respectively). For ease of reference, lettered spectra [(A) to (E)] correspond to the same labels in Figs. 4 and 5. Data older than 2000 Ma are shown in fig. S2. See tables S1 and S2 for details about the compiled samples. Colors group together samples with similar DZ signatures.

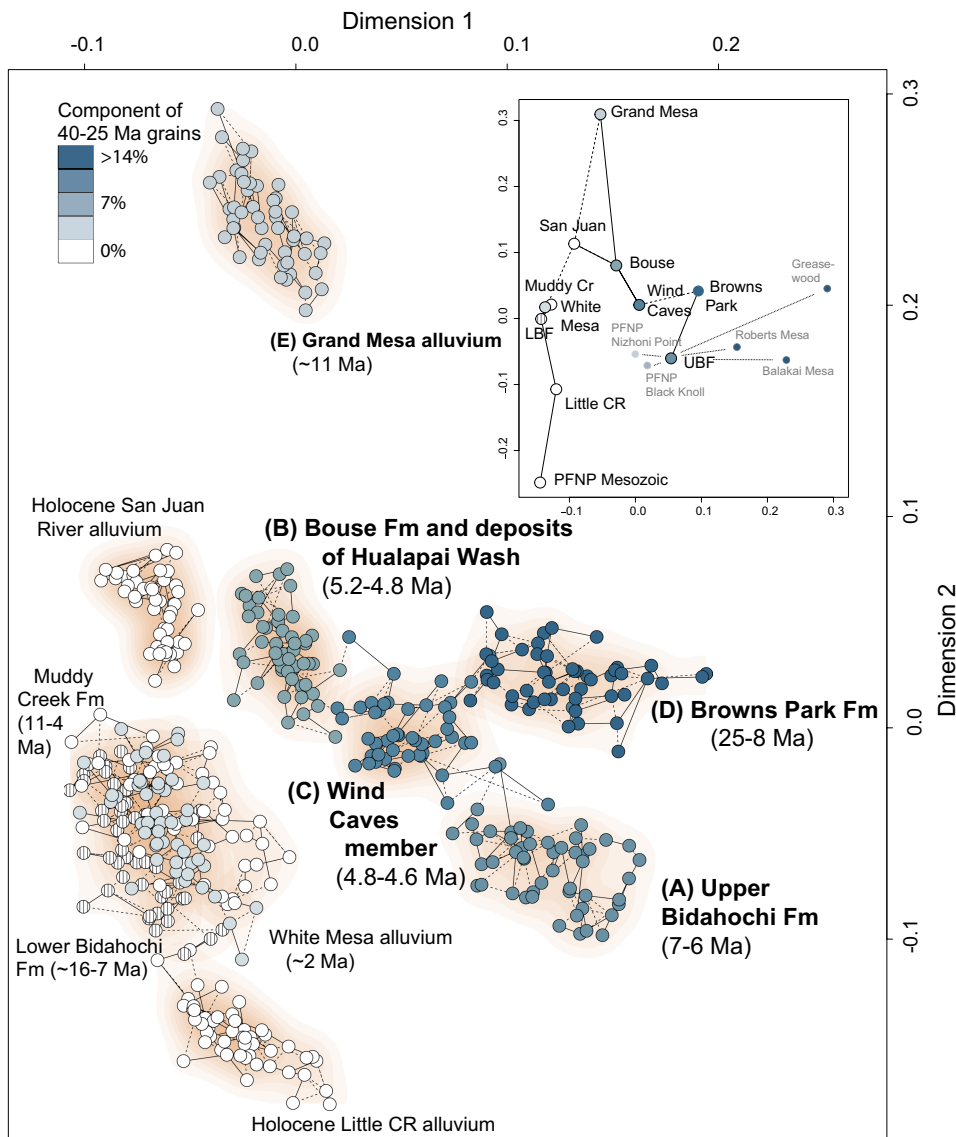


Fig. 4. Nonmetric multidimensional scaling (MDS) analysis showing the dissimilarity between sample groups (61). To characterize the sampling uncertainty, we used a bootstrap resampling procedure to generate 50 random synthetic samples from each sample group (see materials and methods for details). The critical 40- to 25-Ma signature is indicated by the color scale. Known deposits of the CR, including the Bouse Fm, deposits of Hualapai Wash, and Wind Caves member are at the center of the plot. The UBF and Browns Park Fm are closely related to these ancestral lower CR deposits, whereas the Lower Bidahochi (vertically hatched symbols, LBF), Muddy Creek, and White Mesa alluvium are statistically indistinguishable. Orange contours show the density heat map of each sample group. (Inset) The MDS analysis of the compiled sample groups without resampling. Solid and dashed lines show the nearest and second nearest neighbors, respectively.

were sourced from these volcanic centers, rather than proximally from the mafic, nephelinitic Hopi Buttes volcanic field, then this would suggest >800 km of fluvial transport (fig. S5). This possibility is underscored by the trace presence (<3%) of 8- to 6-Ma isotopically juvenile zircons (ϵ_{Hf} up to +6 even in rhyolites) sampled from a borehole through the Twin Falls Caldera (37), which have mantle-like oxygen fugacity estimates and $\text{U}/\text{Yb} < \sim 1$ (38), matching the late Miocene UBF DZ grains. The greater similarity between the CR spectra and Browns Park Formation compared with the Grand Mesa alluvium also suggests that the former may have been the dominant tributary.

The new detrital evidence for the late Miocene Snake River Plain–Green River–CR connection presented here is bolstered by the faunal

similarity between fossil fish species in the UBF and species from the Snake and Sacramento Rivers and the CR (39). The size (as long as 75 cm), enlarged fins, and narrow tail fin base of fish specimens from the UBF suggest fast-moving fluvial habitats (39). Spencer and others' analysis of fish genetic diversity refuted a connection between the ancestral CR and the Rio Grande (16). That idea is also contradicted by the lack of deposits indicating southeast flow in the Little Colorado River valley before the Bidahochi deposition (13). Multiple independent lines of evidence thus suggest that the river system feeding Bidahochi lake included captured paleo Snake River tributaries via the ancestral Green River, rather than solely the San Juan River.

Others suggested that the ancestral CR flowed northwest (34) and deposited the 11- to 4-Ma (12, 40) Muddy Creek Formation in the Virgin River depression and also that the Bidahochi lake drained into these basins (8) (Fig. 1). Although the DZ grains from the UBF show many similarities with the Muddy Creek Formation, the sedimentology of the Muddy Creek Formation and a lack of Oligocene San Juan–derived DZ grains are not consistent with an ancestral CR source and support instead a Virgin River source (12, 40). An earlier, ~15-Ma connection from the Bidahochi basin to the Virgin River depression (8) may have been possible because the LBF has a broadly similar DZ signature to the Muddy Creek Formation, although the Muddy Creek Formation has fewer ~200-Ma grains and a broader Miocene peak. The paleotopography necessary to link the two basins is speculative, however. If a paleocanyon linked the two, it must have been disrupted before UBF time because sediment of that provenance is not known in the Muddy Creek Formation. The first deposits in the Lake Mead region with a clear CR signature are the ~5.2- to 4.6-Ma deposits of Hualapai Wash and the downstream Bouse Formation and Wind Caves member.

Spillover of Bidahochi lake

New DZ and other evidence for CR sediments arriving in the Bidahochi basin warrants a reevaluation of the spillover

hypothesis. Topographic constraints are consistent with a CR-fed lake spilling over into the Grand Canyon. Remnants of the UBF are found at a modern elevation range from 1805 to 2250 m (24). The highest known deposits, interpreted to include beach sand, beachrock, and capping tufa, indicate a paleowater surface (41). Detailed stratigraphic analysis has shown that horizontal contacts between members remain flat toward the west, which is consistent with lacustrine deposits that would have overlapped against the basin's western topographic barrier (25), the Kaibab arch. The estimated elevation of the sill along the Kaibab arch, assuming minor relative topographic changes since the Miocene, would have been roughly 2300 m, based on the highest point along the south rim of the Grand Canyon.

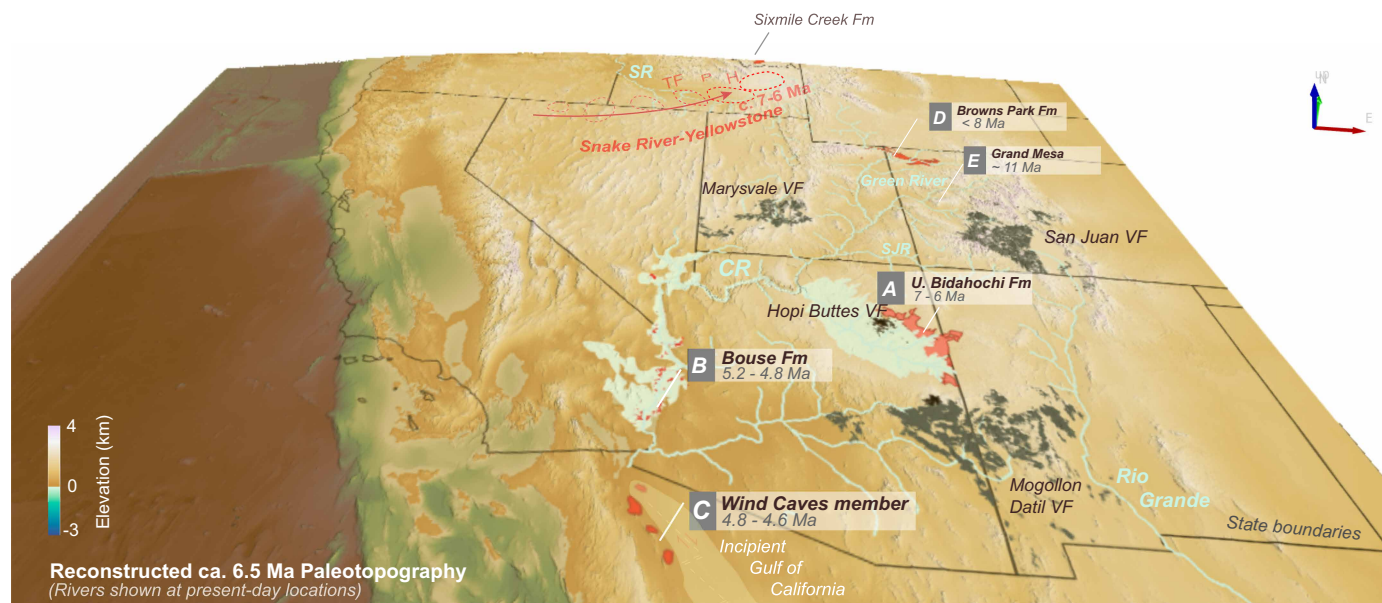


Fig. 5. Visualization of paleotopography at ~6.5 Ma. Visualization was reconstructed with a modern digital elevation model and published western North America strain fields and elevation restoration (62), with a superimposed dynamic topographic bulge at the locus at the Snake River–Yellowstone hotspot around this time (35). The location of the Wind Caves member shown in this figure accounts for large strike-slip translation from its current-day position in southern California, but the relative position of the bulk of the CR drainage system has likely not changed markedly over the past ~6.5 million years. The projection of the shaded perimeters of the various paleolakes (6.5 to 4.6 Ma) on the same paleogeographic time frame does not imply that they existed or reached those maximum extents simultaneously; extant outcrops of Bidahochi Formation and other deposits are shown in red polygons. Bold letters [(A) to (E)] correspond to labeled spectra in Fig. 3. Annotated ages indicate time of CR arrival. TF, Twin Falls volcanic field; P, Picabo volcanic field; H, Heise volcanic field; SJR, San Juan River; SR, Snake River.

Thermochronology data collected in this area have been used as evidence for the existence of a paleocanyon before integration (6–9), with speculation about associated river system(s) (8, 18, 42, 43). Our study does not directly address whether such a paleocanyon existed. A possible paleocanyon notching the Kaibab arch or a north-facing scarp (17) may have localized incision in the middle of the southeastwardly plunging arch as opposed to lower areas down plunge. Notching of the Kaibab arch post-6-Ma uplift (20, 21) and/or erosion can easily account for the small elevation difference between the sill and the highest strata of the UBF. Thus, arguments that Bidahochi lake was not high enough to overtop the Kaibab arch (26) are not supported (17).

Furthermore, these considerations assume minor relative topographic changes over the past 6 million years. If the Bidahochi basin was not a passive topographic low, but dynamically responded to the removal of gravitationally unstable lower lithosphere, the hypothesized local subsidence and uplift (20, 44) would explain (i) the gradual formation of a low that the developing CR flowed into, (ii) transient subsidence that slowed overfilling of the basin, and (iii) subsequent rebound and basin inversion that aided lake overflow.

Available geochronology from both new and published detrital mineral studies (27, 29) and from dating of ashes interbedded (25) in the UBF constrains flow of the CR into the Bidahochi basin as continuing until at least ~6 Ma. Arrival of CR sediment to the Lake Mead area and the lower CR corridor did not occur until after 5.6 Ma (2) and possibly as recently as 4.8 Ma (3, 5), the time of deposition of the Bouse Formation and integration to the proto Gulf of California. This suggests a 1.2- to 0.4-Ma lag between the arrival of the CR to the Bidahochi basin and to depocenters downstream from the Grand Canyon. This lag is much greater than the $\pm 100,000$ (2 σ) errors on geochronologic constraints. Modern sedimentation rates in Lakes Powell and Mead suggest that the Bidahochi basin could have filled with sediment in ~100,000 to 200,000 years (see supplementary materials) (25). However, in the Miocene, lower sedimentation rates (which are consistent with the relatively low local accumulation rates in Fig. 2) would

have been expected, compared with those driven by the more variable and erosive climate conditions since the Pliocene (45). The factors contributing to the change in climate and erosion rates include the opening of the Gulf of California ~10 to 4 Ma (46, 47), increased orographic-induced moisture from the uplift of the Rocky Mountains, and a Mio-Pliocene cooling climate that increased snowpack in the Rockies (48, 49).

Whereas a lake spillover is perhaps the simplest mechanism to establish the course of the CR through the Grand Canyon, aided by cliff scarps and a possible paleocanyon, other processes may have contributed. A similarity in ages between the 16- to 6-Ma Bidahochi Formation and the 13- to 6-Ma spring-fed Hualapai Limestone (11) could indicate a long-lived hydrologic connection facilitated by karst flow (10), but karst piracy seems improbable given the lack of analogous linear collapse features in the Grand Canyon region involving the main karst unit, the Redwall Limestone, which is generally more than 600 m deep. Headward erosion (14–16) is not supported because of the lack of Colorado Plateau detritus in the Miocene deposits at the mouth of the Grand Canyon (11, 50). Groundwater sapping is likely to have contributed to drainage reorganization during integration (11) but cannot be the sole process over the entire length of the Grand Canyon, which would also be a headwater-directed mechanism that would produce Colorado Plateau detritus. Lake spillover, which occurs globally (51), is the well-established mechanism for integration of the CR below the Grand Canyon (22) and now seems to have played a critical role through the Grand Canyon reach as well. It is notable that lake spillover would have established the route of the river, allowing the initiation of new fluvial incision, but catastrophic flooding during that process is not necessarily invoked as contributing substantially to canyon deepening.

More broadly, these results document the importance of downward integration in the establishment of continental-scale river systems and are consistent with the debated hypothesis that dynamic subsidence and uplift could have contributed to the post-6-Ma incision of the Grand Canyon, driving ecological and environmental changes across the western United States.

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ACKNOWLEDGMENTS

New observations from the upper Bidahochi Formation drew from the insights of A. Cohen, whose careful study of paleolakes made lasting contributions to the fields of paleolimnology, sedimentology, and paleoecology. Assistance in the field was provided by S. Skotnicki. The manuscripts benefited from discussions with L. Staisch, S. Beard, L. Walkup, S. Cather, A. Aslan, M. Heizler, and K. Karlstrom and reviews by T. Lawton, W. Holt, J. Spencer, and one anonymous reviewer. We are grateful for the assistance of A. Rasmussen, M. Pecha, and the entire team at the Arizona LaserChron Center. We thank Petrified Forest National Park and the Navajo Nation for permission and permits to conduct research. Any person(s) wishing to conduct geological investigations on the Navajo Nation must first apply for, and receive a permit from, the Minerals Department, P.O. Box 1910, Window Rock, AZ 86515, and telephone no. (928) 871-6587. **Funding:** This work was supported by the National Cooperative Geologic Mapping Program; the Council on Research of the Los Angeles Division of the University of California Academic Senate; NSF-EAR 2048656 to P. Kapp and P. G. DeCelles; the Arizona Geological Survey; and NSF-EAR 2050246 to the University of Arizona LaserChron Center. **Author contributions:** Conceptualization: J.D., B.F.G., R.S.C., J.J.Y.H., P.A.P., P.K.H., S.D.; Analytical methodology and supplemental text: C.S.H.-D., J.A.V., M.I.L., L.S.P., J.J.Y.H., H.G.; Visualization: J.J.Y.H., R.S.C.; Funding acquisition: R.S.C., J.J.Y.H.; Project administration: R.S.C., J.J.Y.H., J.D.; Field work: J.D., B.F.G., R.S.C., J.J.Y.H., P.A.P., P.K.H., S.D., E.H.; Writing – original draft: R.S.C., J.J.Y.H., J.D., J.A.V., B.F.G., P.A.P., P.K.H. **Competing interests:** The authors declare that they have no competing interests. **Data, code, and materials availability:** All data are available in the main text and the supplementary materials. USGS-funded analyses are also reported in (63). USGS-collected samples not destroyed by analysis are currently housed in the Flagstaff office in case of future need. Detrital zircon mounts for samples with the prefix “JH” are stored at the Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, with data also available in Excel format at UCLA Dataverse (64). **License information:** Copyright © 2026 the authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original US government works. <https://www.science.org/about/science-licenses-journal-article-reuse>

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adz6826
Materials and Methods; Supplementary Text; Figs. S1 to S8; Tables S1 to S5; References (65–90); Data S1 to S4

Submitted 10 June 2025; accepted 23 February 2026

10.1126/science.adz6826



Late Miocene Colorado River arrival in the Bidahochi basin supports spillover origin of Grand Canyon

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Science **392** (6795), . DOI: 10.1126/science.adz6826

Editor's summary

The Colorado River has not always flowed through the Grand Canyon area, and it is not known when and how that relationship began. He *et al.* collected uranium-lead ages for thousands of zircon crystals in formations located upstream and downstream of the canyon. Age patterns revealed a “fingerprint” of Colorado River sediment suggesting its arrival into an upstream lake by 6.6 million years ago and its subsequent integration with the Grand Canyon and downstream catchment. The direct connection may have happened through a combination of processes, but the zircon data give support to a long-debated “lake spillover” hypothesis. —Angela Hessler

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