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Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons

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The timing of formation of the Grand Canyon, USA, is vigorously debated. In one view, most of the canyon was carved by the Colorado River relatively recently, in the past 5–6 million years. Alternatively, the Grand Canyon could have been cut by precursor rivers in the same location and to within about 200 m of its modern depth as early as 70–55 million years ago. Here we investigate the time of formation of four out of five segments of the Grand Canyon, using apatite fission-track dating, track-length measurements and apatite helium dating: if any segment is young, the old canyon hypothesis is falsified. We reconstruct the thermal histories of samples taken from the modern canyon base and the adjacent canyon rim 1,500 m above, to constrain when the rocks cooled as a result of canyon incision. We find that two of the three middle segments, the Hurricane segment and the Eastern Grand Canyon, formed between 70 and 50 million years ago and between 25 and 15 million years ago, respectively. However, the two end segments, the Marble Canyon and the Westernmost Grand Canyon, are both young and were carved in the past 5–6 million years. Thus, although parts of the canyon are old, we conclude that the integration of the Colorado River through older palaeocanyons carved the Grand Canyon, beginning 5–6 million years ago.

Geoscientists have debated for almost 150 years how and when the Grand Canyon formed. Recent studies supporting the 'old' canyon model[1–4] suggest that an east-flowing California palaeoriver 80–70 million years ago (Ma), then a west-flowing Arizona palaeoriver 55–30 Ma, incised a canyon in the same location and of a similar 1.5 km depth to the modern Grand Canyon; then much later, this abandoned palaeocanyon was re-used opportunistically by the west-flowing Colorado River as drainage became integrated to the Gulf of California. In this hypothesis, the 'Colorado River did not play a significant role in excavating Grand Canyon' (ref. 1, p. 1312). In contrast, most 'young' canyon models suggest that much of the Grand Canyon was carved by the Colorado River since the time of its integration 5–6 million years ago[5–9].

Our goal here is to integrate geological and thermochronological data to test and reconcile conflicting models for the age of Grand Canyon. Apatite fission track (AFT) thermochronology provides cooling constraints for temperatures of 60–110 °C (ref. 10), which overlap with constraints from apatite (U–Th)/He (AHe) dating for temperatures of 30–90 °C (refs 11,12). These temperatures can be related to burial depths of 1–5 km, depending on the assumed geothermal gradients and surface temperatures, and thus provide constraints on when rocks cooled owing to canyon incision. Here we discuss four segments of Grand Canyon (Fig. 1, inset): Marble Canyon, Eastern Grand Canyon, Hurricane fault segment and Westernmost Grand Canyon. We have no data from Muav Gorge, so it is not discussed.

Our thermochronological interpretations rely mainly on samples that have been dated using both AFT and AHe systems and their joint inversion via thermal modelling[9]. These data constrain a sample's permissible time–temperature path from ~110 to 30 °C (ref. 13). Assuming that palaeo-isotherms at 1–2 km depths were subparallel to palaeotopography[14] provides a test of whether palaeocanyons existed at higher stratigraphic positions directly above modern Grand Canyon. Samples from the modern rim and canyon bottom should have been at similar temperatures when an overhead palaeocanyon existed, but at different temperatures (corresponding to the geothermal gradient) for intervals when no overhead palaeocanyon existed. This paper compares the key AFT, AHe, and ^{4}He/^{3}He data (Supplementary Table 1) for each segment and reports new AFT and AHe data for the debated Westernmost Grand Canyon.

We also apply the geological test that palaeorivers must have flowed down plausible topographic gradients within the hypothesized palaeocanyon systems. Our combined tests falsify the 'old canyon' hypothesis that a continuous 1.5 km deep palaeocanyon followed the path of the modern Grand Canyon and was cut to near-modern depths by 55 Ma (refs 1–4). Instead, our palaeocanyon solution reconciles all datasets and shows that different segments of the modern Grand Canyon had different histories and became linked together by the Colorado River after 5–6 Ma to become the modern Grand Canyon.

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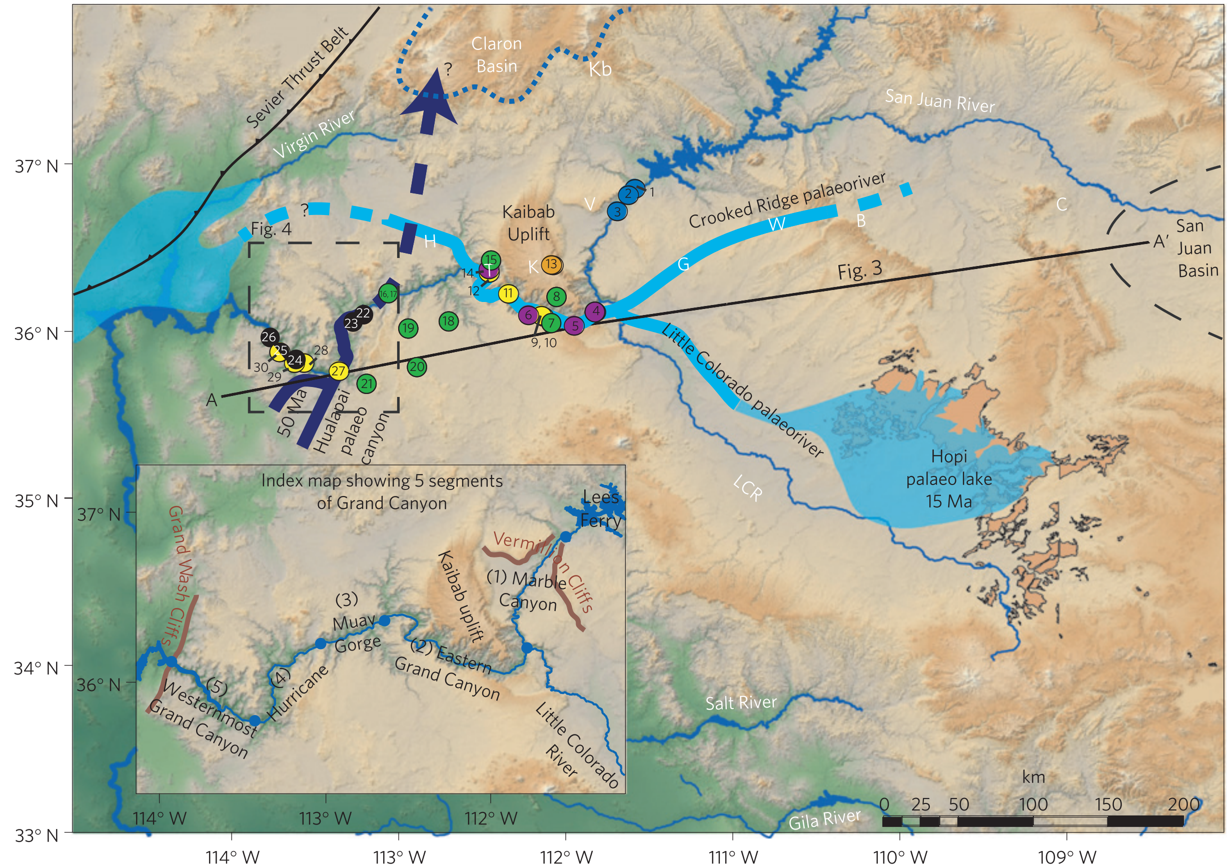

Figure 1 | Map of Grand Canyon. Inset shows segments: (1) Marble Canyon; (2) Eastern Grand Canyon; (3) Muav Gorge; (4) Hurricane fault segment; and (5) Westernmost Grand Canyon. Main map shows inferred drainage at ~15 Ma; B, Black Mesa; C, Chuska Mountains; G, Gap; H, Hack Canyon; K, Kaibab Uplift; Kb, Kaiparowitz Basin; T, Tapeats Creek; V, Vermillion Cliffs; W, White Mesa. Thermochronology samples (Supplementary Table 1): purple, joint AFT and AHE for river-level samples[9]; yellow, river-level samples[2,3]; orange, Kaibab Uplift sample[2,4]; green, rim samples[9]; black, new models. Cross-section line (A–A′) for Fig. 3 is shown.

<6 Ma age of Marble Canyon segment

AFT ages from Marble Canyon range from 39 to 28 Ma; AHe ages range from 20 to 6 Ma (Supplementary Table 1). The AFT data alone indicate that all Marble Canyon river-level samples east of the East Kaibab uplift were at temperatures > 110 °C until ~40 Ma (ref. 15). Converting a thermochronology-derived temperature to depth has appreciable geologic uncertainty, but for our purposes here we assume a range of geothermal gradients of 20–25 °C km^{-1} and a range of surface temperatures of 10–25 °C (Supplementary Table 2). Thus, before 40 Ma, river-level samples were beneath 3.4–5 km of rock. When AFT and AHe data are jointly modelled[9] (Fig. 2a), they constrain the rocks currently at river level to have resided at ~60 °C until times in the range 20 Ma (sample 3) to 6 Ma (sample 1). Marble Canyon was an explicit part of both the hypothesized 70 Ma California and 55–30 Ma Arizona palaeoriver systems (ref. 1, p. 1301); however, thermochronologic data provide no evidence for an 'old' palaeocanyon and refute the model of an 'old' palaeocanyon cut to near modern depths. Instead, Marble Canyon was carved after ~6 Ma (ref. 9; Fig. 2a) and is a 'young' segment of Grand Canyon.

25–15 Ma Eastern Grand Canyon segment

The Eastern Grand Canyon segment yields AFT ages for river-level rocks of 49–47 Ma and AHe ages of 66–19 Ma. River-level rocks are constrained by joint inversion of AFT and AHe (Fig. 2b, samples 4,5,6; ref. 9) to have cooled slowly from 90 to 70 °C between 60 and 25 Ma, followed by rapid cooling starting ~25 Ma. The shortened AFT track lengths of 11.1–12.7 μm (refs 15,16; Supplementary Table 1) and the variable effective uranium concentrations and AHe data constrain temperatures to be within the AFT partial annealing zone (110–60 °C) from 60 to 25 Ma. AHe-based constraints[9] for rim samples (samples 7,8) that are 1.5 km above river samples also suggest slow cooling from 60 to 25 Ma, but with the rim persistently ~30 °C cooler than river samples. This indicates a geothermal gradient of ~20 °C km^{-1} between these sites from 60 to 25 Ma and therefore that no overhead palaeocanyon existed before ~25 Ma. The 90–70 °C constraints indicate that rocks currently at river level were 1.8–4 km deep from 60 to 25 Ma and that this segment was not carved to near modern depths by 70–55 Ma (refs 1–3). Our models (Fig. 2b) show that rim and river cooling paths converge by ~20 Ma despite their 1.5 km difference in elevation. This provides evidence that a ~1.5 km-deep palaeocanyon was carved 25–15 Ma, which we call the East Kaibab palaeocanyon.

A separate study used ^{4}He/^{3}He and AHe data (Fig. 2c, samples 9–12; refs 3,4). The resultant cooling paths (Fig. 2c) were interpreted as supporting the carving of a 70–50 Ma eastern palaeocanyon (ref. 4, p. 143C) on the basis of the permissive overlap (orange) of river level (yellow) with Kaibab uplift (red) thermal history envelopes. However, this Kaibab uplift sample is less suited to test palaeocanyon models, as it is farther removed from the rim of Grand Canyon. Also, a more recent AHe-based Kaibab Uplift constraint (sample 13, Fig. 2c; ref. 4) requires rim temperatures to have been 15–20 °C hotter than the best fit ^{4}He/^{3}He model for the closest river-level samples from 70 to 40 Ma (Fig. 2c). This is geologically unreasonable given the Kaibab uplift sample resided 1.6 km higher than river samples throughout this time (ref. 1, p. 1297). The original

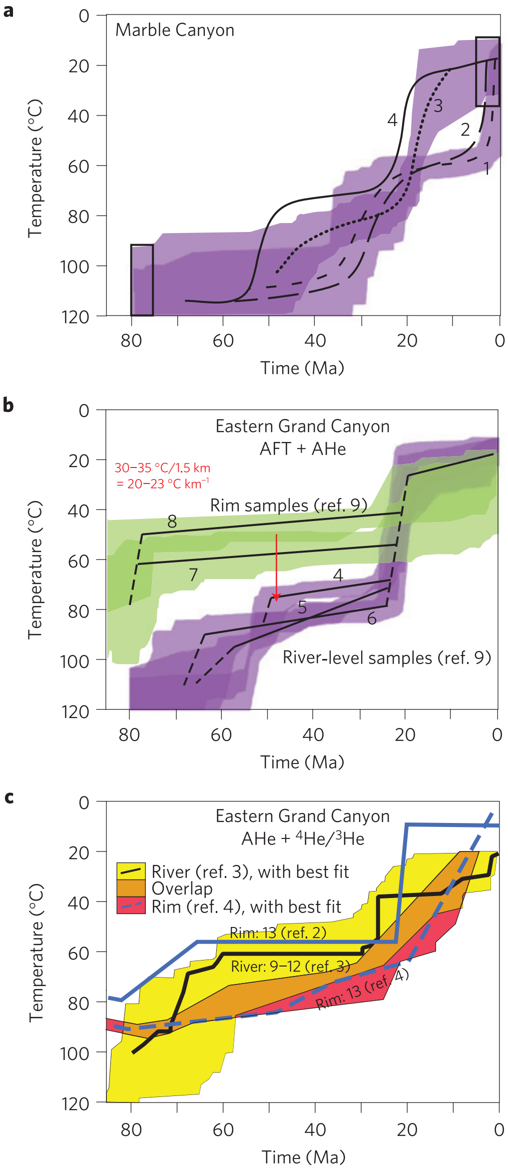

Figure 2 | Thermal constraints. **a**, Marble Canyon samples 1–4 show cooling ages decreasing upstream and canyon carving at Lees Ferry after 6 Ma. **b**, AFT/AHe constraints[9] from adjacent river-level (samples 4–6) and rim (samples 7–8; AHe only) samples show no palaeocanyon from 70 to 25 Ma and carving of East Kaibab palaeocanyon at 25–15 Ma. **c**, $^4He/^3He$ and AHe constraints[3] for river-level samples (samples 9–12) show ~65 °C from 60 to 30 Ma; Kaibab Uplift (sample 13) newer model[4] shows slow cooling (90–65 °C) from 70 to 30 Ma with overlap of river and uplift samples at 80–70 °C, hence 1.8–3.5 km deep from 70 to 30 Ma.

thermal history[2] for the Kaibab uplift sample (Fig. 2c, blue) is in closer agreement with numerous AHe-based constraints from rim samples[9] (Supplementary Fig. 1a).

A geological test of the viability of the 'old canyon' models is to plot the proposed palaeocanyons, at their proposed depths and stratigraphic positions (ref. 1, p. 1309) on a geological cross section and evaluate the resulting palaeoriver gradients. On the basis of thermochronological data[2], Fig. 3a (paths 1 and 2) shows that, from 70 to 30 Ma, the land surface in Eastern Grand Canyon was several kilometres higher above the modern topography than Westernmost Grand Canyon. Thus, assuming 'little or no elevation adjustment of the southwestern Colorado Plateau since 16 Ma' (ref. 1, p. 1298), or since the mid-Tertiary (ref. 1, p. 1311), and even if 70–50 Ma overhead palaeocanyons existed, the proposed east-flowing California palaeoriver (ref. 1, p. 1309) would be required to flow uphill, and the proposed Arizona palaeoriver would have had an unrealistically steep gradient for a regional river system.

By ~15 Ma, thermochronological data indicate the East Kaibab palaeocanyon had its floor 1.4–4 km above modern topography and was probably in the upper Palaeozoic section[9] (Fig. 3b, path 4), not at near-modern depths[1] (Fig. 3a, path 3). This is also supported by the geological constraint that the floor of the East Kaibab palaeocanyon was probably higher than the highest groundwater speleothems (Fig. 3b), which are interpreted as marking approximate groundwater table positions at 2–4 Ma (ref. 17). The rim of the 15 Ma palaeocanyon was no lower than the Triassic strata, as 300 m are still present beneath 8–10 Ma basalts on both rims[18], and palaeocanyon walls were probably made up largely of Jurassic strata similar to those still present in Vermillion Cliffs near Lees Ferry (Fig. 1). Candidates for the palaeorivers that carved the East Kaibab palaeocanyon are the Crooked Ridge (Fig. 3b)[19] and Little Colorado palaeorivers (LCR; Fig. 1).

To evaluate how far west such a 15 Ma palaeocanyon can be documented, we examine thermochronological data from another pair of adjacent river-level and rim-level samples[9] (samples 14, 15; Supplementary Fig. 1b). Like Eastern Grand Canyon, these samples are also separated vertically by 1.5 km and models show they resided at ~60 and ~30 °C, respectively from 50 to 25 Ma; then both cooled to 20–30 °C by 15 Ma. Thus, we infer that East Kaibab palaeocanyon extended about 100 km westwards (Fig. 1).

65–50 Ma Hurricane fault segment

Westernmost Grand Canyon is a fault-lowered and deeply incised segment of the Colorado Plateau where 70–55 Ma palaeocanyons have long been identified and where thermochronological studies[1–4,9,15] constrain different cooling histories compared to Eastern Grand Canyon. AFT ages of river-level samples are 46–74 Ma; AHe ages are 12–100 Ma. The Hualapai drainage system[6,20] was proposed to have flowed northwards from Sevier/Laramide (90–70 Ma) uplifts and to have deposited the ~65–50 Ma Music Mountain Formation within ~1 km deep palaeocanyons that converged along the Hurricane fault system[21,22] (Fig. 4). Preserved remnants of these >50 Ma channels at low elevations in Peach Springs tributary canyon[23] present an obvious problem for 'young canyon' models in terms of how the Hualapai palaeoriver system 'got out' of the Grand Canyon (Fig. 4); either to the west[1] or east[24], or across the canyon[25]. Here, we resolve this by restoration of Neogene west-down faulting to reconstruct a reasonable 65–50 Ma N-flowing Hualapai palaeoriver profile (Fig. 4a and Supplementary Fig. 2 and Note). Slip on fault segments ranges from 213 to 731 m (refs 26,27; Fig. 4a). We restore ~300 m of post-3.6 Ma normal slip on the Hurricane fault to elevate the base of the Hualapai drainage on the down-thrown western side (1,190 m; point C in Fig. 4a) to a pre-faulting elevation of ~1,490 m, compatible with observed 1,480 m elevations of upstream tributary palaeochannel remnants east of the fault (point G, Fig. 4a). North of point C, the Hualapai palaeoriver is constrained to have flowed within modern Grand Canyon at a level at or below the ~1,200 m rim of the inner gorge west of the Hurricane fault (Supplementary Fig. 2). Slip restoration suggests the palaeoriver flowed on the ~1,500 m Esplanade surface between the Hurricane and Toroweap faults. Restoration of an additional ~250 m of post 2–3 Ma slip across the Toroweap fault system[26,27] allows the palaeoriver to have exited north out the Toroweap palaeovalley (now filled with Quaternary basalt) and over the divide near Toroweap Valley (~1,700 m). Regional tilting[21] along the southern end of Fig. 4a can further help resolve the apparent relief paradox (Supplementary Notes).

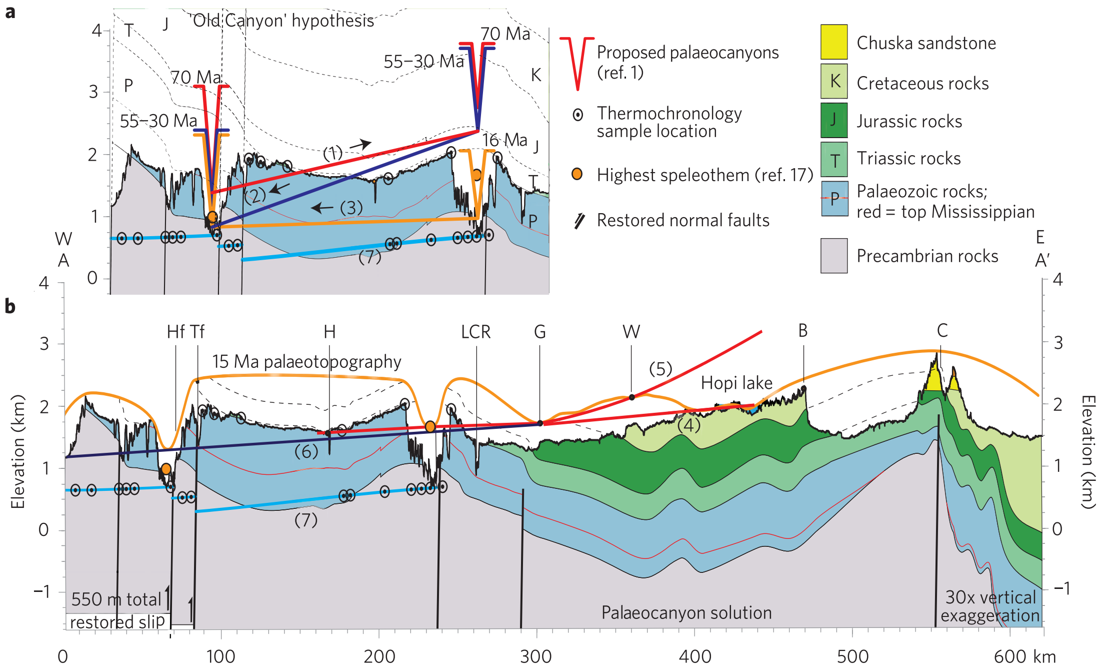

Figure 3 | Proposed palaeocanyon depths and gradients. a, 'Old canyon' models[1–4] plotted on a regional cross section at their proposed[1] stratigraphic levels: (1) the 70 Ma California River[1] would have to flow uphill; (2) the 55-30 Ma Arizona river[1] would have been too steep; (3) and the 16 Ma palaeoriver[1] violates thermochronological constraints that Marble Canyon and Westernmost Grand Canyon were beneath several kilometres of rock. **b**, Same cross section shows our proposed ~15 Ma East Kaibab palaeocanyon carved to the level of the Redwall Limestone in Eastern Grand Canyon; (4) ~15 Little Colorado palaeoriver; (5) ~15 Crooked Ridge palaeoriver; (6) 5-6 Ma Colorado River; (7) Modern Colorado River Hf, Hurricane fault; Tf, Toroweap fault; labels as in Fig. 1.

Thermochronology sample 27 (refs 1,2) is a key location where the Peach Springs tributary canyon enters the modern Grand Canyon. It yields AHe ages of 61–82 Ma, overlapping with the AFT central age of 75.4 Ma (ref. 15). Long track lengths (14 μm) and AFT data[15] require the sample to have cooled rapidly from 80 to 60 Ma (Fig. 4b, AFT path), perhaps as a result of west-up movement on the Laramide Hurricane fault[15]. The AFT data suggests post-Laramide temperatures of ~30 °C, corresponding to burial depths of 200 m (ref. 1) to 1,000 m. Our best estimate that integrates geological data with ~30 °C temperatures is that Hualapai palaeocanyon had been carved to within ~750 m of the modern river level by ~55 Ma (Supplementary Fig. 2). No ^{4}He/^{3}He data are yet available, but this sample is generally compatible with (slightly warmer than) ^{4}He/^{3}He-constrained Westernmost Grand Canyon cooling paths[3,4] (Fig. 4b, samples 27–30).

Thus, the Hurricane fault segment coincides with a palaeocanyon that was carved to approximately half its modern depth by 70–55 Ma (Fig. 1). Its path and depth were influenced by 90–60 Ma reverse movement on the Hurricane fault system and we hypothesize that it flowed northward through now-eroded Mesozoic strata between Grand Canyon and Claron basin (Fig. 1), rather than being part of an 'old' Grand Canyon. AFT/AHe data[9] from farther north in this segment (samples 22, 23) indicate that some rocks were at >60 °C until after 30 Ma, as constrained by AFT track lengths of 12.2–13.3 μm (ref. 15), such that the combined faulting/palaeocanyon complexities in this reach probably produced varying cooling paths.

5–6 Ma Westernmost Grand Canyon segment

Thermochronology-based interpretations of the age of Grand Canyon remain in stark disagreement in Westernmost Grand Canyon[4,28]. Here, the modern canyon parallels the base of a Laramide-initiated Permian (Kaibab) recessional escarpment, which now forms the north rim of Westernmost Grand Canyon (Fig. 4a). We present four new samples with combined AFT and AHe data (Fig. 4b and Supplementary Fig. 3) that show markedly variable and multi-stage cooling of Westernmost Grand Canyon. These data document significant post-Laramide palaeotopographic relief, but not in the form of a simple predecessor palaeocanyon. For example, similar to Eastern Grand Canyon (Fig. 2b), samples 24–26 suggest that Sevier/Laramide cooling occurred in different places (and fault blocks) from 90 to 60 Ma, followed by slow post-Laramide cooling of many samples from 60 Ma to as late as 6 Ma.

Our AFT/AHe constraints differ from the ^{4}He/^{3}He-based 'old canyon' constraints[1–4], where rocks are modelled to have a single-stage cooling with rapid cooling to <30 °C at 90–80 Ma (samples 27–30, Fig. 4b). However, AFT track length data (12.1–13.0 μm; Supplementary Table 1) require that some of the rocks resided in the >60 °C AFT partial annealing zone, and AHe age–effective Uranium concentration correlation (Supplementary Fig. 3a) also constrain higher temperatures of ~60 °C (sample 25) and, hence, 1.4–2.5 km burial depths. Given the present ~1 km depth of samples below the rim of Westernmost Grand Canyon, this suggests that Westernmost Grand Canyon was not cut to near-modern depths until after 6 Ma.

A geological explanation that can reconcile different thermal constraints for different samples is that a highly embayed Kaibab escarpment may have covered parts of the modern canyon from 60–6 Ma (Fig. 4a). We note that ^{4}He/^{3}He data from only sample 28 provided well-constrained temperatures and this sample could plausibly have cooled earlier and to lower temperatures than other samples if the Kaibab escarpment retreated past sample 28 earlier than other samples. The AFT/AHe data of sample 25 constrain a thermal path that is markedly different from nearby sample 30, for which no successful ^{4}He/^{3}He-based constraints were possible[3]. Hence the best reconciliation of all data is that samples from Westernmost Grand Canyon had variable cooling histories (Fig. 4b) dependent on their location relative to Laramide faults and to the

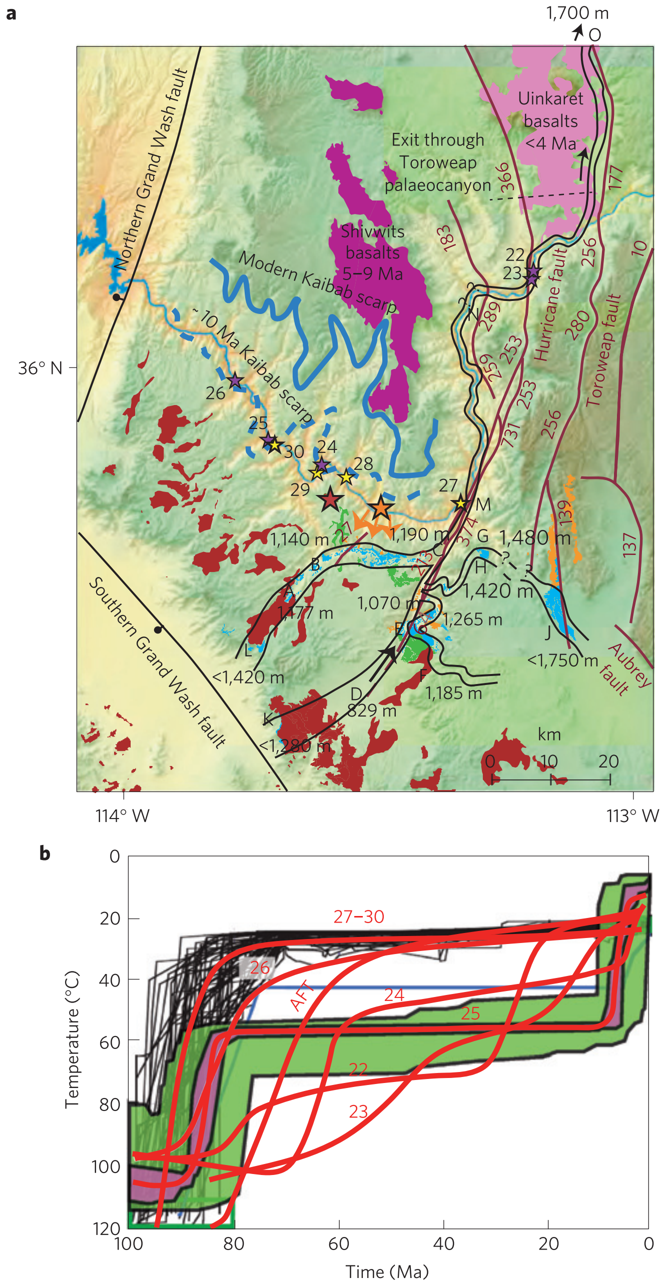

Figure 4 | Westernmost Grand Canyon. a, North-flowing 65–50 Ma Hualapai palaeodrainage (black lines); light blue, Music Mountain Formation; orange, ~50 Ma Hindu fanglomerate deposited across Westernmost Grand Canyon (orange star and arrows); green, Oligocene Buck and Doe Conglomerate; red, Miocene volcanic rocks; solid and dashed dark blue lines, present and inferred ~10 Ma Kaibab escarpment. **b**, AFT/AHe-based constraints from river-level samples show variable cooling histories; e.g. sample 25 resided at ~60 °C (>1.4 km burial depth) from 80 to 6 Ma. Models (samples 27–30; refs 3,4) based on AHe and $^4He/^3He$ analysis (sample 28) suggest ~20 °C after 70 Ma.

retreating Kaibab escarpment, and that some river-level samples (sample 25) were at ~60 °C and buried by 1.4–2.5 km of rock until 6 Ma, supporting a 'young' Westernmost Grand Canyon.

Two geologic datasets also falsify the 'old' Westernmost Grand Canyon. Hindu fanglomerate (~50 Ma) exposed on the south Rim of Westernmost Grand Canyon (orange star in Fig. 4a) has coarse locally-derived fanconglomerate clasts that are imbricated, indicate southward palaeoflow, and could have been derived only from Permian rocks that form the north rim of the Westernmost Grand Canyon (ref. 29, p. 169; Supplementary Discussion). This shows that the Westernmost Grand Canyon was not carved at ~70–50 Ma, in agreement with our AFT/AHe constrained thermal histories. Furthermore, a pre-6 Ma Westernmost Grand Canyon continues to be falsified by the Muddy Creek Formation, which constrains the first arrival of Colorado River sediment to Grand Wash Trough to have been after 6 Ma (refs 30,31), and to the Gulf of California to have been after 5.3 Ma (refs 32,33). Attempts to circumvent this constraint[1–4] using models for dry climate and/or trapping of Colorado River sediment in long-lived lakes are geologically unreasonable given the 25 Ma-long excellent sedimentary record in Grand Wash Trough, as summarized in the Supplementary Discussion.

A palaeocanyon solution for the age of the Grand Canyon

Combined geological and thermochronological data indicate that the Hurricane fault segment of Grand Canyon is 'old' and was carved to about half its modern depth by a north-flowing palaeoriver 65–50 Ma, but this Hualapai palaeoriver did not carve adjacent segments where river-level samples were buried by several kilometres of rock from 70 to 50 Ma. Eastern Grand Canyon segment is intermediate in age and was carved across the Kaibab Uplift to within approximately half the depth of modern Grand Canyon between 25 and 15 million years ago. However, it could not have been linked to Marble Canyon, which was deeply buried, or Westernmost Grand Canyon, where a western exit is precluded by both geology and thermochronology; hence it probably flowed northwest (Fig. 1). Our palaeocanyon solution for carving Grand Canyon suggests that the 5–6 Ma Colorado River became integrated through two young (<6 Ma) segments (Marble Canyon and Westernmost Grand Canyon), one 25–15 Ma segment (Eastern Grand Canyon), and a >50 Ma Hurricane segment. After integration of the Colorado River 5–6 million years ago, all segments were widened and Grand Canyon was deepened during semi-steady river incision over the past 4 Ma at rates of 100–200 m Ma^{-1} (refs 8,34).

Methods

This work is a synthesis and reconciliation of all available thermochronological and geological data on the age of Grand Canyon. New thermal constraints (Supplementary Figs 1 and 3) were based on both AFT and AHe data from the same samples using the program HeFTy 1.7.4 (ref. 10). The constrained thermal paths are required to predict observations of thermochronological ages, fission track length distributions, and AHe age-effective Uranium concentration relationships. Selected input parameters for the apatite AHe models include the following. The equivalent spherical radius of the grain (or grains) calculated from measured dimensions observed under a stereomicroscope[9]. The alpha stopping distances[35]. The alpha calculation[10] is set to 'ejection only', so does not permit implantation. An r_{mr0} value of 0.83 is used, as is typical for apatite-CaF. The uncorrected age and associated error input is based on the averaged uncorrected age for the specific model group. The error is the standard deviation of the age group. The observed group average uranium, thorium, and samarium concentrations as measured by inductively coupled plasma–mass spectrometry are given in parts per million. The most recent diffusion model is used (radiation damage accumulation and annealing model)[36]. Thus, the AHe thermal modelling techniques used in this study account for the variability in ^4He diffusion kinetics caused by crystal damage due to radioactive decays along the U and Th decay series[37]. Additional input parameters for the AFT models include a chlorine weight percentage of 0.10%, a default initial mean track length based on the chlorine weight percentage of 16.17 μm, and a track length reduction standard of 0.893. Each thermal history is labelled with the number of simultaneously run AHe and AFT thermochronometric models. All constrained thermal histories include one AFT analysis and, with the exception of 01GC86, each apatite grain (that is each analysis) is modelled independently yet simultaneously. Refer to Supplementary file 2 in ref. 9 for the analytical data used in the modelling.

Predicted results are compared with observed data and a goodness of fit (GOF) is calculated. GOF indicates the probability of failing the null hypothesis that the modelled data and the observed data are different. Low (high) values of GOF indicate a low (high) probability that the null hypothesis can be rejected and there is hence a poor (good) match to the measured data. GOF values >0.05 are defined as acceptable agreement between modelled and observed data; values >0.5 are regarded as good fits. All thermal models begin at 500 Ma at a temperature of 20 °C to represent the near surface exhumation of basement samples before deposition of the Cambrian Tapeats Sandstone. Temperatures throughout the Palaeozoic are modelled as a near-linear increase towards a maximum burial temperature of 110 °C in the Cretaceous (120 °C for 02GC128, owing to its relatively eastward position). The black boxes are intermediate constraints that were imposed only after numerous random paths revealed these areas of focused generation of all t–T paths. The initial modelling efforts for each sample are run with a large number of cycles (>100,000) and no intermediate constraints. Therefore, we can identify all areas where thermal history solutions are generated and focus the generation of random thermal histories through these zones. As a result, these intermediate constraints do not exclude possible best fit t–T solutions. Each thermal history frame in the figures includes the number of cycles run for the model (I), the number of acceptable-fit solutions (A), and the number of solutions with good-fit (G).

We compare our data with ^{4}He/^{3}He thermochronometry performed in a different study[3] on basement rocks from river-level samples collected near our sample sites. ^{4}He/^{3}He thermochronometry uses the spatial distribution of ^{4}He, U and Th within individual apatite crystals to constrain permissible thermal paths between ~80 and ~30 °C (refs 12,38). Ultimately, adding this analysis to grains also dated both by AFT and AHe should provide the most robust continuous thermal constraints on cooling from ~110 to 30 °C. Cooling paths constrained by ^{4}He/^{3}He data from Eastern Grand Canyon[3] are very similar to constraints from AFT/AHe, but envelopes of good fits are shifted ~20 °C cooler at any given time. This difference may arise from potential inaccuracy in the assumptions about U and Th zonation and the extent of radiation damage annealing[36,37] during burial heating before ~80 Ma; both assumptions require further examination. In Westernmost Grand Canyon, ^{4}He/^{3}He constraints from the single sample that yielded good results (CP06-69) are similar to the AFT model (sample 27) and sample 26, but differ from other samples. Here we have suggested geologic explanations for different cooling histories in different samples, which reinforces the need to do all three analyses on the same samples, rather than assuming an ensemble of rocks had a uniform temperature history[3,4].

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Author contributions

K.E.K. did the writing and data analysis. J.P.L., S.A.K., M.F., D.L.S. and J.W.R. did the thermochronology data analysis. R.S.C., L.J.C., R.A.Y., G.L. and L.S.B. did the geology data analysis.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.E.K.

Competing financial interests

The authors declare no competing financial interests.

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Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons

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In the version of this Supplementary Information file originally published, there were errors in Table 1. This has been corrected in this file on 18 February 2014.

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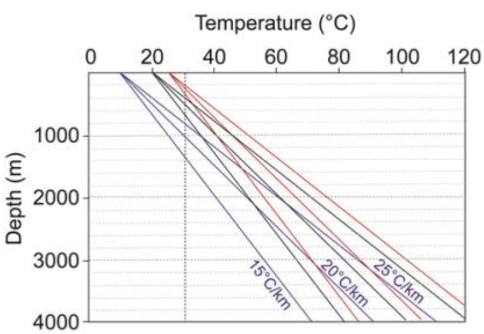
Karl E. Karlstrom et al., Nature Geoscience, 2014

Supplementary Table 1: Key thermochronology samples discussed in text; Bold (23-26) = new thermal history models in this paper

Sample number (Fig 1) (depth in drill hole)	River Mile below Lees Ferry	Elevation (m)	Rock type	AFT central age (Ma)	AFT mean track length (um)	AHe age mean (Ma)	AHe age range (Ma)	AHe eU mean (ppm)	AHe eU span (ppm)	#	4He/3He	Laramide rapid cooling	post-Laramide cooling	post-10 Ma cooling	refs
1. 01GC90	0	river-957	Shinarump ss	30	12.7	10.6	5.6-19.2	49	19-106	4		none from 80-40 Ma	100-60 C/ 40-20 Ma	60-25 C / last 5 Ma	9
2. 01GC92	3.6	river-945	Toroweap ss	28.4	12.2	15.1	7.2-19.4	91	27-239	5		none from 80-40 Ma	100-60 C/ 40-20 Ma	60-25 C/ last 10 Ma	9
3. 01GC93	11.6	river-940	Esplanade ss	39.4		18.5	16.6-20.3	91	55-159	3		none from 80-40 Ma	100-60 C/ 40-20 Ma	not constrained	9
4. 01GC-103	66.3	river- 841	Dox ss	49	12.7	36.4	36.4 - 36.4	6	6	1		120-75 C/ 60-50 Ma	75-70 C/ 50-25 Ma	not constrained	9
5. 98GC-11	78.6	river- 768	Vishnu Schist	49.4	11.1	40.7	22.9 -55.9	10	9-13	3		120-85 C/ 75-65 Ma	85-80 C/ 65-25 Ma	not constrained	9
6. 98GC-20	98.1	river- 720	Boucher granite	46.5	11.7	26.5	23 - 33.6	9	8-11	7		120-85C/ 75-55 Ma	85-80 C/ 55-25 Ma	not constrained	9
7. GCSK-2	S. Rim	rim-2073	Toroweap ss			50.2	39.4 - 61.8	43	30-61	4		80-60C/ 80-75 Ma	60-50 C/ 75-25 Ma	not constrained	9
8. GCNK-1	N. Rim	rim- 2391	Toroweap ss			59.8	40.6 -77.8	25	11-47	4		65-55 C/ 80-75 Ma	55-40 C/ 75-30 Ma	not constrained	9
9. UG90-2	90.3	river-725	Horn granodiorite			54	35-66	52	15-91	7	no	ensemble of river level samples 6-9 shows:			2
10. UG99-1	99	river-716	Tuna granodiorite			33	26-45	17	12-24	4	no	cooling from 120-65 C / 80-60 Ma,			2
11. CP06-Bass (52)	108.4	river- 671	γ Creek pluton (CP06-52)			51	42-57	150	113-180	4	yes	residence at 70 C from 60-30 Ma,			2
12. CP06-Diab	133	river- 610	1.1 Ga diabase			23	19-28	5	4-6	4	yes	cooling 65- 40 C /30-25 Ma (Fig. 2B)		40-20 C / last 10 Ma	2
13. PGC-002	Kaibab uplift	rim- 2292	Esplanade ss			47	19-69	34	26-115	7		90-80C/ 80-60 Ma	80-70C/ 60-25 Ma		1-4,36
14. GCTR-2	133.7	trib- 703	Hakatai sh			32.6	22.9 - 45.5	38	15-63	4		100-60 C/ 100-65 Ma	90-70 C/ 75-25 Ma	40-25 C/ last 15 Ma	9
15. GCTR-9	N. Rim	rim-2181	Supai ss			67.9	53 - 87.1	52	13-100	3		100-70 C/ 100-80 Ma	60-30 C/ 55-25 Ma	not constrained	9
16. GCSH-8	N Rim	rim- 1613	Supai ss			51.8	26.2 - 68.3	67	21-87	4		100-60 C/ 80-70 Ma	55-50 C/ 70-20 Ma	50-25 C/ last 15 Ma	9
17. GCSH-10	N Rim	rim-1503	Supai ss			40.6	13.2 - 71.1	27	7-51	9		100-60 C/ 80-70 Ma	60-40C 70-25 Ma	not constrained	9
18. Sage 1 (206 m)	S Kaibab Rim	rim- 1564	Supai ss?			62.9	31.1 - 86.8	44	15-74	6		80-60 C/ 80-70 Ma	60-45 C/ 70-25 Ma	40-25 C/ last 15 Ma	9
19. Wate 1810 (552 m)	S Kaibab Rim	rim- 1258	Supai ss?			44.1	15.6 - 62.6	46	14-78	5		70-60 C/ 80-70 Ma	60-55 C/ 70-15 Ma	50-25 C/ last 10 Ma	9
20. SBF7 (550 m)	S Kaibab Rim	rim- 1281	Supai ss?			37.2	14 - 54	47	20-90	6		65-60 C/ 80-60 Ma	55 C/ 60-5 Ma	50-25 C/ last 10 Ma	9
21. BM1 (31 m)	S Kaibab Rim	rim- 1619	Toroweap ss?			67.8	38.4 - 103	49	16-95	8		100-70 C/ by 100 Ma	55-45 C/ 80-25 Ma	40-25 C/ last 15 Ma	9
22. 98GC-34	189.7	river - 488	granite	45.7	13.3	14.4	12.1-16.7	10	6-13	3		100-80 C/ 55-45 Ma	70-50 C/40-20 Ma	not constrained	15
23. 02GC128	**190.7**	**river- 465**	**granite**	73.5	-	**27.6**	**26.7 - 28.9**	**8**	**3-11**	**3**		**100-80 C/ 90-70 Ma**	**80-75 C/ 75-25 Ma**	**60-25 C/ 20-0 Ma**	**9,this paper**
24. 01GC86	**243.2**	**river-372**	**granodiorite**	62.8	13	**50**	**29.2 -72.3**	**14**	**11-17**	**3**		**100-50C/ 70-60 Ma**	**50-40 C/ 60-6 Ma**	**40-25 C/last 6 Ma**	**9,this paper**
25. 01GC87	**252.3**	**river 366**	**granodiorite**	68.7	12.1	**82.5**	**69.5 - 91.9**	**152**	**70-232**	**7**		**100-60 C/ 90-80 Ma**	**60-55 C/ 80-8 Ma**	**60-25 C/last 6 Ma**	**9,this paper**
26. 01GC89	**260**		**granite**	63.2	-	**69.8**	**63.8 - 79.7**	**24**	**10-50**	**3**		**90-40 C/ 90-70 Ma**	**40-25 C/ 70-6 Ma**	**not constrained**	**9,this paper**
27A. 98GC38	225	river 427	granodiorite	75.4	14							100-40 C/ 90-60Ma	40-30 C/ 60-6 Ma	not constrained	15
27B. CP06-65	224.9	river 415	granodiorite			75	61-81	38	32-48	4	no	ensemble of river level samples 27-30 shows cooling from			2,3
28. CP06-69	239.6	river-366	granite			89	83-100	12	11-13	5	yes	100-30 C/ 90-70 Ma	30-20 C/ 70-5 Ma		2,3
29. CP06-71a	245	river-366	granodiorite			71	68-75	9	5-14	4	no viable models				2,3
30. GC863	~252.3	river 366	granite			73	68-90	58	47-85	6	yes; complex U zonation				2,3

Supplementary Table 2-- Cenozoic geothermal gradient and surface temperature assumptions for the Colorado Plateau region				
Area	**Gradient C/km**	**Surface temperature**	**Timeframe**	**Reference**
Gold Butte area- Lake Mead	18-20	10	pre-17 Ma	39,40
Gold Butte area- Lake Mead	20	10	pre-17 Ma	39
Gold Butte area- Lake Mead	20, or 20-25	10	pre 17 Ma	41
Gold Butte area- Lake Mead	25	--	pre-17 Ma	42
Virgin Mountains	20-25	10	Miocene	43
Grand Canyon	20-30	10	Cenozoic	16
Grand Canyon	20-30	--	Cenozoic	15
Grand Canyon	25	20-25	last 70 Ma	1
Grand Canyon	25	10	last 70 Ma	2
Grand Canyon	25	25	post-70 Ma	3
Grand Canyon	25	10	middle Cenozoic	9
AZ Transition Zone	20-30	--	Miocene	44
Basin and Range	30-50	--	Miocene	44

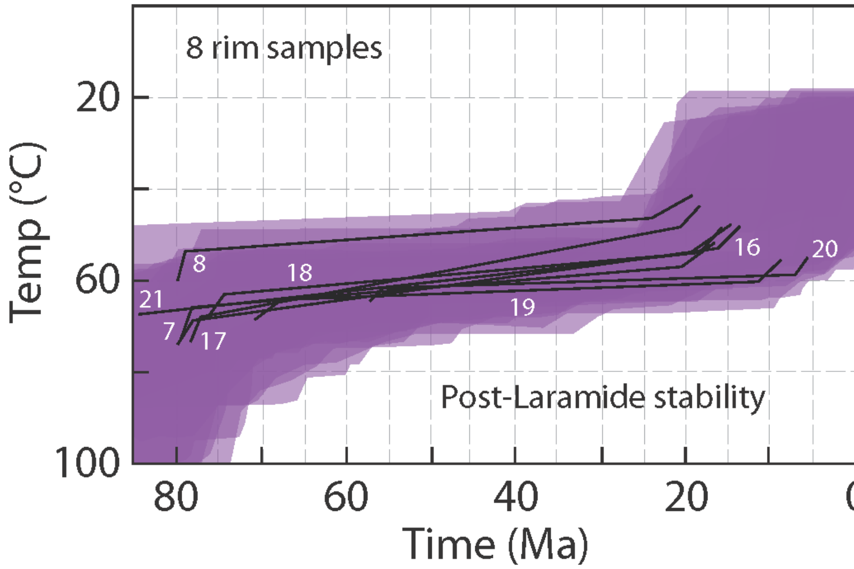


	Depth to 30°C isotherm		
Ts	15°C/km	20°C/km	25°C/km
10	1350 m	1000 m	800 m
20	650 m	500 m	400 m
25	150 m	120 m	100 m

Figure and Table show possible depths to 30 °C isotherm based on different assumed values for surface temperature and geothermal gradient.

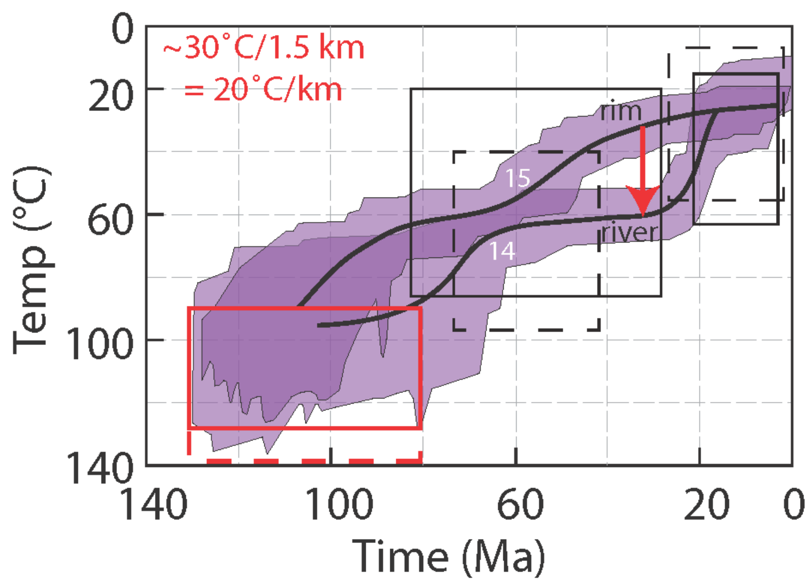
Geothermal gradient and surface temperature assumptions. Assumptions about geothermal gradients and surface temperatures introduce considerable geologic uncertainty in converting temperature to depth in thermochronological interpretations. The Wernicke[1] and Flowers and Farley[3,4] papers chose to use a surface temperature value of 25 °C (for both rim and river) and a conductive geothermal gradient of 25 °C/km. These values minimize their interpreted paleodepths. But, surface temperature and geothermal gradients undoubtedly varied over the last 70 Ma, and at different elevations once topography became established. In contrast, many workers (see references above) assign values of 10-25 °C as a reasonable range of surface temperatures and past workers have inferred geothermal gradients in the range of 18- 30 °C/km for this region and time period. The figure at left shows, for example, that the 30 °C isotherm could be at depths ranging from 100 m to 1350 m if one considers a full range of permissible geothermal gradients and surface temperatures. A 20 °C modeled temperature for western Grand Canyon river-level rocks[3] would suggest depths of 0-800 m, whereas modeled 60 °C temperatures[9] (Fig. 4b) would suggest depths of 1.4-3.4 km. Present depth of western Grand Canyon samples is about 1 km below the Esplanade rim and 1.5 km below the Shivwits Plateau. We question whether existing understanding of diffusion of helium in apatite is good enough to meaningfully resolve temperatures below ~25-30 °C, especially in a region where surface temperatures exceed 40 °C much of each summer and where aquifer water temperatures exceed 25 °C. Interestingly, the 20-25 °C temperatures of springs emerging from the Redwall-Muav aquifer inside Grand Canyon may establish the 25 °C isotherm at depths of ~ 1 km below the Kaibab surface for much of the Colorado Plateau. And where aquifer temperatures exceed 25-30 °C, the portions of thermal models below ~30 °C may simply represent resetting of apatites below the aquifer rather than conductive cooling due to exhumation.

1a.

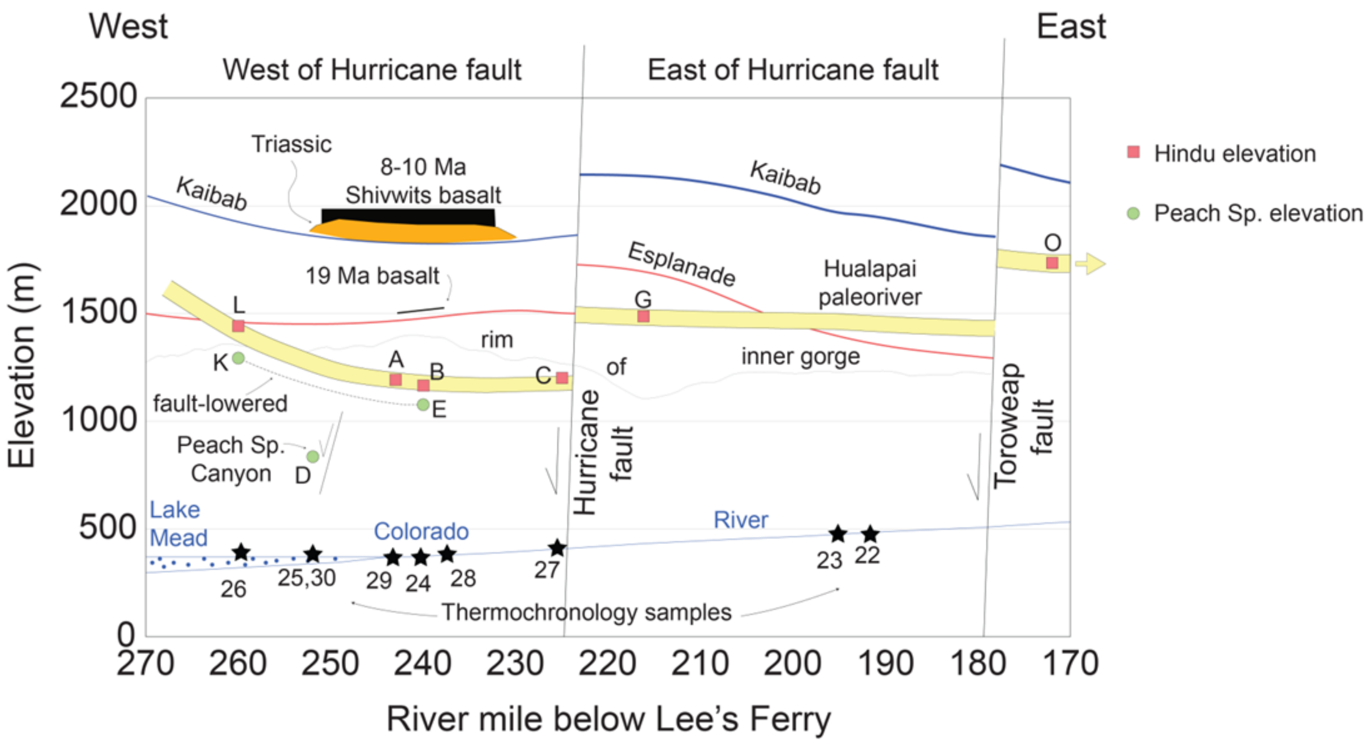


Supplementary Figure 1a. Thermal histories of South Rim samples and boreholes demonstrate post-Laramide stability and uniform thermal history for the southern Kaibab plateau involving slow cooling from ~60-40 °C from 60- 25 Ma, compatible with erosional removal of about 1 km of strata (most of the Jurassic section) during this time period. Onset of more rapid cooling at 20-10 Ma suggests more rapid stripping of Kaibab surface of most of the Triassic section as East Kaibab Paleocanyon was carved, compatible with 8-10 Ma basalts resting on Triassic strata on both rims of the Canyon (Red Butte and Shivwits volcanic field). Lines represent medial lines of models from[9].

1b.



Supplementary Figure 1b. Thunder River vertical traverse (samples 14 and 15 of Fig. 1 and Supplementary Table 1) shows rim and river level samples resided at 25-35 °C different temperatures from 55-25 Ma before both cooling to 25-30 °C at 15-20 Ma. This is similar to Eastern Grand Canyon and suggests that East Kaibab paleocanyon extended as far west as river mile 134 (Fig. 1). Models were constructed in HeFTy using an iterative approach. Initial starting constraints (red boxes, where solid is GCTR-9 and dashed is GCTR-2 were used to create rough thermal history models. These models were then refined using additional constraints (black boxes) that encompassed all of the possible paths of the first run.



Supplementary Figure 2. Paleoprofile of the 65-50 Ma Hualapai paleocanyon deposits compared to the modern Colorado River. Elevations of the base of the Hindu and Peach Springs paleocanyon segments are labeled A-O (see Fig. 4a and Supplementary Note). Peach Springs Canyon outcrops (D,E) are in the immediate hangingwall of the Hurricane fault and are interpreted to be fault-lowered relative to the Hindu paleochannel. The Hualapai paleocanyon system incised to the level of the Esplanade surface by about 50 Ma west of the Toroweap fault. Restoration of ~300 m offset across the Hurricane fault and ~ 250 m across the Toroweap fault allows the paleoriver system to exit north, out Toroweap Valley, hence across the future path of Grand Canyon. 8-19 Ma basalts preserve paleosurfaces that are compatible with thermochronological data for : sample # 25 which had T >60 °C and paleodepth ~1.5 km from 60-8 Ma; and sample # 24 which had T~ 40 °C and paleodepth of ~ 0.6-1 km from 60-5 Ma (see Supplementary Fig. 3)

Supplementary Note: Data for restoring the Hualapai paleocanyon system to its pre-faulting configuration

Hualapai Paleocanyon deposits: elevation constraints of channel bases.

This supplement provides notes on elevation constraints for the base of the 65-50 Ma Music Mountain Formation[45] channel remnants shown in Figure 4a. We use modern elevations to give modern vertical differences (relief) between control points with full awareness that faulting, tilting, and differential uplift may have modified these from their original elevations. The goal is to show how restoration of documented fault slip can reconstruct a viable N-flowing paleoprofile for the Hualapai drainage system. There are relatively few well defined and clearly exposed channel bases. These are considered key elevations as, after the original old channels became clogged by aggradation or from structural blockages, the Music Mountain sediments spread over the landscape as a widespread braidplain or pediment deposit, perhaps over a timespan of 10-20 Ma. Such gravels cover the surface at higher and higher elevations above the channel bases and clast content becomes increasingly enriched upward in exotic volcanic clasts. Music Mountain gravels can also be reworked to lower levels, for example along the Supai Road where they are interbedded with a Pleistocene ash, such that interpretation of lag deposits has significant uncertainty and is not used in this analysis.

A, B, C, D, E, & F are locations where bedrock contacts underneath Music Mountain gravels are visible or determined by well logs. Errors are generally less than about one contour interval (12 m, or 40 feet).

A = 1177 m (3860 feet): base of Milkweed Canyon type locality[46].

B = 1140 m (3740 feet): base of stranded channel remnant between Milkweed and Hindu Canyons, but possibly offset relative to A and C due to faulting and monocline development near Milkweed Canyon and Bridge Canyon[47].

C = 1190 m (3900 feet): Gravel remnants on bedrock where Lost Man Canyon (Hindu paleochannel) drops off into Peach Springs Canyon (contact not cleanly exposed, but obvious on air photos)

D = 829 m (2720 feet): Base of Truxton Bendix well, gravels are not necessarily in thalweg, so this is a maximum elevation of the base of the channel[21].

E = 1070 m (3400-3600 feet): approximate elevations of lowest channel base in Peach Springs Canyon along Hurricane fault. Low elevations are interpreted to be due to numerous fault strands and lowering relative to C via faulting along the Hurricane fault and formation of a hangingwall anticline just west of the Hurricane fault. Lowest elevation is only approximate in the wash and is on the west side of the canyon[23].

F = 1185 m (3890 feet): base from old wells logged by Darton for Santa Fe Rialroad at Peach Springs[48].

G,H,I = Locations are approximate elevations where bedrock is covered by Music Mountain Formation gravels; contacts are reasonably constrained by obvious topography in “hanging” channel segments. These were measured during helicopter work with Peter Huntoon and Karen Wenrich and during later additional fieldwork in Hell’s Canyon by R. Young.

G= west of Blue Mountain Seep; 1480 m (4850 feet)

H= Hell’s Canyon divide; 1417 m (4650 feet)

I = lower Hell’s Canyon; 1265 m (4150 feet).

J= Blue Mountain gravel pit – 1750 m (5750 feet), unexposed base of presumed channel would be lower than this. This location is east of the Toroweap fault and elevations here are comparable to the 1700 m elevation needed for rivers to exit north along Toroweap Valley. It is possible that these gravel exposures represent a separate strand of the Hualapai paleoriver system that flowed north in Prospect Valley to Toroweap Valley along the synclinal axis of the Toroweap monocline.

K = Bedrock threshold where Peach Springs Member of the Buck and Doe Conglomerate overlies Precambrian basement at Grand Wash Cliffs north of Valentine, Arizona, is near 1280 m (4200 feet). The base of the only observable Tertiary outcrop at the plateau margin north of Route 66 is poorly exposed; it underlies Miocene basalts (1490 m; 4900 feet) and is mostly covered with coarse talus deposits. This elevation is too high to realistically match the well elevation at Truxton (approximately 14.5 km to the NE). The visible channel is probably a tributary to the main channel that would be located further south nearer the present location of Route 66 (near 1128 m; 3700 ft).

L = Elevation of contact of channel gravels with granite, but not necessarily in base of channel; volcanic rocks nearby may be obscuring lower contact. This elevation seems high relative to channel elevation at A and may be a maximum height. Obscure faulting under volcanics and monocline deformation on SE side of Milkweed Canyon may have altered heights along parts of the L-A segment.

M. Divide east of Diamond Peak at elev 850 m (2800 feet) provides a possible straight path for the Peach Springs paleocanyon segment to join the modern Grand Canyon reach.

N. Hualapai paleocanyon is constrained to have been within the N-S modern segment of Grand Canyon and in the hangingwall of the Hurricane fault system from Diamond Peak to Whitmore Wash and may have flowed near the ~1220 m (4000 feet) elevations of the Esplanade surface on west side of the Hurricane fault. Numerous <1160 m (3800 feet) topographic "benches" along portions of Grand Canyon between Peach Springs Canyon and Andrus Canyon may be deeply eroded remnant straths.

O. Outlet at Toroweap Valley is loosely constrained by 1160-1220 m (3800-4000 feet) elevations of Esplanade rim outcrops that lavas flowed over and the ~1700 m (5600 feet) divide near Toroweap Valley on the eastern (upthrown) side of the Toroweap fault.

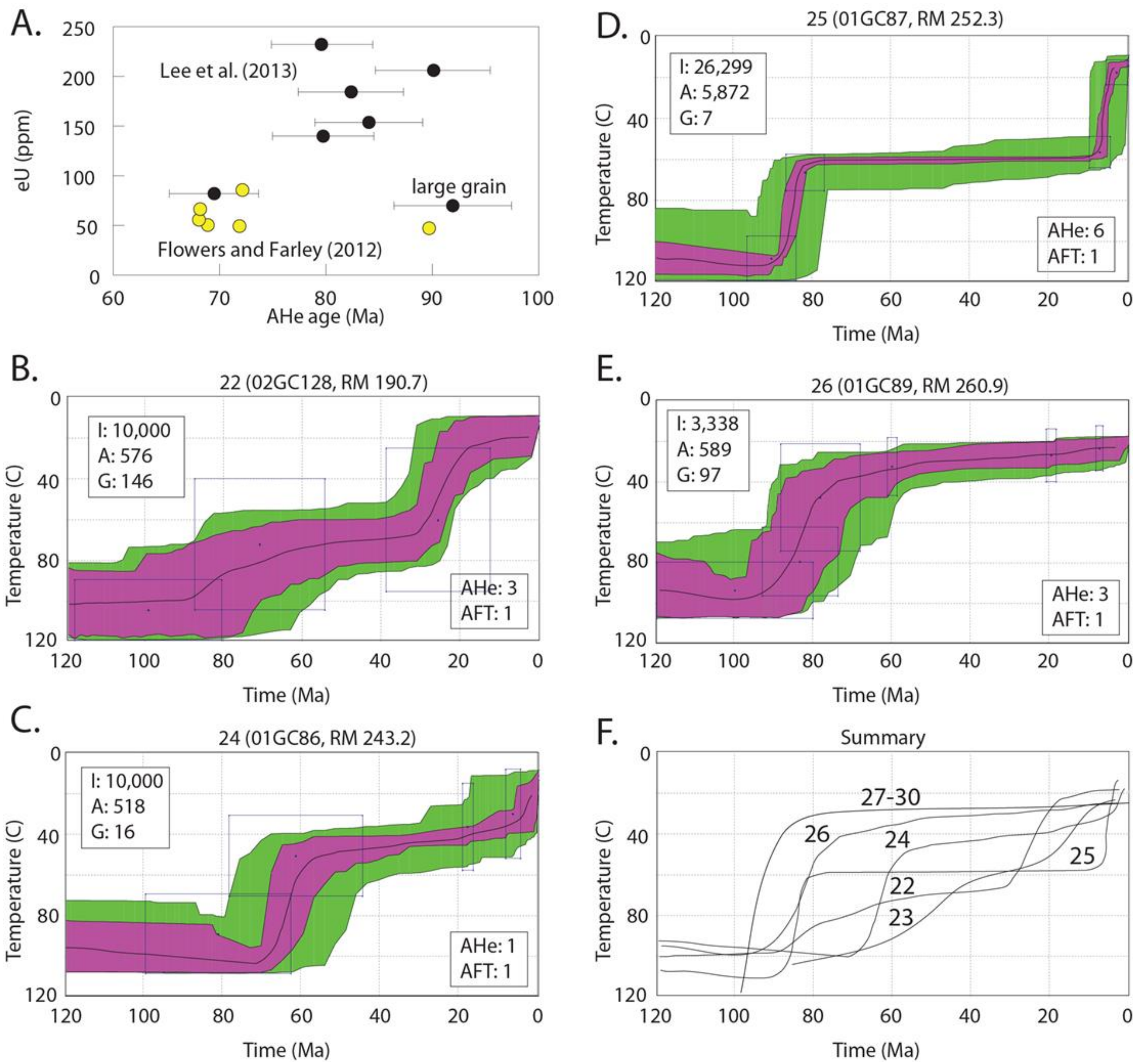
Notes on post-Miocene west-down fault offset used to restore the Hualapai Paleocanyon deposits to their ~ 50 Ma position.

Slip timing is described in[27], as follows:

The Hurricane system and possibly the Toroweap system had a history of Laramide west-up contractional displacement[27,49-50] which we ignore here such that the following restoration of normal slip provides minimum values to restore 50 Ma geometries. It is probable that the different paleocanyon segments shown in Figure 4 are of somewhat different age and that their heights reflect an evolving river system that was responding to west-up contractional deformation associated with the Meriwhitica, Peach Springs, and Hurricane monoclines[50]. Such complexities are not needed to restore the paleochannels to a reasonable N-flowing geometry but they offer a caution that paleochannels may have flowed at higher paleoelevations that we report here using our minimal restoration of post- 3 Ma west-down displacements.

The Hurricane fault system has numerous strands along its >250-km-long strike length[51] with anastomosing strands within Grand Canyon region. It has a maximum west-down slip of about 731 m in the Three Springs area[26,52] (Fig 4A). Cumulative west-down displacement amounts to 400-500 m where it crosses the Colorado River in the Whitmore wash area. Displacement seems to decrease north of the Colorado River in the area of Figure 4 to values of 366 m, but[18] reported offset of 610 m of the 3.6 ± 0.18-ka Bundyville basalt to the north. This slip is similar to cumulative slip on the directly underlying Mesozoic strata, such that we interpret most or all of the ca. 300-700 m of west-down normal slip on the Hurricane fault to have taken place after 3.6 Ma. Displacement decreases southward in Peach Springs Canyon from 374 to 64 m, although these numbers are minimum cumulative displacements. Our restoration of 300 m west-down slip across the fault in the area of the Lost Man Canyon paleochannel segment (point C of Figure 4) is supported by paleocahannel segments at 1480 m east of the fault (point G of Figure 4). Additional lowering of paleochannels by ~ 100 m directly along the fault (point E, 1070 m) is compatible with the scale of hanging wall anticline lowering seen in differential incision rate studies[27].

The Toroweap fault system is several hundred-km-long[53] and forms the microseismically active neotectonic edge of the Colorado Plateau[54]. North of Grand Canyon, it extends ~250 km as the Sevier/Toroweap fault zone[55]. Total west-down stratigraphic separation of Paleozoic units is variable along strike. In the segment of most interest, where it crosses Grand Canyon, stratigraphic separation is about 200 m with about 60 m this post the 600 ka basalt[27]. Thus, like the Hurricane fault, most displacement took place in the last 2–3 Ma. South of Grand Canyon, the Toroweap fault links with the Aubrey fault and has distributed west-down displacement up to ~ 500 m. Thus, our use of 250 m to restore the 65-50 Ma Hualapai palechannels is conservative and the paleochannels may easily have flowed northeast at stratigraphic levels above 1750 m and across the Colorado Plateau north of the Kaibab uplift.



Supplementary Figure 3- New joint AFT-AHe constrained thermal histories for western Grand Canyon: 3a. Correlation of AHe age and eU for sample #25 (01GC87; River Mile 252.2), which is near the location of # 30 (GC863[3]; Reference Point Canyon); note that the thermal history (Fig. 4d) for this sample as constained by joint inversion of AFT data (AFT age= 68.7 Ma and track lengths of 12.1 um, n=101) and AHe shows the rock resided at ~60 C from 80-6 Ma. This is in stark disagreement with the AHe and $^4He/^3He$ model[3] for sample # 28 that shows that the rock resided at ~20 °C during this time interval (both shown in f). 3**b.** Sample # 22 is on east side of Hurricane fault and shows, based on AHe and AFT (but no track length data), long term residence at ~70 °C from 70-30 Ma, then cooling 30-20 Ma, perhaps as tributary to East Kaibab paleocanyon. **3c.** Sample #24, criticized by[3], but has new robust AFT and track length data (and 3 AHe analyses) that constrain T to have been ~50 °C from 65-50 Ma in disagreement with the $^4He/^3He$ analysis of #28[3], that shows rocks cooling through 25 °C by 80 Ma. **3d.** sample # 25 is based on robust AFT, track length, and AHe data that constrain models showing that river level rocks were still deeply buried until 6 Ma, reinforcing Westernmost Grand Canyon as a "young" segment. **3e.** Sample # 26 has poor quality AFT data (only 3 grains and 4 track lengths) but has high quality AHe data; this sample shows post-Laramide thermal stability at temperatures of 45-60 °C suggesting burial depths of ~ 1-1.5 km below a paleosurface that was above the Esplanade surface and could have been as high as the Kaibab rim; this is in conflict with $^4He/^3He$ models[3,4]. Sample #26 is from the west (upthrown) side of the Meriwhitica monocline; model shows that it cooled to ~40 °C in the Laramide, then resided at ~ 30 C; this model has only four confined fission tracks and needs additional data. **3f.** Summary of western Grand Canyon thermal history models show different cooling histories. Our geological explanation for different cooling paths involves differential retreat of a ~ 1km-high highly embayed Kaibab escarpment such that some samples cooled in the Laramide and others in the Neogene. Cooling of #24,25 in the last 6 Ma supports a "young" Westernmost Grand Canyon segment.

Supplementary Discussion: Sedimentary deposits that falsify a proposed[1] "old" Westernmost paleocanyon segment

Any paleocanyon investigation requires evidence for both the water needed to carve a proposed canyon and the sedimentary basin archive of the eroded volume of material excavated from a paleocanyon and its drainage basin. Past water pathways are difficult to prove, but a proposed drainage system is permissive if there were drainage basin areas of sufficient size and reasonable drainage paths for water to carve the paleocanyons. In contrast, a paleocanyon hypotheses is weakened if proposed pathways do not follow reasonable topographic paleoprofiles (e.g. California River in Fig. 3a). Sedimentary basin evidence needed to support a given paleocanyon includes the right volume of sediment, of the right age, and permissive detrital zircon signature, to have come from the paleocanyon and its headwaters. Likewise, sedimentary evidence to falsify a given paleocanyon hypothesis involves dated sedimentary basin deposits that block the proposed river pathway with sediments not derived from that drainage system.

A recent summary from the 2010 decadal meeting of Grand Canyon geologist[56] claimed that there was near- consensus on the age of the Lower Colorado system. This consensus argues that the 5-6 Ma age of integration of the Colorado River system through Grand Canyon accomplished the surface water connection between Rocky Mountain/ Colorado Plateau drainages and the Gulf of California. As presented in abstracts from that meeting[57], papers referenced therein, and subsequent published papers (referenced below). The 5-6 Ma age for integration is documented by data from the 5.3 Ma age of the first sediments arriving in the Gulf[32], its detrital zircon signature suggesting Colorado Plateau provenance[58], and estimates of sedimentary budgets suggesting that the volume of sediment in the Colorado River delta (including basins of southern California that have been displaced northwards along the San Andreas fault system) is similar to the material eroded off of Colorado Plateau in the last 6 Ma[59]. This 5-6 Ma integration concensus is also honored in "old canyon" models that propose that the Colorado River was integrated through a previously carved Grand Canyon that was in the same location and about the same depth as modern Grand Canyon[1-4]. However, two sedimentary units block the proposed precursor canyons.

Muddy Creek constraint: The Miocene Muddy Creek Formation (Rocks of Grand Wash trough of Bohannon, 1984) is a sedimentary succession in Grand Wash Trough that is well exposed across the modern path of the Colorado River at the very mouth of Grand Canyon[60]. Numerous geologists have concluded that this unit has stratigraphy and sedimentary facies indicative of locally derived sediments deposited in internally drained basins and no sedimentary evidence for deposits from the Colorado River deposits or any other far- traveled river[5,61-63]. Specific constraints include an alluvial fan bracketed in age between ~14 Ma and ~ 9 Ma that originated from the Grand Wash Cliffs at Pearce Canyon and extended southwest across the modern path of the Colorado River. Remnants of this fan can be found on both sides of the modern Colorado River at the mouth of the Grand Canyon. Thus, no Colorado River or major precursor river could have flowed through the modern Lake Mead region until after 6 Ma, the youngest age on the Hualapai Limestone that formed a lake/marsh system in this closed basin from 12-6 Ma[30]. Similar relationships are also found in the Lower Colorado River corridor where first arrival of Colorado River sediments are constrained to be 5.3-4.8 Ma[64-65].

Recent "old canyon" papers[1-4] have tried to circumvent the Muddy Creek constraint with the following arguments. 1. A smaller drainage (< 5% of the modern Colorado River drainage basin) called the Arizona River occupied a previously carved western Grand Canyon. 2. This canyon existed for "most of the Miocene" (23-5 Ma[2] or 55-6 Ma[1]). 3. This river had its headwaters mostly in carbonate rock, hence might not have transported significant detritus. 4. Any detritus might have been caught in the delta of an intracanyon lake and not reached Grand Wash Trough. 5. Deposits from this river delta were removed during later erosion of Grand Canyon. 6. The alluvial fan that blocks the path of the modern river[60] may be an example of filling and inactivity of an existing canyon.

These arguments built upon an earlier paper[66] but this scenario is not geologically tenable for the reasons outlined below (with corresponding numbers for each argument). 1) The 50 Ma Arizona River is also proposed to have transported detritus to the Los Angeles Basin[1], hence such a river would have had appreciable stream power and drainage basin area. This aspect of the Arizona River hypothesis has been refuted based on detrital zircon analysis[33], 2) Paleotopography and smaller streams undoubtedly existed, but existence of an Arizona River flowing for tens of millions of years (20 to 50 Ma) in a precursor Grand Canyon is not compatible with thermochronological data nor documented by sedimentary evidence. Voluminous Oligocene and Miocene deposits in closed basins of the Basin and Range refute the idea[1] of limited "fluvial detritus" during an "arid Miocene climate". 3) The proposed drainage basin area includes voluminous Mesozoic and Paleozoic clastic rocks such that the appeal to a lack of siliciclastic detritus is unrealistic. 4) The proposed lake-delta that trapped sediment from reaching the Grand Wash Trough could not have persisted for the long time periods proposed as even small rivers fill their lakes and overtop their dams on sub-millennial timescales. 5) The concept that later erosion has removed all the evidence is falsified by preserved sedimentary units in nearby paleocanyons that suggest continued generally northward stream flow from 55-18 Ma on the Hualapai Plateau, with no evidence for a west-flowing river. Also, 24 Ma to 18 Ma sedimentary units are preserved below the Muddy Creek deposits in the Grand Wash trough and to the north and west. 6) The unlikely nature of the model that the canyon filled and re-incised in the same location was also addressed[31] and such a model also suffers based on timescale issues and lack of Colorado River sediment. Instead, sedimentary and detrital zircon evidence[67] continue to support the Muddy Creek constraint that no appreciable volume of Colorado Plateau-derived detritus entered Grand Wash Trough near the mouth of the Grand Canyon during the 25-6 Ma deposition of the Lower Horse Springs Formation or Muddy Creek Formation, which spanned much of the interval of the Arizona paleoriver[1].

Hindu Fanglomerate constraint: One of the simplest arguments against a 70-50 Ma westernmost Grand Canyon is the regional sedimentary infilling of Laramide drainage channels on the Hualapai Plateau continuously from Eocene (~ 55 Ma) through late Miocene time (~ 18 Ma). These deposits are also geologically incompatible with the model that western Grand Canyon had been carved to near its modern depth by 50 Ma. Citations documenting the southward transport of the Hindu fanglomerate across the path of modern western Grand Canyon state[29,68]: "However, a short distance to the southeast (near Bridge Canyon) stratigraphically older fanglomerate gravels occur at a slightly lower elevation and contain a high percentage of clasts derived from the Coconino Sandstone [now thought to also include Torowap Formation clasts]. The nearest Coconino Sandstone outcrops are now to the north on the Shivwits Plateau, 1500 feet (460m) higher in elevation and north of the Colorado River in this vicinity."[29] And: "Following the cessation of Laramide channel development it appears that younger drainages spread local gravels northeast across the Hualapai Plateau toward older, south-sloping alluvial fans, which headed along the southern edge of the Shivwits Plateau (local north rim of the modern Grand Canyon)"[29]. The geometry of these deposits falsifies models for an "old" westernmost Grand Canyon carved to near-modern depths. Figure 4a shows the present geometry of the Kaibab escarpment (dark blue line) and also the inferred earlier (> 20 Ma due to presence of the 19 Ma Separation Hill basalt) location (dashed blue line) of the Kaibab escarpment. Note that the ~ 8 km separation between the present escarpment and the river may be similar to the separation between the Hindu paleochannel and the past escarpment position.

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