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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 $^4He/^3He$ 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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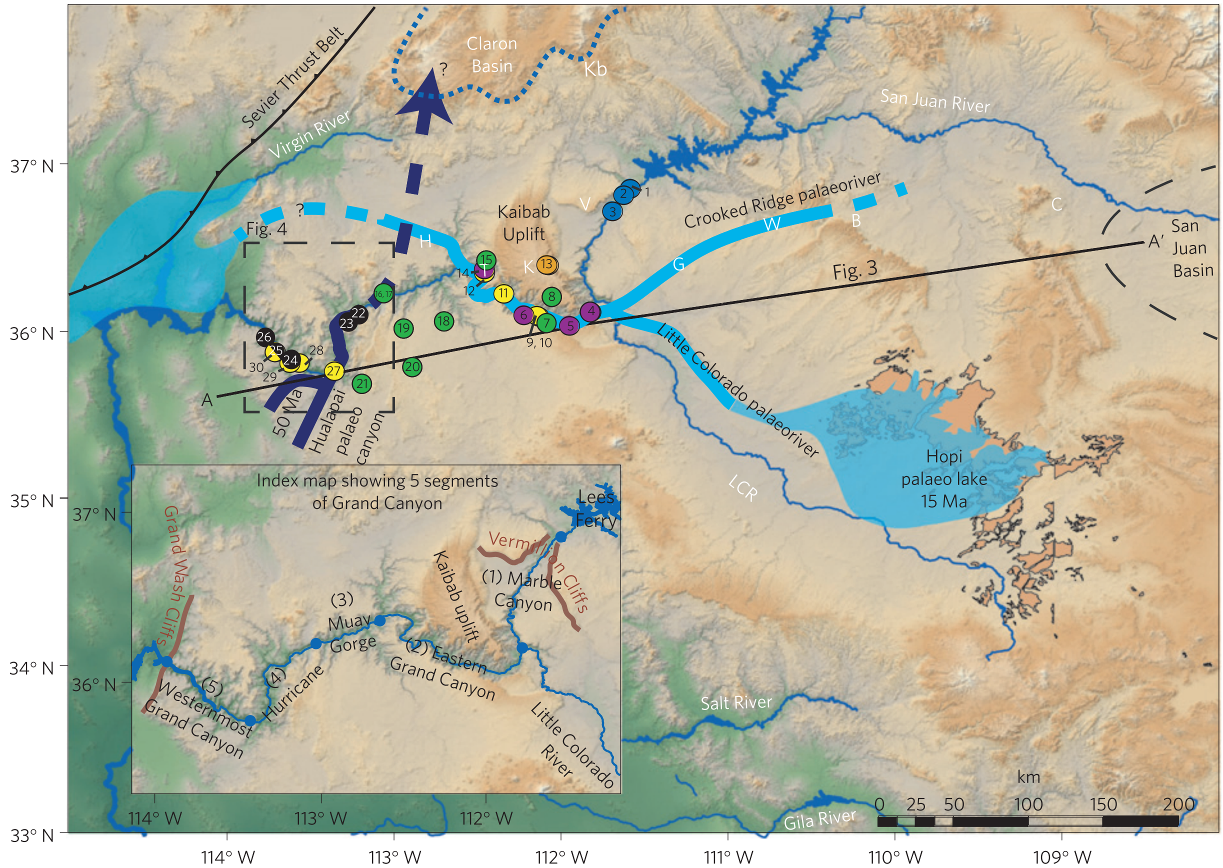


**Figure 1 | Map of Grand Canyon.** Inset shows segments: (1) Marble Canyon; (2) Eastern Grand Canyon; (3) Muav Gorge; (4) Hurricane fault segment; and (5) Westernmost Grand Canyon. Main map shows inferred drainage at ~15 Ma; B, Black Mesa; C, Chuska Mountains; G, Gap; H, Hack Canyon; K, Kaibab Uplift; 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 $^4He/^3He$ 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 $^4He/^3He$ 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

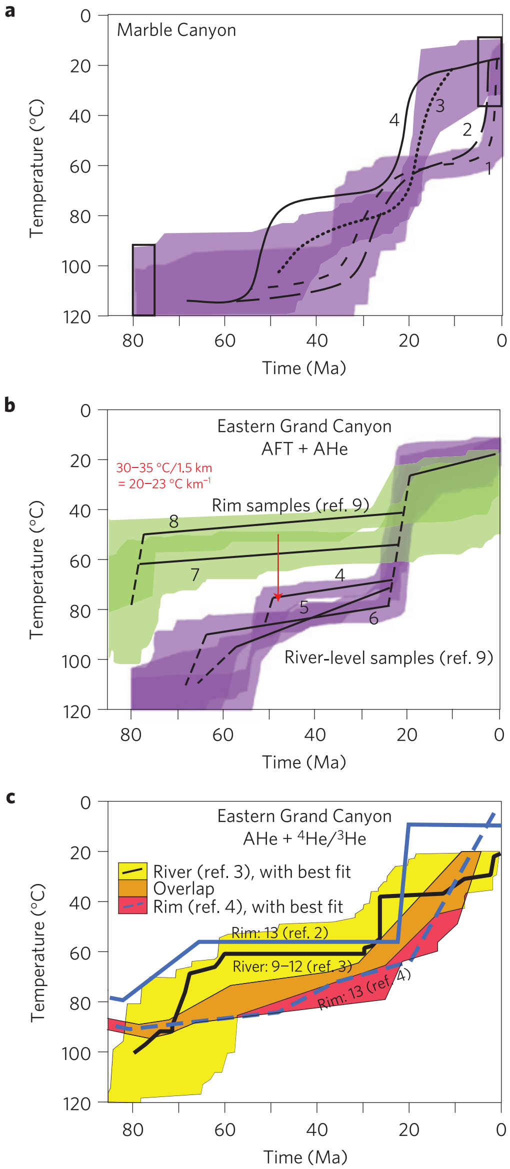


**Figure 2 | Thermal constraints. a**, Marble Canyon samples 1–4 show cooling ages decreasing upstream and canyon carving at Lees Ferry after 6 Ma. **b**, AFT/AHe constraints[9] from adjacent river-level (samples 4–6) and rim (samples 7–8; AHe only) samples show no palaeocanyon from 70 to 25 Ma and carving 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).

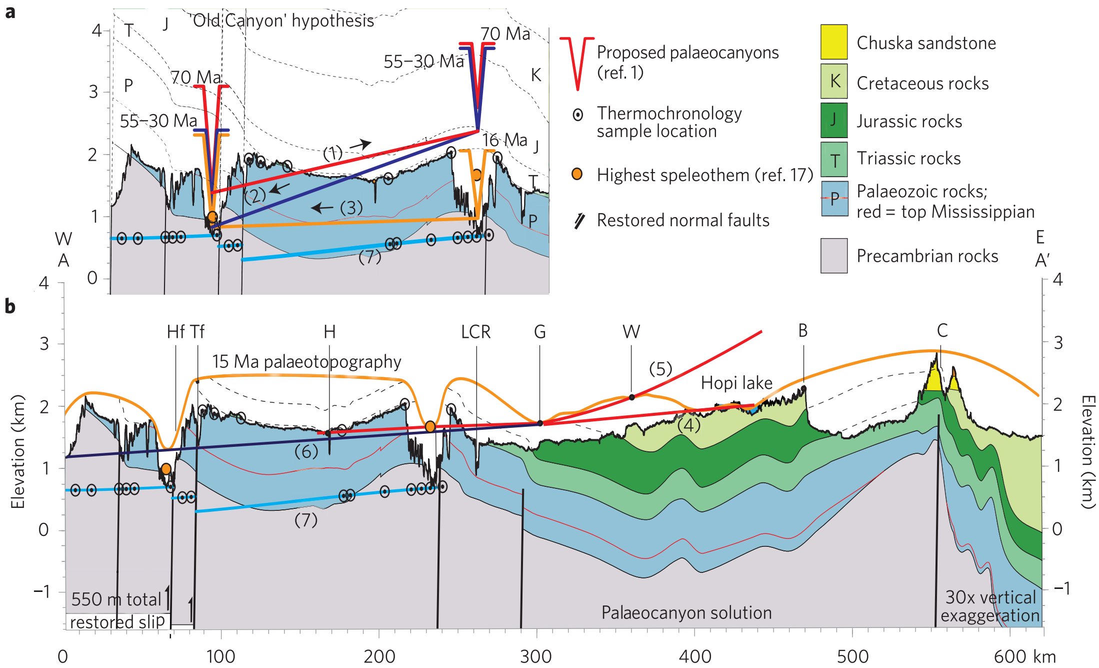


**Figure 3 | Proposed palaeocanyon depths and gradients.** **a**, 'Old canyon' models[1–4] plotted on a regional cross section at their proposed[1] stratigraphic levels: (1) the 70 Ma California River[1] would have to flow uphill; (2) the 55-30 Ma Arizona river[1] would have been too steep; (3) and the 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

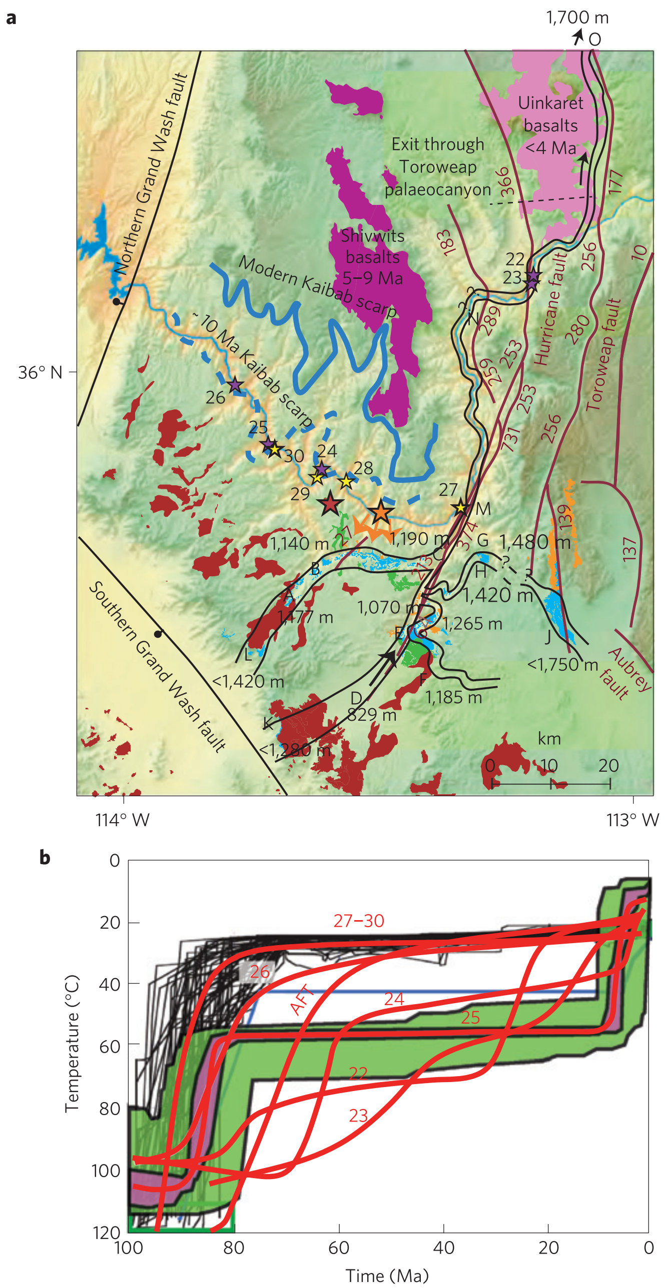


**Figure 4 | Westernmost Grand Canyon. a**, North-flowing 65–50 Ma Hualapai palaeodrainage (black lines); light blue, Music Mountain Formation; orange, ~50 Ma Hindu fanglomerate deposited across Westernmost Grand Canyon (orange star and arrows); green, Oligocene Buck and Doe Conglomerate; red, Miocene 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 $^4$He/$^3$He 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 $^4$He 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.