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6 Ma age of carving Westernmost Grand Canyon: Reconciling geologic data with combined AFT, (U–Th)/He, and ^{4}He/^{3}He thermochronologic data

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ABSTRACT

Conflicting hypotheses about the timing of carving of the Grand Canyon involve either a 70 Ma ("old") or <6 Ma ("young") Grand Canyon. This paper evaluates the controversial westernmost segment of the Grand Canyon where the following lines of published evidence firmly favor a "young" Canyon. 1) North-derived Paleocene Hindu Fanglomerate was deposited across the present track of the westernmost Grand Canyon, which therefore was not present at ∼55 Ma. 2) The 19 Ma Separation Point basalt is stranded between high relief side canyons feeding the main stem of the Colorado River and was emplaced before these tributaries and the main canyon were incised. 3) Geomorphic constraints indicate that relief generation in tributaries and on plateaus adjacent to the westernmost Grand Canyon took place after 17 Ma. 4) The late Miocene–Pliocene Muddy Creek Formation constraint shows that no river carrying far-traveled materials exited at the mouth of the Grand Canyon until after 6 Ma.

Interpretations of previously-published low-temperature thermochronologic data conflict with these lines of evidence, but are reconciled in this paper via the integration of three methods of analyses on the same sample: apatite (U–Th)/He ages (AHe), ^{4}He/^{3}He thermochronometry (^{4}He/^{3}He), and apatite fission-track ages and lengths (AFT). HeFTy software was used to generate time–temperature (t–T) paths that predict all new and published ^{4}He/^{3}He, AHe, and AFT data to within assumed uncertainties. These t–T paths show cooling from ∼100 °C to 40–60 °C in the Laramide (70–50 Ma), long-term residence at 40–60 °C in the mid-Tertiary (50–10 Ma), and cooling to near-surface temperatures after 10 Ma, and thus support young incision of the westernmost Grand Canyon.

A subset of AHe data, when interpreted alone (i.e. without ^{4}He/^{3}He or AFT data), are better predicted by t–T paths that cool to surface temperatures during the Laramide, consistent with an "old" Grand Canyon. However, the combined AFT, AHe, and ^{4}He/^{3}He analysis of a key sample from Separation Canyon can only be reconciled by a "young" Canyon. Additional new AFT (5 samples) and AHe data (3 samples) in several locations along the canyon corridor also support a "young" Canyon. This inconsistency, which mimics the overall controversy of the age of the Grand Canyon, is reconciled here by optimizing cooling paths so they are most consistent with multiple thermochronometers from the same rocks. To do this, we adjusted model parameters and uncertainties to account for uncertainty in the rate of radiation damage annealing in these apatites during sedimentary burial and the resulting variations in He retentivity. In westernmost Grand Canyon, peak burial conditions (temperature and duration) during the Laramide were likely insufficient to fully anneal radiation damage that accumulated during prolonged, near-surface residence since the Proterozoic. We conclude that application of multiple thermochronometers from common rocks reconciles conflicting thermochronologic interpretations and the data presented here are

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best explained by a "young" westernmost Grand Canyon. Samples spread along the river corridor also suggest the possibility of variable mid-Tertiary thermal histories beneath north-retreating cliffs.

1. Introduction to the "age of Grand Canyon" controversy

The 140-year-long controversy about the age of the Grand Canyon was initially posed in terms of the hypothesis that the Colorado River was older than the tectonic uplifts it carves across (Powell, 1875; Dutton, 1882) and an alternate hypothesis that a younger river became erosionally superimposed on older, deeper monoclinal structures (Davis, 1901). It has long been recognized that Laramide-aged deposits from north-flowing rivers were present in the westernmost Grand Canyon (Young, 1966; Elston and Young, 1991) and some workers have related these deposits to an "old", Laramide-aged (∼70 Ma) Grand Canyon (e.g. Wernicke, 2011). As more research in the area was done, early proponents of a "young" (<6 Ma) Grand Canyon (e.g. Babenroth and Strahler, 1945; Blackwelder, 1934; Longwell, 1946; Lucchitta, 1966, 1972; McKee et al., 1967; Strahler, 1948) based their conclusions on the locally-derived Miocene–Pliocene Muddy Creek Fm., which stipulates that no far-traveled material reached the Grand Wash Trough through the mouth of the Grand Canyon between ∼13 and 6 Ma.

Low-temperature apatite thermochronology methods began to be applied to Grand Canyon incision by Naeser et al. (1989) and Kelley et al. (2001). Subsequent studies have included apatite fission track (AFT), (U–Th)/He ages (AHe), and $^4He/^3He$ thermochronometry ($^4He/^3He$) such that the combined data should resolve continuous t–T paths from ∼110 °C to surface temperatures of 10–25 °C. AFT relies on the temperature sensitivity of annealing the damage done by spontaneous fission of ^{238}U to the crystal structure. An AFT age is determined by the number of these 'fission tracks' relative to the parent isotope, while the lengths of the tracks (i.e., the degree of shortening from a ∼17 μm initial length) provide information about residence time in the partial annealing zone (110–60 °C; Ketcham et al., 2007). AHe dating is sensitive to temperatures of 90–30 °C, where apatite crystals begin retaining radiogenic ^4He at different temperatures depending on initial U and Th parent concentrations (Shuster et al., 2006; Flowers et al., 2009). $^4He/^3He$ thermochronometry provides additional information about a given sample's continuous cooling path and is especially sensitive to the lowest resolvable temperatures of the three methods (Shuster and Farley, 2005). The datasets, individually and combined, can be used to constrain multiple time–temperature (t–T) cooling paths that predict the data within acceptable statistical confidence. Cooling paths are then related to burial depths by assuming values for surface temperature and geothermal gradient, which in this area are commonly assumed to be 10–25 °C surface temperatures and a 25 °C/km geothermal gradient (Wernicke, 2011; Karlstrom et al., 2014).

Wernicke (2011) hypothesized that a NE-flowing 70–80 Ma California River and then a SW-flowing 55–30 Ma Arizona River both followed the modern Colorado River's current path through the Grand Canyon and carved the canyon to within a few hundred meters of its modern depth by ∼50 Ma. In this hypothesis, the Colorado River "was not an important factor in the excavation of Grand Canyon". Flowers and Farley (2012) noted a major difference between eastern and western Grand Canyon cooling histories but supported an "old" westernmost Grand Canyon and stated: "The western Grand Canyon $^4He/^3He$ and AHe data demand a substantial cooling event at 70–80 Ma, and provide no evidence for the strong post-6 Ma cooling signal predicted by the young canyon model." Flowers and Farley (2013) further supported the conclusion of "... apatite $^4He/^3He$ and (U–Th)/He (AHe) evidence for carving of the western Grand Canyon to within a few hundred meters of modern depths by ∼70 million years ago (Ma)".

Other workers have proposed a more complex landscape evolution for individual canyon segments (Fig. 1A, inset map). Laramide rivers flowed generally north across the Grand Canyon-Colorado Plateau region (McKee et al., 1967; Young, 2001), perhaps following the Hurricane fault system (Fig. 1; Karlstrom et al., 2014). Thermal histories generated by AHe and AFT data from Lee et al. (2013) and Karlstrom et al. (2014) indicated different cooling histories for rim and river-level rocks in the Eastern Grand Canyon before 25 Ma but similar temperatures after 15 Ma, indicating that no canyon existed in this segment until the incision of an East Kaibab paleocanyon at 25–15 Ma. Thermochronologic data from these studies and others (Warneke, 2015) also indicate that Marble Canyon was not incised until the past 5–6 Ma.

Karlstrom et al. (2014) proposed a "paleocanyon solution" whereby an "old" 70–55 Ma paleocanyon segment paralleling the Hurricane fault and an "intermediate" NW-flowing 25–15 Ma East Kaibab paleocanyon segment were linked together by the 5–6 Ma Colorado River as it was downwardly integrated from the Colorado Plateau to the Gulf of California. In this hypothesis, most of the Grand Canyon was incised by the Colorado River in the past 6 Ma. Karlstrom et al. (2017) reinforced this paleocanyon hypothesis and suggested that the 25–15 Ma East Kaibab paleocanyon was carved by an ancestral Little Colorado (not Colorado) River. Laramide (70–50 Ma) thermochronologic ages seen in many samples of that study were attributed to northward cliff retreat of Mesozoic strata off the Mogollon highlands rather than carving of a ∼70 Ma Grand Canyon. Fox and Shuster (2014) proposed that thermochronologic data from the westernmost Grand Canyon were compatible with "young" incision provided that sufficient radiation damage was retained during burial, thereby effectively changing the predicted temperature sensitivity of the system at the time of canyon incision. However, interpretations of thermochronology data from the westernmost Grand Canyon segment remain in controversy (Flowers et al., 2015).

Here we applied the three different apatite thermochronology methods using apatite from the same sample from the westernmost Grand Canyon to resolve conflicting thermal histories generated by inverse modeling of different datasets originating from the same sample. Our key sample (sample #1; see Table 1) has new, high precision $^4He/^3He$ data, multiple AHe ages, and AFT data and is from the same location as the single Flowers and Farley (2012) $^4He/^3He$ sample (#2) upon which their "old" Canyon conclusion was mainly based. These are from Separation Canyon, RM 240, where RM = river miles downstream of Lees Ferry (Stevens, 1983). We also report two new samples with combined AFT and AHe data and two new samples with AFT data that span from RM 225–260. Our objective is to re-evaluate and reconcile all new and published thermochronologic data from the westernmost Grand Canyon including AFT and AHe from Lee et al. (2013), AHe from Flowers et al. (2008), and $^4He/^3He$ from Flowers and Farley (2012).

Westernmost Grand Canyon is defined as the segment between Diamond Creek (RM 225) and the Grand Wash Cliffs (RM 276) (Fig. 1). We use the term "old" Canyon for time–temperature (t–T) paths that have a single cooling pulse at 70–55 Ma during which rocks cool to <30 °C and hence to within ∼ 200 m of river level using a 25 °C surface temperature and a 25 °C/km geothermal gradient (Wernicke, 2011). We use the term "young" Canyon for either

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