Earth and Planetary Science Letters 474 (2017) 248–256

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Westernmost Grand Canyon incision: Testing thermochronometric resolution

M. Fox [a,b,*,1], A. Tripathy-Lang [a,b], D.L. Shuster [a,b], C. Winn [c], K. Karlstrom [c], S. Kelley [d]

[a] Department of Earth and Planetary Science, University of California, Berkeley, CA, USA
[b] Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA, USA
[c] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, USA
[d] Earth and Environmental Sciences Department, New Mexico Institute of Mining and Technology, Socorro, NM, USA

ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form 21 June 2017
Accepted 27 June 2017
Available online 18 July 2017
Editor: A. Yin

Keywords:
Grand Canyon
thermochronometry
radiation damage
LA-ICP-MS

ABSTRACT

The timing of carving of Grand Canyon has been debated for over 100 years with competing endmember hypotheses advocating for either a 70 Ma ("old") or <6 Ma ("young") Grand Canyon. Several geological constraints appear to support a "young" canyon model, but thermochronometric measures of cooling history and corresponding estimates of landscape evolution have been in debate. In particular, ^{4}He/^{3}He thermochronometric data record the distribution of radiogenic ^{4}He (from the ^{238}U, ^{235}U and ^{232}Th decay series) within an individual apatite crystal and thus are highly sensitive to the thermal history corresponding to landscape evolution. However, there are several complicating factors that make interpreting such data challenging in geologic scenarios involving reheating. Here, we analyze new data that provide measures of the cooling of basement rocks at the base of westernmost Grand Canyon, and use these data as a testbed for exploring the resolving power and limitations of ^{4}He/^{3}He data in general. We explore a range of thermal histories and find that these data are most consistent with a "young" Grand Canyon. A problem with the recovered thermal history, however, is that burial temperatures are under predicted based on sedimentological evidence. A solution to this problem is to increase the resistance of alpha recoil damage to annealing, thus modifying He diffusion kinetics, allowing for higher temperatures throughout the thermal history. This limitation in quantifying radiation damage (and hence crystal retentivity) introduces non-uniqueness to interpreting time–temperature paths in rocks that resided in the apatite helium partial retention zone for long durations. Another source of non-uniqueness, is due to unknown U and Th distributions within crystals. We show that for highly zoned with a decrease in effective U of 20 ppm over the outer 80% of the radius of the crystal, the ^{4}He/^{3}He data could be consistent with an "old" canyon model. To reduce this non-uniqueness, we obtain U and Th zonation information for separate crystals from the same rock sample through LA-ICP-MS analysis. The observed U and Th distributions are relatively uniform and not strongly zoned, thus supporting a "young" canyon model interpretation of the ^{4}He/^{3}He data. Furthermore, we show that for the mapped zonation, the difference between predicted ^{4}He/^{3}He data for a uniform crystal and a 3D model of the crystal are minimal, highlighting that zonation is unlikely to lead us to falsely infer an "old" Grand Canyon.

1. Introduction

The origin of Grand Canyon has been the subject of debate since the first workers attempted to understand this spectacular landform (e.g. Powell, 1879; Davis, 1901). Over the last decade, thermochronometry has emerged as a geochemical approach to measure valley incision as it does not require measuring sediment flux and identifying the source of sediments, nor does it rely on using erosional or depositional features (such as fluvial terraces) that are erased through time due to erosion (Shuster et al., 2005). Low-temperature thermochronometry is based on the temperature dependent retentivity of daughter products of radioactive decay that are sensitive to relatively low temperatures (hence near-surface depths). This approach has been extensively applied to resolve debate surrounding Grand Canyon incision. Unfortunately, the resulting conclusions have also been controversial with different datasets supporting a 70 Ma ("old") or <6 Ma ("young") Grand

---

[*] Corresponding author.
E-mail address: m.fox@ucl.ac.uk (M. Fox).
[1] Now at Department of Earth Sciences, University College London, London, UK.

http://dx.doi.org/10.1016/j.epsl.2017.06.049

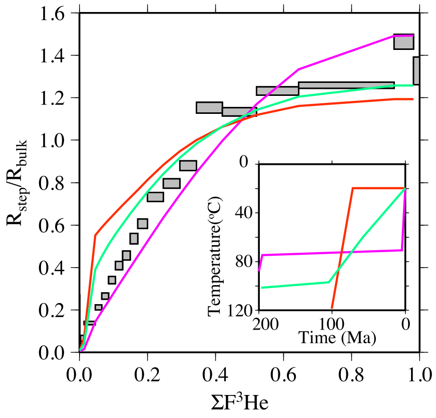

Fig. 1. $^4He/^3He$ data from the Separation Pluton in westernmost Grand Canyon. The x-axis is cumulative release fraction of proton-induced ^3He; y-axis is the R_{step}/R_{bulk} value (where R_{step} is the ratio of $^4He/^3He$ measured in a single step, R_{bulk} is the ratio of all steps summed). The data are precise due to a large abundance of Helium released in each heating step. The (U–Th)/He age of this crystal is 93.4 ± 1.43 Ma. Three reference time–temperature paths (inset) that predict this age are shown to illustrate the resolving power of the data, when assuming a spatially uniform U and Th distribution within the crystal.

Canyon (e.g., Flowers et al., 2008; Flowers and Farley, 2012, 2013; Lee et al., 2013; Karlstrom et al., 2016, 2014), as highlighted in Fig. 1. Much of this inconsistency arises because the sedimentary deposits of parts of Grand Canyon are insufficiently thick to have completely reset the applied thermochronometric systems during maximum burial conditions. Put simply, Grand Canyon incision is a difficult problem for modern methods of low-temperature thermochronometry. A companion paper by Winn et al. (2017) summarizes the debate surrounding the incision of westernmost Grand Canyon segment and highlights discrepancies amongst interpretations of thermochronometric data and geological evidence.

In the case of Grand Canyon, some of the discrepancies between different thermochronometric interpretations and geological evidence can be explained by identifying more complex landscape evolution possibilities (Karlstrom et al., 2014) or through more complex thermal histories (Fox and Shuster, 2014). Furthermore, the requirement to account for these discrepancies, combined with extensive geological constraints, makes westernmost Grand Canyon an excellent natural laboratory for exploring the limitations of the apatite (U–Th)/He thermochronometric system. In this respect, we can address the general question: what geomorphic scenarios can be excluded using high precision thermochronometric data? Here, we present a numerical analysis of apatite $^4He/^3He$ data (Winn et al., 2017) in terms of permissible time–temperature paths, and explore the possibility that much of the signal can be explained simply by changing the U and Th zonation of the crystal. We show that zonation variations can lead to dramatic differences in the time–temperature interpretation of thermochronometric data and present numerical and analytical approaches to account for this zonation.

Apatite $^4He/^3He$ thermochronometric data record the thermal history of rocks at the base of westernmost Grand Canyon with thermal resolution from ~90–30 °C (Farley, 2000; Shuster et al., 2006), and thus, for a reasonable geothermal gradient (~30 °C/km), should resolve incision of westernmost Grand Canyon. Data presented in Winn et al. (2017) and are from sample 10GC161(RM 240) are from the Paleoproterozoic Separation pluton, which crops out from RM 239.5 to 239.8 (RM = river miles downstream of Lees Ferry from Stevens, 1983). This pluton is a weakly foliated, medium grained granite that is similar to other Lower Granite Gorge plutons that range in age from 1710 to 1680 Ma (Karlstrom et al., 2003). First, we provide a brief summary of thermochronometric data from Grand Canyon, which highlight the range of geomorphic scenarios currently permitted by different thermochronometric data and interpretations. Second, we summarize the challenges faced with the interpretation of (U–Th)/He based thermochronometry in this geological setting and how this complexity provides potential to more tightly constrain thermal histories. Third, we then present the numerical methods used to maximize the amount of information we can extract from the data, but also the resolving power of the data. Finally, we present the results of our analysis and discuss the implications for the analysis of (U–Th)/He based thermochronometry in general and the Grand Canyon. Despite complicating factors and sources of uncertainty, we show that the data support a "young" Canyon model.

2. Background

2.1. Thermochronometry and Grand Canyon debate

Thermochronometry constrains the range of possible thermal histories of rocks at the base of the canyon during both burial by Paleozoic and Mesozoic strata and canyon incision, and thus can provide an *in-situ* record of landscape evolution. The transition between loss and retention of ^4He in the apatite (U–Th)/He system occurs between ~90–30 °C due changes in thermally activated diffusive loss of radiogenic ^4He (Zeitler et al., 1987; Farley, 2000; Shuster et al., 2006). Assuming a reasonable geothermal gradient (~30 °C/km), these temperatures correspond to 1–3 km. For Grand Canyon, apatite (U–Th)/He ages predicted for multiple time–temperature paths help understand the incision history (e.g., Flowers et al., 2008; Flowers and Farley, 2012; Wernicke, 2011; Lee et al., 2013; Karlstrom et al., 2014, 2016). However, these inferred time–temperature paths are non-unique, and our knowledge of the He diffusion kinetics in apatite fundamentally limits their accuracy.

Using bulk (U–Th)/He ages, Flowers et al. (2008) concluded that "the gorge and the plateau surface had similar Early to mid-Tertiary thermal histories, despite their >1500 m difference in vertical structural position... indicating that a 'proto-Grand Canyon' of kilometer-scale depth had incised post-Paleozoic strata by the Early Eocene". Wernicke (2011) hypothesized that a 70–80 Ma California River flowing NE, followed by a 55–30 Ma Arizona River flowing SW, carved Grand Canyon to within a few hundred meters of its modern depth.

Lee et al. (2013) and Karlstrom et al. (2014) presented (U–Th)/He ages and apatite fission track data (sensitive to ~110–60 °C: Carlson et al., 1999) from rim and river-level rocks in the eastern Grand Canyon that suggest different cooling histories prior to 25 Ma, but similar temperatures after 15 Ma. They interpret these data to indicate that no canyon existed in this segment until the 25–15 Ma incision of an East Kaibab paleocanyon; further, their data indicate that Marble Canyon was not incised until the last 5–6 Ma. Karlstrom et al. (2014) then proposed a paleocanyon solution in which most of modern Grand Canyon was incised by the Colorado River in the last 6 Ma. Karlstrom et al. (2016) reinforced this paleocanyon hypothesis by re-modeling thermochronometric data (from Flowers et al., 2008) from the Little Colorado River valley; these data support incision of the 25–15 Ma East Kaibab paleocanyon by a 25–15 Ma ancestral Little Colorado River. Older 70–50 Ma thermochronometric ages seen in many samples are attributed to northward cliff retreat of Mesozoic strata off the Mogollon highlands rather than carving of a 70–25 Ma Grand Canyon.

Apatite $^4He/^3He$ thermochronometry involves stepwise degassing of individual crystals that have been irradiated with energetic protons, and thus contain a spatially uniform distribution of artificial ^3He (Shuster and Farley, 2004). The results of the stepwise degassing experiment reveals the spatial distribution of ^4He within the crystal, which can then be used to constrain possible