Did incision of the Three Gorges begin in the Eocene?

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Abstract

Like the other large river systems that drain the India-Asia collision, the Yangtze River was assembled through a series of Cenozoic capture events. These events are important for orogenic erosion and sediment delivery, but their timing remains largely unknown. Here we identify enhanced cooling in the Three Gorges region in central China, a key capture site during basin development, beginning at 40-45 Ma. This event is not visible in regional thermochronological data but is near-contemporaneous with the onset of widespread denudation in the Sichuan Basin, just upstream of the Three Gorges. While we cannot rule out alternative explanations, the simplest mechanism that links these events is progressive capture of the middle Yangtze River by the lower Yangtze and the onset of incision in the Three Gorges. This model agrees with independent mid-Cenozoic estimates for the timing of middle Yangtze River diversion and capture, and provides a plausible outlet for large volumes of erosional detritus from the Sichuan Basin.

Keywords: Yangtze River, low-temperature thermochronology, Three Gorges, fluvial incision

Introduction

The India-Asia collision zone is drained by large river systems that convey enormous sediment loads to the Asian marginal seas (Métivier et al., 1999; Clift et al., 2004). It has long been argued that these rivers have grown in part by large-scale capture events (Brookfield, 1998), such as diversion of Punjab drainage from the Ganges to the Indus (Clift and Blusztajn, 2005) and diversion of the upper and middle Yangtze away from the Red River (Clark et al., 2004; Clift et al., 2004). Such events have major effects on patterns of erosion and sediment dispersal, but their recognition onshore is often hampered by later erosion or the lack of datable sedimentary deposits. Offshore sedimentary basins can record the timing of large-scale drainage diversion, but their utility may be limited by incomplete data or onshore storage (Clift et al., 2004; Clift, 2006).

Here, we use low-temperature thermochronology to infer the timing of Yangtze River evolution in the Three Gorges region of central China (Fig. 1). Several lines of evidence have been used to argue that the Yangtze grew by the amalgamation of several smaller rivers, beginning with the progressive capture of the southwest-flowing middle Yangtze River by the east-flowing lower Yangtze River at the Three Gorges (Barbour, 1936; Clark et al., 2004; Clift et al., 2006) (Fig. 1). This capture led to integration of the Sichuan Basin into the lower Yangtze system. While the presence of barbed tributaries and tilted terraces has been used to argue that the middle Yangtze reversed course to flow east through the Three Gorges at some point in the Cenozoic (Clark et al., 2004), there is no direct onshore evidence of the timing of capture, and offshore records are obscured by sediment storage in the lower Yangtze basin (Clift, 2006; Chappell et al., 2006). Prior work has suggested a Pleistocene age for the Three Gorges (e.g., Li et al., 2001; Yang et al., 2006), but these studies generally yield minimum estimates based on the age or provenance of young (post-Pliocene) rocks, and are thus unable to rule out older events.

An indirect clue to the timing of middle Yangtze capture was provided by Richardson et al. (2008), who argued for widespread erosion of 1.5 to 4 km across the Sichuan Basin beginning at about 40 Ma. This erosion marked the end of sustained Triassic-Eocene(?) clastic sedimentation in the basin (Burchfiel et al., 1995), and Richardson et al. (2008) proposed that erosion was driven by linkage of the middle and lower Yangtze rivers and establishment of an outlet at the Three Gorges, through which sediment could be removed. Capture of the middle Yangtze would have resulted in a large increase in drainage area of the lower Yangtze, leading to rapid incision in the Three Gorges area and localized cooling of the upper crust. The timing of this cooling is thus a test of the link between Yangtze River evolution and erosion in the Sichuan Basin. If cooling rates in the gorge increased at or just before 40 Ma, and if the Three Gorges area underwent a cooling event that did not extend more regionally, then it is plausible to suggest a causal relationship between erosion within the Sichuan Basin, the capture of the middle Yangtze River, and the inception of the Three Gorges.

Study Area

The Three Gorges region, with up to 3 km of relief, separates the low-elevation, low-relief areas of eastern China and the Sichuan Basin (Fig. 1). While most of the area is underlain by Paleozoic and Mesozoic carbonate rocks (Ma et al., 2002), the Yangtze River transects the Huangling anticline at the eastern margin of the gorges (Fig. 2) and exposes approximately two vertical kilometers of the Proterozoic Huangling Granite massif (Li et al., 2002; Ling et al., 2006). Folding of the anticline occurred before Early Cretaceous time, because Lower

Cretaceous Shimen Formation rocks are draped unconformably on both flanks of the anticline, with dips of 5-15˚ (Fig. 2).

We use apatite (U-Th)/He (AHe) and fission-track (AFT) techniques to constrain the low temperature (<100˚C) thermal history of the Huangling Granite near Sandouping, site of the Three Gorges Dam (see Data Repository for analytical details). Samples were obtained along a pseudo-vertical transect from altitudes of 190 m to 1923 m within 27 km of the Yangtze River. The AFT and AHe ages are sensitive to the time at which the samples passed through temperatures as low as 45°C depending on cooling rates, grain size and other factors such as radiation damage (Reiners and Brandon, 2006; Shuster et al., 2006). The topography in the area precludes a true vertical profile, and we discuss the implications of this below.

Results

Mean AHe single-grain ages (Fitzgerald et al., 2006) range from 46±16 Ma (2σ) for sample H1 at the base of the section (190 m) to 45±12 Ma for sample H4 (Table DR1), which marks a break in slope in the age-elevation relationship at 1350 m (Fig. 2). Samples above this break in slope yield older single-grain ages. The exception to this pattern is sample H3, which yields widely scattered ages; the reasons for this are not clear but may involve the presence of microscopically undetectable zircon or other U-bearing inclusions.

The AFT samples (Table DR2) yield scattered central ages ranging from 86±10 Ma (2σ) to 133±11 Ma, and show no systematic variation with elevation (Fig. 2). To explore the AFT results in more detail, thermal forward modelling of apparent ages and horizontal confined fission-track lengths were undertaken using the HeFTY software (Ketcham, 2005), including

Dpar measurements (Donelick, 1993) as a proxy for chemistry. The modelling was completed without the AHe data, to avoid forcing the sample time-temperature paths through the AHe ages. The lowermost sample (H1, Fig. 3) remained in the AFT partial annealing zone (APAZ) at T ~ 70°C until the onset of more rapid cooling (1-2°C/Myr) at about 40 Ma. At higher elevations, samples H1.5, H3, and H5 record broadly similar, monotonic post-Cretaceous cooling paths which permit, but do not require, a comparable acceleration in cooling rate at ~40-45 Ma. The highest sample, H6, was already at temperatures of < 60°C by 40 Ma (Fig. 3), and thus lies outside the temperature range at which the model results can be confidently interpreted. All samples spent prolonged periods in the APAZ.

Discussion and Conclusions

What is the expected thermochronologic signature of gorge incision, and how can we differentiate this from regional exhumation? We suggest two potential signatures: (1) more rapid cooling of the lower samples relative to those at higher elevations, indicating an increase in relief (Braun, 2002; Schildgen et al., 2007), or (2) a cooling event which involved all samples (and thus no increase in local relief), but which is not observed outside the gorge area. It is tempting to interpret the steep AHe age-elevation relationship below 1350 m (Fig. 2) as evidence for rapid cooling of the lower samples at 40-45 Ma. We can only tentatively exploit this relationship, however, because of the large horizontal span of our transect (27 km). The admittance ratio α, the ratio of relief on the AHe closure isotherm to topographic relief, is ~0.7 (Braun, 2002; Reiners et al., 2003), implying that the slope of the AHe age-elevation relationship is greater than the likely exhumation rate by at least a factor of three. Prolonged residence in the APAZ most likely accounts for the large scatter in fission-track age, and we infer that there has been insufficient cooling to expose the base of the APAZ and yield an unambiguous AFT age-elevation relationship.

One indication of gorge incision after 45 Ma is that AFT sample H1 has cooled by 50°C, whereas sample H6 has cooled by only 5-40°C, since that time (Fig. 3). implying differential cooling of 10-45°C. Present-day geothermal gradients in the region range from ~15˚C km^{-1} at the western margin of the Gorges (Xie and Yu, 1988) to 23-40˚C km^{-1} in the extensional Jianghan Basin to the east (Xie et al., 1988). Using an average value of 20°C km^{-1}, this implies differential exhumation of the lower samples by 0.5 to 2.3 km since 45 Ma. Compression of isotherms beneath the gorge could increase the local geothermal gradient by ~20% (Stüwe et al., 1994), decreasing these estimates to ~0.2 to 2.0 km. Thus, while we cannot entirely rule out uniform cooling on this basis, it is likely that the lower samples record some degree of differential incision.

A second argument in support of gorge incision comes from thermal modelling of the AHe data. Following Reiners et al. (2003), we calculate the depth to the closure isotherm for each AHe sample using 1d numerical models (Brandon et al., 1998). Total exhumation of each sample is the model closure depth plus the difference between sample elevation and elevation smoothed over a 10 km circle, to account for bending of near-surface isotherms. Model exhumation rate is then the total exhumation divided by the sample age. Again assuming a geothermal gradient of 20°C km^{-1}, model closure temperatures are 46-51°C, and model exhumation rates are 13 to 39 m Myr^{-1}. The highest rates are limited to samples at or below 1350 m (H1, H2, and H4), while rates for the upper samples are lower by a factor of ~2-3, again consistent with greater differential incision of the lowermost samples. Total model exhumation of sample H6 is 1.7 km, meaning that gorge incision most likely began in the Precambrian-Paleozoic sedimentary cover overlying the Huangling Granite.

In summary, our AFT forward models are consistent with a moderate increase in exhumation rate at 45-40 Ma, although only sample H1 actually requires this increase, and both AFT and AHe data support more rapid cooling of the lower samples in the transect. If this cooling event occurred, how widespread was it? Reiners et al. (2003) concluded that the Dabie Shan, east of the Three Gorges (Fig. 1), underwent slow exhumation throughout the Cenozoic, with no increase in rates after 60 Ma. AFT samples from the eastern Qinling Shan, to the north of the study area, likewise show slow cooling since at least 70-100 Ma (Enkelmann et al. 2006), with no indication of more rapid cooling during the Cenozoic. Finally, Hu et al. (2006) reported AHe and AFT ages and AHe model exhumation rates that are comparable to ours (Fig. 2). Their samples from the southern Qinling Shan and northern Huangling areas cooled show no evidence for enhanced cooling rates after 60 Ma (Hu et al. 2006). In contrast, their sample QL-34 (Fig. 1) records a very similar cooling history to H1: prolonged residence at ~70°C, followed by an increase in cooling rate (to 1-5°C Myr^{-1}) at ~40 Ma. Hu et al. (2006) cited the sample's proximity to the Yangtze River but gave no reasons for its anomalous behavior. Enhanced cooling at 45-40 Ma thus appears to be limited to the area near the Yangtze River, and there is no evidence for a regional cooling event at this time.

If differential incision in the Three Gorges occurred, and was unrelated to regional cooling events, how can that be linked to the development of a through-going Yangtze River? The fact that gorge incision is effectively synchronous with the onset of erosion across the Sichuan Basin at ~40 Ma (Richardson et al., 2008) supports a causal link, and we argue that capture of the middle Yangtze and Sichuan Basin by the lower Yangtze is the simplest mechanism that can account for near-simultaneous gorge incision and large-scale basin denudation (Fig. 4). Progressive capture would have generated increased discharge in the lower Yangtze as the capture site migrated upstream (Fig. 4), leading to locally increased exhumation rates in the gorge area. This migration (e.g., Clark et al., 2004) would have lowered base level in the Sichuan Basin, leading to extensive regional denudation, and would also have provided an outlet for the removal of erosional detritus. The inferred timing of gorge incision is broadly consistent with existing constraints on middle Yangtze capture – before 24 Ma based on isotopic data in the Gulf of Tonkin (Clift et al., 2006), or before Oligo-Miocene time based on structural interpretations (Clark et al., 2004).

We cannot rule out cooling mechanisms in the Three Gorges that were coeval with, but unrelated to, erosion in the Sichuan Basin, although given the proximity of the two areas these would require a degree of serendipity. For example, it is possible that samples H1 and QL-34 were perturbed by a local thermal event or by pre-existing, short-wavelength topography which we are unable to resolve. There is also poorly-documented evidence of late Eocene normal faulting in the Jianghan Basin (Ulmishek, 1992), which could have triggered local footwall erosion and more rapid cooling of the Huangling Granite. This faulting does not explain the near-simultaneous onset of erosion in the Sichuan Basin, however, and does not necessarily exclude gorge incision; in fact, fault activity may well have steepened the lower Yangtze River and enhanced its capacity to incise headward, thus aiding capture. In any case, our results provide the first indication that incision of the Three Gorges may have occurred as early as the Eocene, consistent with independent estimates of middle Yangtze capture, and that this incision provided a plausible outlet for the progressive removal of large volumes of sediment from the Sichuan Basin.

Acknowledgements

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Figure Captions

Fig. 1. A, location map showing upper, middle, and lower reaches of the Yangtze River (separated by dashed lines). Box shows Three Gorges study area. B, geological map of the eastern end of the Three Gorges (modified from Ma *et al*. 2002). Samples H1 to H6 from this study are marked with stars, while those from Hu et al. (2006) that fall within our transect are marked with circles. HGr, Huangling Granite and related intrusive rocks; pC, Precambrian; Pz, Palaeozoic; TJ, Triassic-Jurassic; K, Cretaceous.

Fig. 2. Age-elevation relationships for apatite (U-Th)/He (AHe) and fission track (AFT) samples from the Huangling Granite. White symbols mark samples from this study, grey symbols mark those from Hu et al. (2006). All age errors (x-axis) are ±2 s.d.; all elevation errors (y-axis) are ±50 meters.

Fig. 3. Results of AFT thermal modelling, derived from HeFTy model (Ketcham, 2005). Light grey regions show 95% confidence envelopes on the temperature-time path, defined by the Kolmogorov-Smirnov test applied to the track length distribution; dark grey regions show 50% confidence envelopes. Grey bar on each plot indicates the time period 45-40 Ma for

reference. Single-crystal AHe ages are plotted as circles at a model closure temperature of 50˚C.

Fig. 4. Proposed model of Three Gorges incision and Yangtze River evolution. A, prior to ~45 Ma the Sichuan Basin was isolated from the proto-lower Yangtze River. Location of eastern Tibetan Plateau is shown for reference; our data do not constrain the timing of plateau growth. B, gorge incision beginning at ~45 Ma (shown by Vs) and progressive capture of the middle Yangtze River lowered base level and drove rapid erosion in the Sichuan Basin. C, by ~35 Ma erosion had propagated headwards across the Sichuan Basin.

Figure 1
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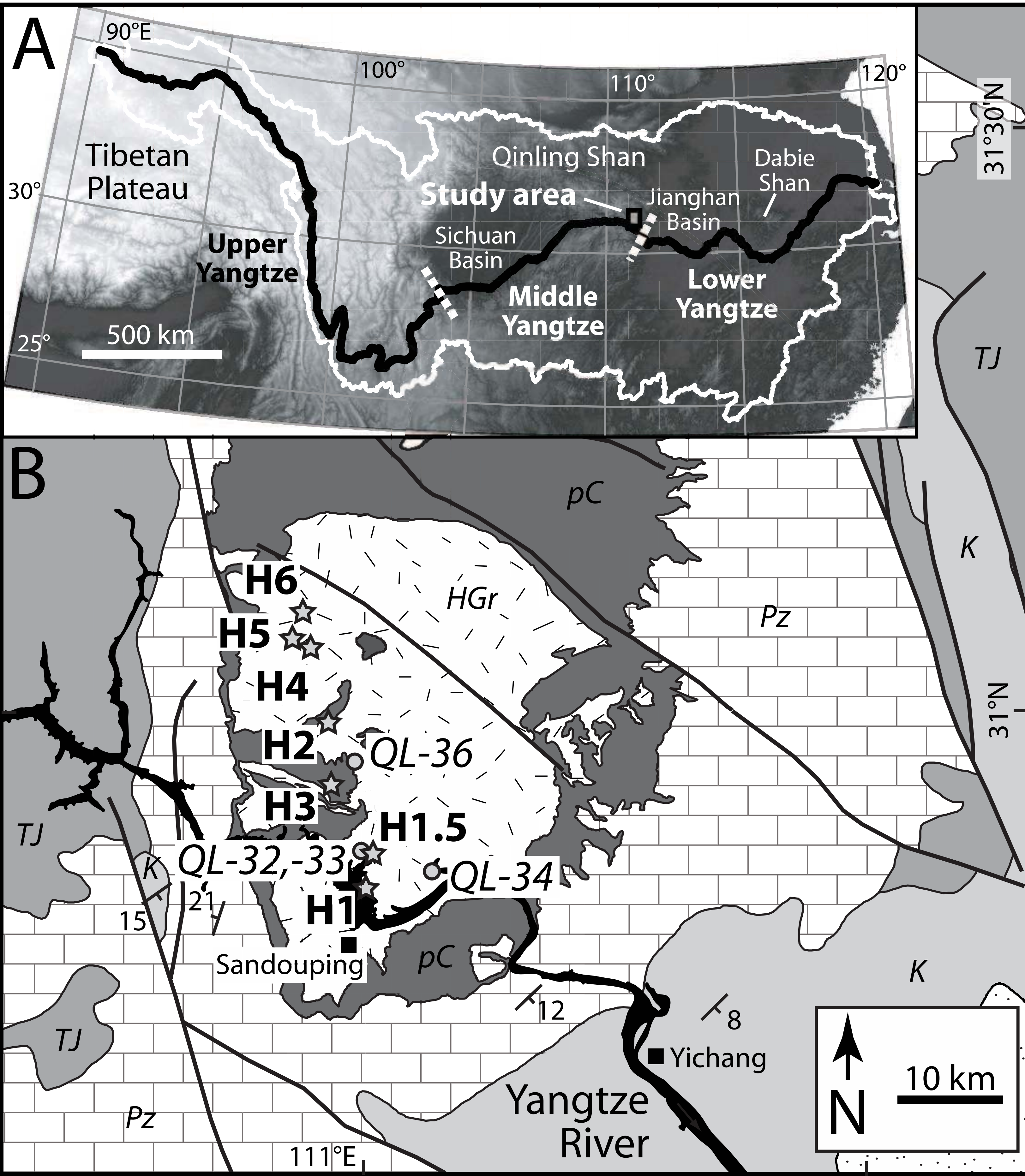

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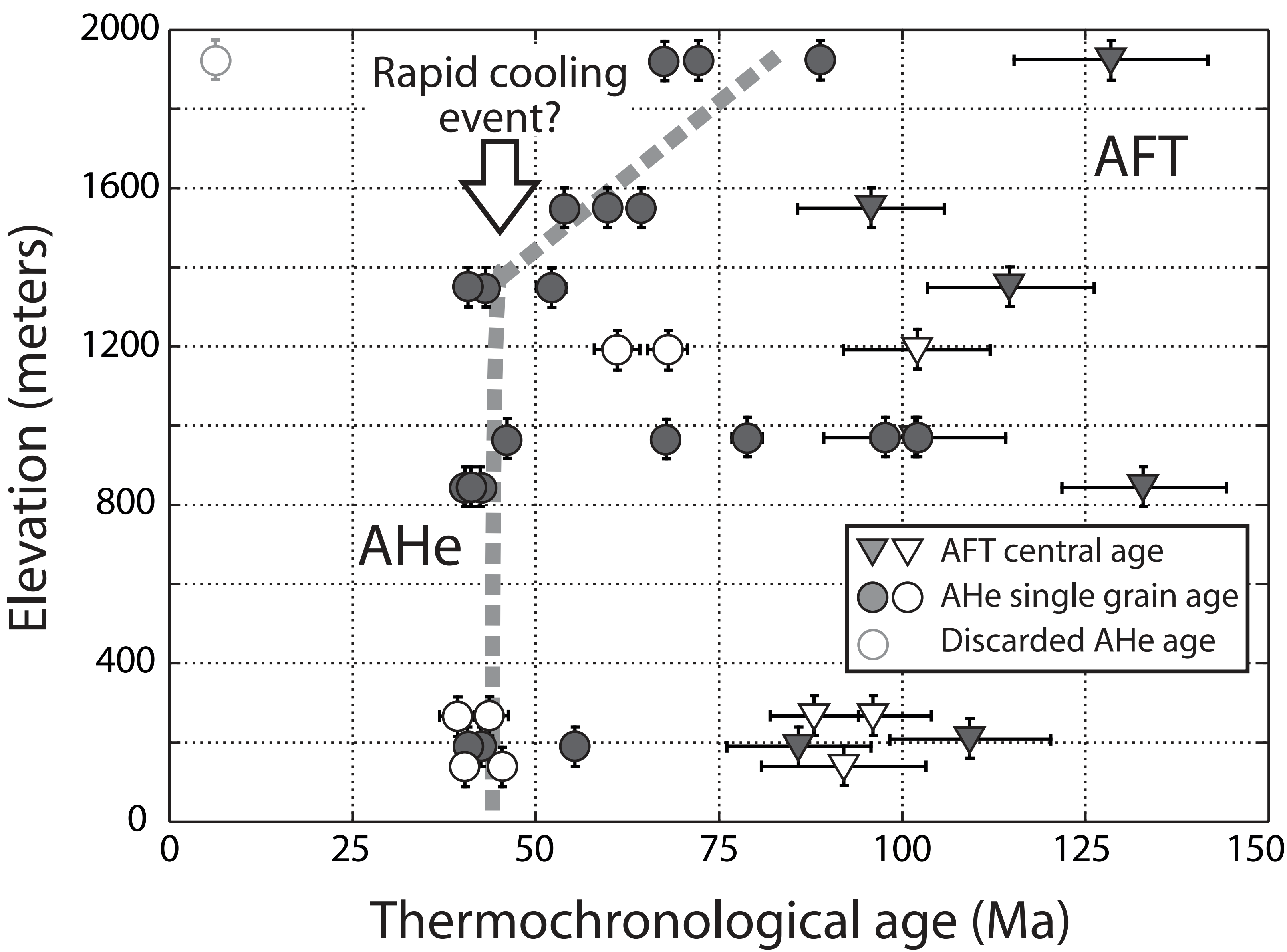

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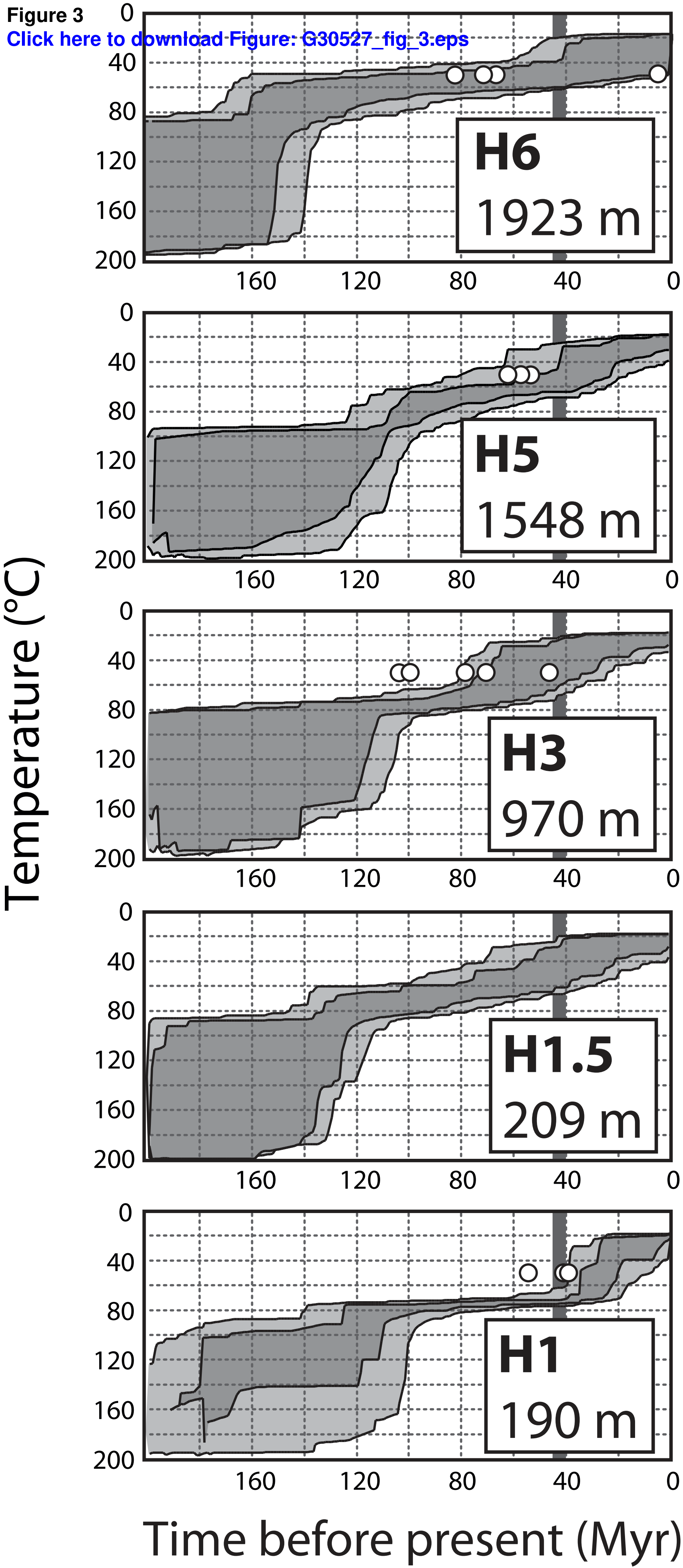

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