Late Cenozoic uplift of southeastern Tibet

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ABSTRACT

The age of surface uplift in southeastern Tibet is currently unknown, but the initiation of major river incision can be used as a proxy for the timing of initial uplift. The topographically high eastern plateau and gently dipping southeastern plateau margin are mantled by an elevated, low-relief relict landscape that formed at a time of slow erosion at low elevation and low tectonic uplift rates prior to uplift of the eastern Tibetan Plateau. Thermochronology from deep river gorges that are cut into the relict landscape shows slow cooling between ca. 100 and ca. 10–20 Ma and a change to rapid cooling after ca. 13 Ma with initiation of rapid river incision at 0.25–0.5 mm/yr between 9 and 13 Ma. A rapid increase in mean elevation of eastern Tibet beginning at this time supports tectonic-climate models that correlate the lateral (eastern) expansion of high topography in Tibet with the late Miocene intensification of the Indian and east Asian monsoons.

Keywords: Tibet, thermochronology, thermal modeling, tectonics, Indian monsoon, east Asian monsoon, Miocene.

INTRODUCTION

A substantial part of the high topography related to the Tibetan orogen has developed east of the main Himalayan collision zone (Fig. 1, inset) where a crustal volume of >2 × 10⁷ km³ has been added in Cenozoic time. However, eastern Tibet lacks large-magnitude, late Cenozoic shortening structures commonly associated with crustal thickening (Burchfiel et al., 1995; Leloup et al., 1995; Wang and Burchfiel, 1997; Wang et al., 1998), consistent with crustal thickening by eastward flow of the deep crust without significant horizontal deformation of the surface (e.g., Royden et al., 1997; Clark and Royden, 2000). Thus, one of the few means of dating crustal thickening in eastern Tibet is through the fluvial response to an increase in mean elevation.

The regional topographic slope of the southeastern Tibetan Plateau is defined by low-relief, upland erosion surfaces which we interpret as remnants of a once-continuous, low-elevation paleolandscape (or relict landscape) prior to plateau uplift (Clark, 2003). These remnant surfaces are preserved because fluvial incision of deep river gorges, initiated on major rivers and principal tributaries, has not yet progressed through the entire fluvial network. Because remnant surfaces have not yet adjusted to modern uplift and trunk stream incision rates, they act as passive markers to vertical motion of the Earth’s surface and their modern altitude provides a useful datum for measuring surface uplift and the magnitude of river incision. Therefore, the timing of accelerated erosion rates related to forming deep river canyons can be used as a proxy for the timing of plateau uplift.

Changes in erosion rate can be interpreted from the cooling history of the shallow crust by using low-temperature thermochronometers such as the apatite (U-Th)/He and fission-track (AFT) systems. Cooling ages collected on a vertical elevation transect track the thermal history of a crustal section relative to the Earth’s surface. When samples cool through their closure temperatures (~40–80 °C for (U-Th)/He (Farley, 2000) and <125 °C for apatite fission tracks (e.g., Gledowell et al., 1983; Green et al., 1986)) in response to erosional or structural exhumation, their age vs. elevation relationship can be used to determine the rate of exhumation using reasonable assumptions about the geothermal gradient (e.g., Stockli et al., 2000). The incision of major rivers into the relict landscape is manifested by a dramatic transition from slow to rapid erosion rates, producing an increase in

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Figure 1. Sample location map and generalized Cenozoic tectonic structures (from Burchfiel et al., 1995; Wang et al., 1998). Colored symbols represent individual sample locations grouped by vertical transect location. Yellow shading outlines extent of relict landscape surface. Note that Sichuan Basin is not Cenozoic depocenter. Surface of Sichuan Basin is cut across deformed Mesozoic strata with less than few hundred meters of Cenozoic sedimentary cover.
remnant surface occurs locally across the Xianshuihe fault (Appendix Fig. 1). Mean (U-Th)/He ages range from 50 to 112 Ma on the Daocheng transect and a single sample at Pamai were collected within 840 m of the elevation of the relict landscape surface along the Yangtze River and three of its major tributaries, the Yalong, Dadu, and Anning Rivers (Fig. 1; Table DR1 [see footnote 1]). Rugged terrain, restricted accessibility, and limited exposure of lithologies appropriate for (U-Th)/He dating prohibited collection of a transect from the plateau surface to the bottom of the river gorge in any single locality. Consequently, we collected elevation transects covering as great an elevation range as possible in multiple localities (Table DR1; see footnote 1). The (U-Th)/He mean ages of 17±20 Ma on the Anning transect define a steep age vs. elevation gradient for a similar depth interval (Table DR2 and DR3; see footnote 1). The slopes of both transects are poorly defined owing to the narrow elevation range of each transect (300–550 m) and the large scatter in some of the ages.

The deepest samples collected beneath the plateau surface come from the Yalong and Danba transects (1800 and 2880 m depth) (Fig. 1). Mean (U-Th)/He ages are 9.4–5.5 Ma on the Danba transect and 10.8–4.6 Ma on the Yalong transect (Table DR2 and DR3; see footnote 1). Together, these ages exhibit a steep, well-defined depth vs. age trend with a slope of ~0.25 mm/yr collected over an elevation interval of nearly 1 km (Appendix DR1; see footnote 1). Pooled mean AFT ages range from 10.5 to 8.4 Ma at Danba and from 6.4 to 4.7 Ma at Yalong (Fig. 2; Table DR4 [see footnote 1]). The Danba AFT data define a steep depth vs. age trend, whereas the Yalong AFT data are scattered (Appendix DR1; see footnote 1). Long AFT track lengths on all of these samples are consistent with rapid cooling rates (Table DR4; see footnote 1) (e.g., Gleadow et al., 1986).

**LOW-TEMPERATURE THERMOCHRONOLOGY**

We present data from 29 granitoid samples collected for apatite (U-Th)/He thermochronology and a subset of eight samples collected for AFT thermochronology (Fig. 1; Table DR1 [see footnote 1]). Samples were collected across the relict landscape and in the river gorges along the Yangtze River and three of its major tributaries, the Yalong, Dadu, and Anning Rivers (Fig. 1; Table DR1 [see footnote 1]). We subtract each sample elevation from the average local elevation of the relict landscape in order to estimate the minimum depth for each sample. The depth of each transect beneath an originally subhorizontal surface provides a common reference frame between transects (Clark, 2003; Appendix DR1 [see footnote 1]).

The Daocheng transect and a single sample at Pamai were collected within 840 m of the elevation of the relict landscape surface (Fig. 1). Mean (U-Th)/He ages range from 50 to 112 Ma on the Daocheng transect and 58 ± 6 Ma at Pamai (Fig. 2; Tables DR2 and DR3 [see footnote 1]). The large age range within a narrow elevation interval indicates slow cooling, likely accompanied by slow erosion, between ca. 50 and 120 Ma (Appendix DR1; see footnote 1).

The Dadu and Anning transects span an intermediate depth range of between 1500 and 2150 m below the relict landscape surface (Fig. 1). In the vicinity of both transects, an elevation step of ~0.5–1 km in the remnant surface occurs locally across the Xianshuihe fault (Appendix DR1; see footnote 1). Mean (U-Th)/He cooling ages of 5–21 Ma from the Dadu transect exhibit a positive correlation between age and elevation with a slope of ~0.03 mm/yr (Tables DR2 and DR3; see footnote 1). The (U-Th)/He mean ages of 17–20 Ma on the Anning transect define a steep age vs. elevation gradient for a similar depth interval (Table DR2 and DR3; see footnote 1). The slopes of both transects are poorly defined owing to the narrow elevation range of each transect (300–550 m) and the large scatter in some of the ages.

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**REGIONAL COOLING PATTERN AND FORWARD THERMAL MODELING**

To a first approximation, the cooling pattern observed from the regional (U-Th)/He data is consistent with a protracted period of slow erosion or slow cooling beneath the relict landscape surface from ca. 100 to after ca. 20–10 Ma (Fig. 2). The variation in mean ages vs. depth suggests slow erosion rates (~0.02 mm/yr) or slow cooling by conduction (~1 °C/m.y.) beneath a surface that has been subject to <2 km of total erosion since 100 Ma. These alternatives are indistinguishable on the basis of our data. Taken separately, the ages on the Anning transect suggest an early initiation of rapid cooling (ca. 20 Ma). Because large errors are associated with these samples and rapid cooling is observed over only a few data points, we prefer to use the ages on...
We choose a range of nominal closure temperatures, 90±110 °C, for a second finite-difference algorithm (Wolf et al., 1998; Farley, 2000). The (U-Th)/He ages were computed from this thermal history using a one-dimensional thermal model with a standard entrenchment of river gorges (Fig. 2). We forward modeled the ob-
presented here are along strike of the highest portion of the plateau margin (i.e., perpendicular to the regional topographic gradient). If uplift or geothermal gradient were spatially variable in this region, we would expect greater age variability between transects in the deepest river gorges (i.e., Danba and Yalong) than is observed. However, we expect that future transects collected more interior to the high plateau or more distal along the plateau margin (i.e., parallel to the regional topographic gradient) will show age variation related to the lateral growth of the plateau margin.

Late Miocene initiation of major river incision is broadly contemporaneous with development of high topography near the Sichuan Basin between 12 and 5 Ma (Kirby et al., 2002) and the initiation of the modern strike-slip and normal faulting pattern in eastern Tibet at 8±4 Ma (e.g., Wang et al., 1998; Chen et al., 2000). We suggest that these major regional events that took place in eastern Tibet from ca. 13 to 5 Ma were related to the onset of crustal thickening beneath the easternmost plateau margin (east of long 100°E).

River gorges require that an increase in mean topography occurred prior to or coeval with the initiation of major river incision because elevated topography is necessary in order to create deep river canyons. It is possible that rapid incision of the major rivers lagged behind the onset of uplift, depending on climatic conditions. However, we suggest that the changes in elevation probably induced river incision at least within 1±2 m.y. of the initiation of surface uplift.

Uplift and increased precipitation may have had important synergistic effects that are responsible for the synchronicity between monsoon strengthening and the development of high topography and rapid river incision in eastern Tibet. Perturbation of wind patterns by the lateral expansion of the Tibetan Plateau are thought to have led to the strong seasonality associated with the modern-day monsoonal climate observed in Southeast Asia (Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992, 1997). Uplift of eastern Tibet may have strengthened precipitation (related to regional climatic changes and orographic effects) so that increased elevation and increased precipitation acted in concert to increase river incision rates. It is significant that the ages we obtain for the initiation of rapid fluvial incision in Tibet (13±9 Ma) closely approximate the estimated timing of environmental change (8.5 Ma; e.g., Kroon et al., 1991; Prell et al., 1992; An et al., 2001) and are consistent with a strong link between the lateral (eastern) expansion of high topography in Tibet and the synchronous (or slightly later) late Miocene intensification of the east Asian monsoon.

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