

Thermochronologic evidence for plateau formation in central Tibet by 45 Ma

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ABSTRACT

The timing of Tibetan plateau development remains elusive, despite its importance for evaluating models of continental lithosphere deformation and associated changes in surface elevation and climate. We present new thermochronologic data [biotite and K-feldspar ⁴⁰Ar/³⁹Ar, apatite fission track, and apatite (U-Th)/He] from the central Tibetan plateau (Lhasa and Qiangtang terranes). The data indicate that over large regions, rocks underwent rapid to moderate cooling and exhumation during Cretaceous to Eocene time. This was coeval with >50% upper crustal shortening, suggesting substantial crustal thickening and surface elevation gain. Thermal modeling of combined thermochronometers requires exhumation of most samples to depths of <3 km between 85 and 45 Ma, followed by a decrease in erosional exhumation rate to low values of <0.05 mm/yr. The thermochronological results, when interpreted in the context of the deformation and paleoaltimetric history, are best explained by a scenario of plateau growth that began locally in central Tibet during the Late Cretaceous and expanded to encompass most of central Tibet by 45 Ma.

INTRODUCTION

Tibetan plateau growth has influenced geodynamic processes through its high gravitational potential energy, and has affected the global climate system (Harrison et al., 1992; Molnar et al.,

1993; Ruddiman et al., 1997). Common to many models of Tibetan plateau formation are the assumptions that most of Tibet was near sea level prior to the India-Asia collision at 55–50 Ma, and that the plateau grew northward and eastward

away from the Indus-Yarlung suture (Fig. 1; Houseman and England, 1996; Tapponnier et al., 2001; Rowley and Currie, 2006). The deformation history of central Tibet, however, implies substantial crustal thickening and elevation in this region by the time India collided with Asia.

During Cretaceous–Early Eocene time, the Lhasa terrane collided with the Qiangtang terrane to the north. This led to Early Cretaceous shortening along the intervening Bangong suture (Fig. 1) and as much as 240 km of north-south shortening by growth of the Qiangtang culmination (Fig. 1; Kapp et al., 2005, 2007a; Guynn et al., 2006). South-directed thrusting, in response to continued Lhasa-Qiangtang collision, propagated southward into the northern Lhasa terrane thrust belt (~50% shortening; Fig. 1) during mid-Cretaceous to Early Eocene time (Murphy et al., 1997; Kapp et al., 2003; Volkmer et al., 2007). At the same time, in the southern Lhasa

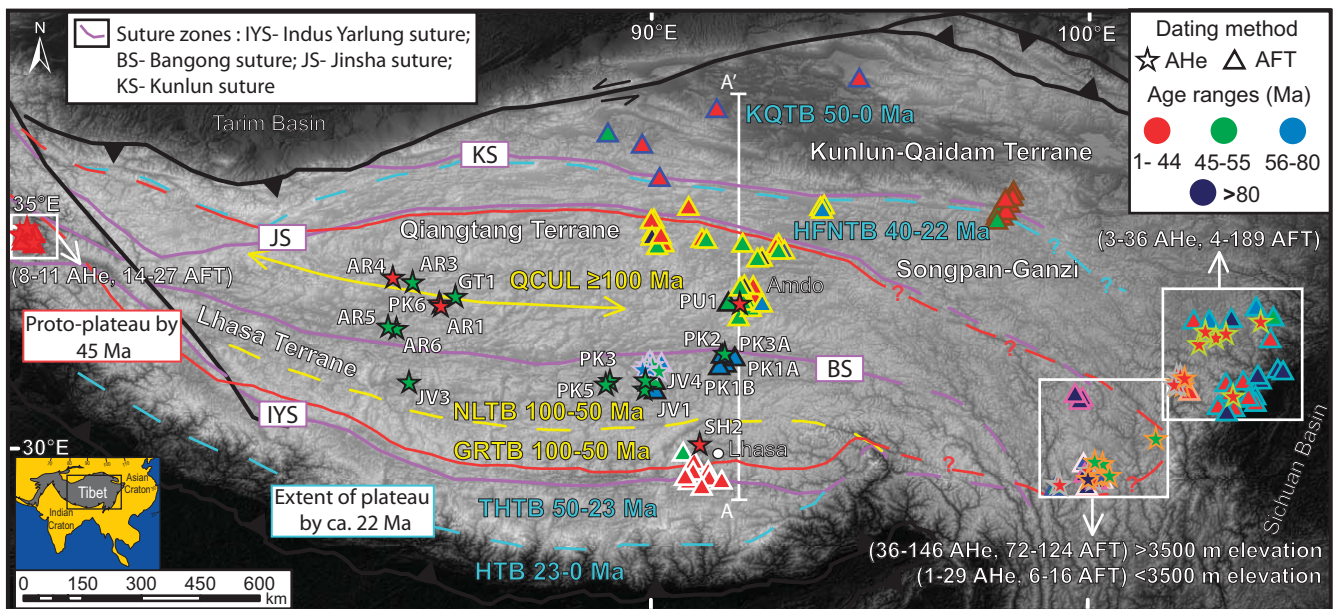


Figure 1. Shuttle Radar Topography Mission map showing tectonic elements of Tibetan plateau, line of swath profile (Fig. 3), and locations of samples: outline colors indicate following: black—this study; white—Copeland et al. (1995); turquoise—Arne et al. (1997); blue—Jolivet et al. (2001); green—Kirby et al. (2002); beige—Reid et al. (2005); orange—Clark et al. (2005); brown—Yuan et al. (2006); pink—Lai et al. (2007); yellow—Wang et al. (2008); dark red—van der Beek et al. (2009); gray—Ouimet et al. (2010); purple—Hetzl et al. (2011). AFT—apatite fission track. Contractional structures and age of activity: QCUL—Qiangtang culmination; NLTB—northern Lhasa terrane thrust belt; GRTB—Gangdese retroarc thrust belt; THTB—Tethyan Himalayan thrust belt; HTB—Himalayan thrust belt; HFNTB—Hoh-Xil-Fenghuo Shan-Nanqian thrust belt; KQTB—Kunlun-Qaidam thrust belt.

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terrane, the Gangdese retroarc thrust belt (Fig. 1) shortened >50% during northward subduction of Neotethyan oceanic lithosphere (Kapp et al., 2007b). How shortening was accommodated in the lower crust is unknown. Nevertheless, it is reasonable to conclude that 50% shortening over such a large region (modern north-south width of ~500 km) led to substantial crustal thickening and elevation gain in central Tibet. This deformation history, together with widespread exposures of nearly flat-lying Paleogene volcanic rocks, led to the proposition that plateau-like conditions were established in parts of these terranes by 50 Ma (Murphy et al., 1997; Kapp et al., 2007a, 2007b).

Except along active rifts (e.g., Harrison et al., 1992) and deeply incised river valleys (Clark et al., 2005; Ouimet et al., 2010), the modern plateau is distinguished from its high-relief margins by low erosion rates (<0.04 mm/yr; Lal et al., 2004; Hetzel et al., 2011). Thermochronologic studies in parts of the northwestern Himalaya and western Tibet indicate steady, slow erosion since at least 35 Ma, and were interpreted to indicate the establishment of a plateau by that time (van der Beek et al., 2009). When low erosion rates were established in the plateau interior is not well known, but can be addressed by application of low-temperature thermochronology. Apatite fission track (AFT) and apatite (U-Th)/He (AHe) ages can be interpreted to record the time elapsed since cooling of rock through a temperature window called the partial retention zone (AFT ~60–120 °C; AHe ~50–80 °C), constraining the timing and rate of cooling and indirectly exhumation.

Rock samples collected in the Qiangtang and Lhasa terranes (Fig. 1) were analyzed using biotite and K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$, AFT, and AHe dating (for details on methods, see the GSA Data Repository¹). The samples were collected >25 km from active rifts over a large (~32 × 10⁴ km²) well-mapped area to resolve the regional temporal-spatial distribution of exhumation. The 19 new samples analyzed in total (yielding 15 AHe ages, 7 AFT ages, and 5 $^{40}\text{Ar}/^{39}\text{Ar}$ ages) include 9 Mesozoic granites and 1 metasedimentary rock in the Qiangtang terrane, 5 Cretaceous granites in the northern Lhasa terrane, 3 Cambrian–Ordovician orthogneisses within the Bangong suture near Amdo (Fig. 1), and 1 Eocene granite near Lhasa (Fig. 1).

Inverse thermal-kinetic modeling of AFT ages and track length data, together with AHe

data, was conducted using the HeFTy program (Ketchum, 2005). Kinetic effects (apatite chemistry for AFT; radiation damage for AHe) are accounted for in the modeling (Table DR6 in the Data Repository). $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of biotite and K-feldspar and multidomain diffusion modeling of K-feldspars constrain cooling through the ~350–100 °C window, and when combined with AFT and AHe can resolve indirectly the exhumation history of the mid-upper crust.

RESULTS

Samples of a Cretaceous granite in the Lhasa terrane (JV4) and one in the central Qiangtang terrane (PU1) yielded $^{40}\text{Ar}/^{39}\text{Ar}$ biotite ages of 120 ± 0.3 Ma and 68.9 ± 0.1 Ma, respectively (Figs. DR2 and DR3; Table DR4). The Qiangtang granite (PU1) furthermore yielded a K-feldspar total gas age of 68.6 ± 0.2 Ma, similar to its U-Pb zircon crystallization age of 69.2 ± 1.2 Ma (Fig. DR1; Table DR3), consistent with granite emplacement at shallow levels and rapid conductive cooling. K-feldspar multidomain diffusion modeling of JV4 yielded a thermal history that shows rapid exhumation from the mid-crust beginning ca. 100 Ma (Fig. 2A). Previously published $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar studies on samples of Amdo orthogneiss (PK1A, PK2, PK3A; Guynn et al., 2006), for which we here present new AHe and AFT data, and other granites along the Bangong suture in Tibet (Kapp et al., 2003, 2007a) similarly show episodes of rapid cooling from mid-crustal levels to <150 °C during the Cretaceous.

The 7 AFT ages for central Tibetan samples range from 75 to 53 Ma (Fig. 1; Fig. DR4; Table DR5) and the 15 AHe ages range from 55 to 15 Ma (Fig. 1; Table DR7), the majority (11 of 15) being 49 ± 6 Ma. Of the four youngest ages (37 Ma, 28 Ma, 19 Ma, 15 Ma), three are from Qiangtang terrane samples located in the hanging walls of small-displacement thrust faults that cut mid-Cenozoic strata (Kapp et al., 2005). The youngest age (15 Ma) is from a sample collected within an externally draining river valley near Lhasa in the southern Lhasa terrane (SH2, Fig. 1). Overall, most AFT and AHe ages are Cretaceous–early Cenozoic, indicating minimal exhumation since ca. 45 Ma.

Only samples PU1, PK3, and JV1 provided acceptable results when AFT and AHe data were used together for the thermal-kinetic modeling; other samples were modeled using either AFT or AHe data (Table DR6). The 10 samples modeled all show a transition from relatively rapid to very slow cooling between 85 and 43 Ma (red dots in Fig. 2B). The narrow range of most AHe ages, ca. 50 Ma, over large distances in central Tibet (Fig. 2C), however, is consistent with widespread, relatively rapid cooling through the AHe partial retention zone

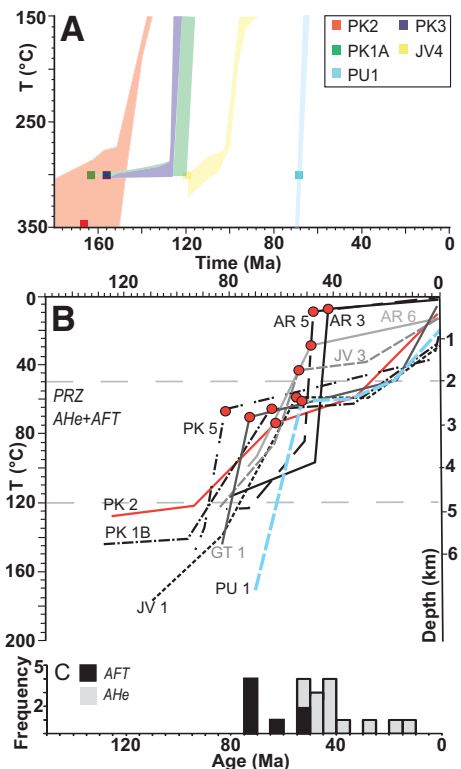


Figure 2. Cooling histories. A: Multidomain diffusion K-spar modeling results. **B:** HeFTy program modeling results showing best fits for each sample. Red dots indicate inflections points showing decreases in cooling rate. Converted depth scale using paleogeothermal gradient of 25 °C/km. PRZ—partial retention zone; AFT—apatite fission track; AHe—apatite (U-Th)/He. **C:** Histogram of AFT and AHe ages (this study).

at the time (Fig. 2B). Assuming a paleogeothermal gradient of 25 °C/km yields average erosional exhumation rates of 0.05–0.01 mm/yr for modeled samples since their transition to slow cooling (Fig. 2B). A subset of the samples shows a later episode of cooling (Fig. 2B), including three AHe ages, that may be attributed to localized thrust reactivation.

DISCUSSION AND CONCLUSION

The new data presented here, combined with a low-temperature thermochronologic study of an igneous complex in the Lhasa terrane (Hetzel et al., 2011; same region as JV1 and JV4 samples; Fig. 1), suggest that in most places in central Tibet, erosion rates of <0.05 mm/yr were established by ca. 45 Ma. These low rates are consistent with widespread exposures of flat-lying 45–38 Ma volcanic rocks above an angular unconformity in the northern Qiangtang terrane (Wang et al., 2008), requiring that the underlying rocks were shortened and at the surface before volcanism. The more rapid Late Cretaceous to Eocene cooling in central Tibet was attributed by Hetzel et al. (2011) to the

¹GSA Data Repository item 2012040, details of geochronologic and thermochronologic analysis and samples (Figures DR1–DR4; Tables DR1–DR5 and DR7), and description of thermal modeling (Figure DR5; Table DR6), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

formation of a low-elevation erosional planation surface during a period of tectonic quiescence by southward-draining rivers. The interpretation, however, is inconsistent with $\geq 50\%$ upper crustal shortening in the Lhasa terrane between 100 and 52 Ma, coeval Gangdese arc magmatism, and Paleocene–Eocene internally drained, syncontractural basins in central Tibet (Horton et al., 2002). Furthermore, the observation that some planation surfaces cut rocks as young as Miocene (Shackleton and Chengfa, 1988), after uplift to near-modern elevations by Eocene–Oligocene time based on paleoaltimetry (Rowley and Currie, 2006; DeCelles et al., 2007; Quade et al., 2011), suggests that planation surfaces can form at high elevation.

Although several factors influence erosion rates, we interpret the initiation of slow erosion in central Tibet as a proxy for establishment of regional low relief at high elevation. Samples showing a transition to slow cooling before 55 Ma (Fig. 2B) suggest that pre–India–Asia collision tectonism may have led to localized regions of protoplateau development. The early impact of the India–Asia collision, however, appears to have caused major plateau expansion based on the narrow range of most AHe ages at 49 ± 6 Ma (Fig. 2C). A possible mechanism is underthrusting of greater Indian lithosphere as far north as the northern Qiangtang terrane by 45 Ma, when volcanism initiated in this region, and during a time interval when India–Asia convergence rates were >90 mm/yr (van Hinsbergen et al., 2011). Between 32 and 20 Ma, volcanism swept back as far south as the Indus–Yarlung suture, maybe in response to rollback of greater Indian lithosphere (DeCelles et al., 2011).

A compilation of our data with published low-temperature thermochronologic ages from other parts of Tibet reveals a northward trend to younger ages (Fig. 3; Table DR2). AFT ages in the northern Qiangtang and Songpan–Ganzi terranes are mainly Eocene to Oligocene and overlap in time and space with the northward-younging Paleocene to Early Miocene Hoh–Xil–Fenghuo Shan–Nanqian thrust belt (Spurlin et al., 2005; Wang et al., 2008; Fig. 1). A southward younging of ages from central Tibet is also apparent (Fig. 3), but the younger ages in the southern Lhasa terrane are interpreted to record mid-Cenozoic exhumation in the hanging wall of the out-of-sequence Gangdese thrust system (Yin et al., 1999; Harrison et al., 2000) rather than when substantial elevation was obtained. The Tethyan Himalayan thrust belt (Fig. 1) initiated during the Early Eocene (Ratschbacher et al., 1994; Aikman et al., 2008). Major upper crustal shortening ceased by ca. 40 Ma in the northern Qiangtang terrane, ca. 22 Ma in the Songpan–Ganzi terrane (Wang et al., 2008), and ca. 23 Ma in the Tethyan Himalayan thrust belt when the Main Central thrust zone initiated

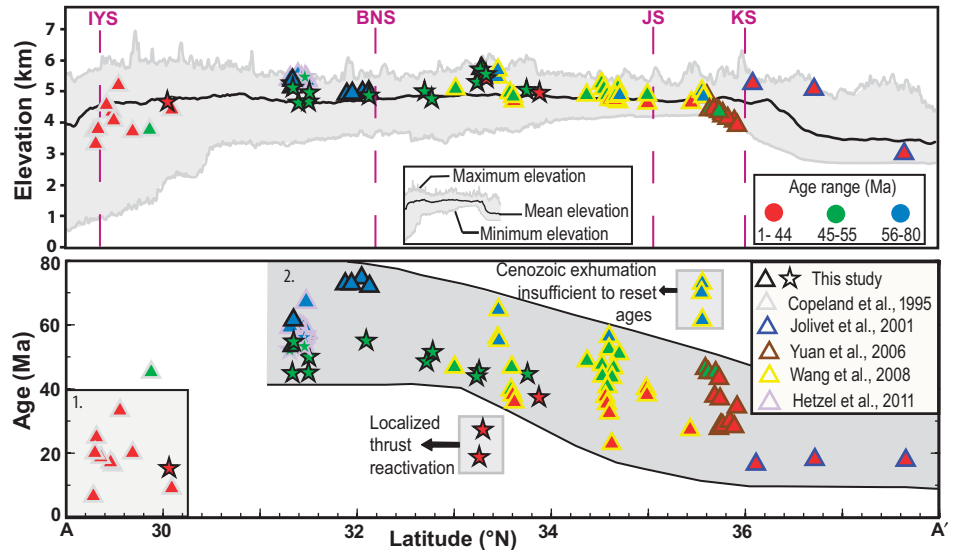


Figure 3. Top: 1400-km-wide topographic swath profile along 92°E (Fig. 1) onto which low-temperature thermochronologic ages from 84°E to 98°E are projected. Purple dashed lines indicate locations of sutures: IYS—Indus–Yarlung; BNS—Bangong; JS—Jinsha; KS—Kunlun. Symbols as in Figure 1. Bottom: Low-temperature thermochronologic ages projected into profile. 1—Fields indicating timing of Gangdese thrust system and river incision in region. 2—Fields indicating northward younging trend in ages.

(Hodges et al., 1996). Collectively, the history of deformation and exhumation is well explained by the establishment of a plateau in the Qiangtang and Lhasa terranes by Eocene time, and its subsequent northward and southward growth during the India–Asia collision (e.g., Kapp et al., 2007a; Wang et al., 2008).

Studies in eastern Tibet identified low-relief landscapes that are deeply incised (Clark et al., 2005, 2006; Ouimet et al., 2010). In this area, rocks at high elevation (>3500 m) yield Mesozoic to early Cenozoic AFT and AHe ages, similar to those in central Tibet, and those at lower elevations within gorges (<3000 m) yield mainly Neogene ages (Fig. 1). Modeling of these data suggests initiation of river incision at 15–9 Ma, interpreted as a response to rapid uplift of low-relief landscapes as the crust was thickened by channel flow of mid-crust from beneath central Tibet (Clark et al., 2005). Near Lhasa, within a deeply incised river valley, we obtained an AHe age of 15 Ma, consistent with AHe ages from intermediate elevations in eastern Tibet. Near Lhasa, however, the rivers are incising into an interior part of the plateau that obtained high elevation by no later than 15 Ma (Spicer et al., 2003), and probably by Eocene time (Rowley and Currie, 2006; Kapp et al., 2007b). The Yellow River has incised and eroded headward into extensive Miocene lacustrine strata deposited in closed basins (Wu et al., 2008) and other vast, formerly internally drained regions of the northeastern plateau since 1.8 Ma (Craddock et al., 2010). On the basis of these observations, we propose the possibility that at least some of the low-

relief landscapes in eastern Tibet were part of a high plateau significantly prior to Miocene river incision.

In conclusion, the history of exhumation, deformation, and basin development in Tibet supports the proposition that plateau-like conditions began developing in central Tibet during the Late Cretaceous and were regionally extensive by 45 Ma. Future studies are needed to test the possibility of northward underthrusting of greater Indian lithosphere beneath central Tibet by 45 Ma and to better resolve the eastward plateau growth history between central Tibet and the Longmen Shan, which has undergone major surface uplift since Middle Miocene time (e.g., Kirby et al., 2002).

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