Exhumation History of the Gangdese Batholith, Southern Tibetan Plateau: Evidence from Apatite and Zircon (U-Th)/He Thermochronology

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ABSTRACT

To test previously suggested exhumation histories of the Gangdese Batholith in the central part of the Transhimalayan plutonic belt, we conducted paired apatite and zircon (U-Th)/He thermochronological investigations of the Yarlung Zangbo gorge in the central part of the batholith. Age-elevation relationships and multisystem thermochronometers showed three periods of accelerated exhumation (∼46–48, ∼22–18, and ∼11–8 Ma). Combining these data with previously published thermochronological ages and synthesizing these ages with regional geological events provides an entire exhumation history. The Cretaceous–Early Paleogene exhumation of the Gangdese Batholith was probably caused by both the northward subduction of the Neo-Tethys and the collision between the Lhasa and Qiangtang blocks. The Early Miocene rapid exhumation might be a response to shortening caused by the Gangdese Thrust or erosion driven by dynamic uplift following lithospheric delamination. In contrast, the Late Miocene exhumation is coincident with both the proposed capture of the Yarlung Zangbo gorge by a foreland draining catchment and the intensification of the Asian monsoon, as well as normal faulting. Hence, the latest stage of exhumation might be attributed to the incision of the Yarlung Zangbo gorge, the activity of a north-south fault, or both.

Online enhancements: supplementary tables.

Introduction

The Transhimalyan Batholith is a product of the northward subduction of Neo-Tethyan oceanic lithosphere beneath Asia prior to and during the early stages of collision of India and Asia [e.g., Yin and Harrison 2000; Zhu et al. 2012]. The surface uplift and exhumation history of the Tibetan Plateau has played a critical role in both global climate [Raymo and Ruddiman 1992] and seawater chemistry [Richter et al. 1992; Misra and Froelich 2012], thus, many studies have attempted to determine the timing of plateau growth [e.g., Harrison et al. 1992, Chung et al. 1998; Rowley and Currie 2006; Wang et al. 2008; Dai et al. 2012]. Thermochronological studies employing biotite and K-feldspar, 40Ar/39Ar, apatite fission track, and apatite (U-Th)/He reveal that central Tibetan Plateau has experienced slow exhumation for 45 m.yr. [fig. 1a; Rohrmann et al. 2012]. However, the Gangdese Batholith in southern Tibetan Plateau has undergone discontinuous exhumation since the Late Eocene, with one pulse of rapid exhumation around 20 Ma (Copeland et al. 1987, 1995; Richter et al. 1991; Pan et al. 1993; Chen et al. 1999a, 1999b). Little is known about when this batholith began to experience a low exhumation rate [e.g., Copeland et al. 1987].

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Figure 1. a, Topography map of the Tibetan Plateau showing the major suture zones and major terranes (Yin and Harrison 2000). The major sutures are as follows: AKSZ = A’Nemaqin Kunlun suture zone, JSSZ = Jinshajiang suture zone, BNSZ = Bangong Nuijiang suture zone, YZSZ = Yarlung Zangbo suture zone. The area of low erosion rate by 45 Ma is from Rohrmann et al. (2012). b, Simplified geological map showing the distribution of the Gangdese Batholith (Pan et al. 2004) with the locations of Coqin (Murphy et al. 1997), Dajin (Yan et al. 2005), Lajiazi (Wan et al. 2001), Chazi, and Wenbu (Ding and Lai 2003).

The Gangdese Batholith is the central part of the Transhimalayan plutonic belt, which also contains the Kohistan-Ladakh Batholith in the west and the Burma Batholith in the east (fig. 1b). The Gangdese Batholith is exposed throughout southern Tibet from Kailas in the west to Lyingchi in the east (fig. 1b). Systematic geochronological studies indicate that plutonic rocks of this batholith were formed between the Late Triassic and the Eocene, with a peak in magmatic activity between 65 and 41 Ma (Chu et al. 2006, 2011; Wen et al. 2008; Zhu et al. 2011). The Cretaceous-Paleogene sediments of the Xigaze forearc basin, which lies in front of the Gangdese Batholith, were mostly derived from the batholith (Dürr 1996, Wang et al. 2012), indicating that erosion and exhumation of the Gangdese Batholith began as early as the Cretaceous. However, extant thermochronological studies do not show the Cretaceous exhumation (fig. 2; e.g., Copeland et al. 1987). Furthermore, a number of thermochronological studies have been conducted in the Ladakh Batholith, and various models have been proposed for explaining the exhumation history of the region (Kirstein et al. 2006, 2009; Kumar et al. 2007; van der Beek et al. 2009; Kirstein 2011).

To test previously proposed exhumation histories, we conducted paired apatite [AHe] and zircon [ZHe] [U-Th]/He analyses for most samples from one transect along the Yarlung Zangbo gorge in central Gangdese Batholith (fig. 3a). Age-elevation relationships (AERs) and multisystem thermochronometers, in combination with published thermochronological data, geological mapping in the Coqin area (Murphy et al. 1997), and leucogranites in central-northern Gangdese (Ding and Lai 2003), allowed us to obtain the entire exhumation history of the Gangdese Batholith.
Exhumation History of the Gangdese Batholith

Figure 2. Histograms of thermochronological data from the Gangdese Batholith. Apatite fission-track data are compiled from Copeland et al. (1987, 1995), Pan et al. (1993), and Yuan et al. (2002, 2009); biotite 40Ar-39Ar data are from Copeland et al. (1987); K-feldspar data are from Copeland et al. (1995); and apatite and zircon (U-Th)/He data are from this study. A color version of this figure is available online.

Geological Setting and Sampling

The Late Triassic to Eocene Gangdese Batholith is widely exposed in the Lhasa terrane (Chu et al. 2006, 2011; Wen et al. 2008; Zhang et al. 2010, 2012; Guan et al. 2012), together with Cretaceous to Tertiary terrestrial volcanic rocks of the Linzi-zong Group (figs. 1b, 3a; Mo et al. 2008; Lee et al. 2009). The Cretaceous to Paleogene Xigaze forearc basin lies south of the Gangdese Batholith (e.g., Dürr 1996; Wu et al. 2010). Farther south, the Yarlung Zangbo suture zone trends nearly east-west and separates rocks of Indian affinity to the south from Asian rocks to the north. The north-dipping Gangdese Thrust system and the south-dipping Renbu-Zedong Thrust system developed along the margin or south of the Gangdese Batholith (figs. 3a, 4a; Yin et al. 1994).

Our study area is located northwest of Xigaze, in central Gangdese Batholith (figs. 3a, 4a). In this area, the Gangdese Thrust juxtaposes the Cretaceous forearc basin deposits over the Yarlung Zangbo ophiolites and Tethyan sedimentary rocks. In the hanging wall of the Gangdese Thrust, a major south-dipping backthrust places the Xigaze Group over Tertiary sediments and the Gangdese plutonic rocks. The south-dipping Renbu-Zedong Thrust also occurs within ophiolites and Tethyan sedimentary rocks (fig. 4a; Yin et al. 1994). Locally, the Gangdese Batholith is predominantly diorite and granodiorite (Tafti et al. 2009; Tang et al. 2009).

We collected 18 samples from a transect in the Yarlung Zangbo gorge, at elevations ranging from 3756 to 5110 m. This transect spanned a short horizontal distance of ~8 km, along which samples were collected with a typical vertical separation of 1534 m. Only eight samples produced good-quality grains and were analyzed. Apatite (U-Th)/He analyses were performed on six samples that yielded datable apatites. Five of the six samples were analyzed for ZHe ages, and two additional ZHe from samples XC13 and XC15 were dated. Three samples (XC01, XC07, and XC18) were analyzed for zircon U-Pb ages. Five of these samples were collected from biotite granodiorite (XC01, XC04, XC07, XC15, and 5045-7), whereas the other three samples were from hornblende diorite porphyry (XC09, XC13, and XC18). Sample 5045-7 was obtained from a drill core at a depth of 425 m, and the other seven samples were collected from the surface. The rocks examined in this study do not show any petrographic evidence for metamorphism or meteoric alteration.

Methods

The samples were crushed mechanically. Apatite and zircon grains were concentrated by using standard heavy liquid and magnetic separation techniques. Apatite and zircon grains were handpicked and photographed under a polarizing Leica MZ16 stereographic microscope outfitted with a Q-imaging 5-megapixel digital imaging system. All grains were examined under transmitted light (plane polarized and cross polarized) and reflected light while grains were submerged in ethyl alcohol to identify those with inclusions. Only optically inclusion-free, euhedral, unfractured grains were selected (Farley 2002; Ehlers and Farley 2003; Reiners 2005). The selected grains were digitally measured, and geometric parameters were used to characterize the morphology of each grain and to calculate α-ejection corrections. After careful selection, apatite and zircon grains were encapsulated in niobium tubes and then loaded into a 46-well copper planchette. Helium concentration was measured by 3He isotope dilution using a Balzers QMS 200 quadrupole mass spectrometer at the University of California, Santa Cruz, helium thermochronology laboratory. Apatite grains were degassed at ~1000°C for 3 min. For apatite analyses, one of every five grains was analyzed with a second extraction (He reextraction) to ensure complete degassing and to monitor for potential He release from...
Figure 3.  

a, Topography map of the southern Tibetan Plateau from 30-m-resolution digital elevation model data showing the major thrust faults (Yin et al. 1994), the normal faults (Taylor and Yin 2009), the distribution of the Gangdese Batholith (Pan et al. 2004), and major apatite fission-track ages (Copeland et al. 1995; Yuan et al. 2002, 2009). Major thrusts are as follows: GT = Gangdese Thrust, RZT = Renbu-Zedong Thrust. 

Figure 4.  a, Topography map of the study area showing major faults and their ages [Yin et al. 1994].  b, Elevation profile (path F–F’ indicated in a of this figure and in fig. 3a) along the transect showing the sample location and the weighted mean ages of these samples.
more retentive undetected U- and Th-bearing inclusions in analyzedapatite. Zircon grains were heated for 10 min at ~1300°C and reheated until >98% of the He was extracted from the crystal.

After He measurements, apatite and zircon grains were spiked using a mixed $^{232}$Th-$^{233}$U tracer. Apatites were dissolved in concentrated HNO$_3$, and zircons were dissolved in HF and HNO$_3$ for isotope-dilution inductively coupled plasma mass spectrometry (ICP-MS) analysis of U and Th. Mass spectrometry was performed at the University of California, Santa Cruz, on a Thermo Scientific X-series II quadrupole ICP-MS. Two fragments of Durango fluorapatite standard were analyzed along with our samples, yielding consistent ages with an average value of 31.4 ± 1.06 Ma. Two replicate analyses of single zircon grains from the Fish Canyon tuff yielded a weighted mean age of 28.6 ± 1.2 Ma. Five grains were dated for each sample to assess reproducibility and for outlier detection. Apatite and zircon ages were corrected for α-ejection using standard procedures of Farley et al. (1996) and Hourigan et al. (2005), respectively.

Zircon U-Pb dating of three representative samples (XC01, XC07, and XC18) were accomplished synchronously by laser-ablation ICP-MS at the Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Laser sampling was performed using a NewWave and ATL 193-nm ArF excimer laser-ablation system (UP193FX). Laser-ablation spot diameter was 35 μm. Element and isotope ion-signal intensities were acquired by using the Agilent 7500a ICP-MS instrument. Plešovec zircon references (Sláma et al. 2008) were used as external standard for the matrix-matched calibration of U-Pb dating. National Institute of Standards standard reference material 612 reference glasses were analyzed as an external standard for the trace element content calibration. Off-line isotope ratios and trace element concentrations were calculated using GLITTER, version 4.0, common Pb correction and sample ages were calibrated and calculated using ComPbCorr, version 3.15 (Anderson 2002). U-Pb concordia diagrams, weighted mean calculations, and probability density plots of U-Pb ages were made using Isoplot, version 3.0.

Results and Interpretation

Two biotite granodiorite samples (XC01 and XC07) and one hornblende diorite porphyry sample (XC18) yielded U-Pb zircon crystallization ages of 46.79 ± 0.47, 47.36 ± 0.69, and 170.4 ± 1.1 Ma, respectively (fig. 5; table S1, available in the online edition or from the journal of Geology office). These results are consistent with those for previous zircon U-Pb, where zircons from the biotite granodiorite yielded $^{206}$Pb/$^{238}$U age of ~48 Ma, whereas the hornblende diorite porphyry was emplaced at 172–173 Ma (Tafti et al. 2009). The biotite plateau $^{40}$Ar/$^{39}$Ar ages of biotite granodiorite and hornblende diorite porphyry were reported as 46.96 ± 0.42 and 48.57 ± 0.31 Ma, respectively (Tang et al. 2009).

Single-grain apatite and zircon (U-Th)/He ages are listed in tables S2 and S3, both available in the online edition or from the journal of Geology office. All six samples analyzed for AHe present good results, with single-grain ages ranging from 6.54 ± 0.23 (1σ) to 14.5 ± 0.73 (1σ) Ma (table S2). Weighted mean ages of five grains in each sample range from 8.1 ± 1.9 to 11.3 ± 1.9 Ma (table S2). These samples do not show any consistent correlation between AHe age and grain radius. Weighted mean ages of populations were used for discussion in the following sections. The samples lack positive correlations between age and eU (effective U concentration, a parameter that weights the decay of the two isotopes for their current particle productivity, calculated as eU = U + 0.235 × Th; Shuster et al. 2006; Flowers et al. 2009, Farley et al. 2011), but they present a steep AHe AER (fig. 6).

The single-grain ZHe ages of the seven samples vary from 12.78 ± 0.41 (1σ) to 31.58 ± 1.08 (1σ) Ma (table S3). All ZHe ages are older than the corresponding AHe ages for the same sample (fig. 6). The weighted mean ages of five grains in each sample vary from 16.7 ± 3.8 to 22.2 ± 5.4 Ma (table S3). All of these samples also show a steep ZHe AER (fig. 6).

Both apatite and zircon (U-Th)/He ages show some intrasample variations. Dispersion is common for (U-Th)/He data sets and is generally attributed to at least one of the following factors. The intragrain zonation of U and/or Th elements would lead to both an incorrect α-ejection correction and intergrain variations in diffusion kinetics (Hourigan et al. 2005; Farley et al. 2011; Flowers and Kelley 2011). For AHe, the occurrence of inclusions of U-bearing minerals, such as zircon and monazite, contributes daughter 4He but may not be dissolved during dissolution ofapatite grains for ICP-MS measurement of U and Th, resulting in parentless 4He and an older grain age. Only optically inclusion-free grains were used, limiting the likelihood of this positive age bias (Ehlers and Farley 2003). Because most undetected U- and Th-bearing inclusions (such as zircon) are more retentive than ap-
Figure 5. U-Pb plots for samples XC01, XC07, and XC18. a, c, e, Concordia plot of all analyzed zircons. b, d, f, Weighted average of $^{206}\text{Pb}/^{238}\text{U}$ ages. Analyses in light gray are highly discordant and are excluded in weighted mean age calculation. Horizontal bars represent the mean. A color version of this figure is available online.
Figure 6. Apatite and zircon weighted mean \((U-\text{Th})/\text{He}\) ages versus sample elevation. The apparent exhumation rate derived from the AHe age-elevation relationship is \(\sim 0.42 \text{ km/Ma}\), but the extremely low \(R^2\) value \((R^2 = 0.32)\) implies that it might be the false exhumation rate. A color version of this figure is available online.

Apatites, the lack of significant He yield during reextraction experiences limits the probability of the inclusions. On the basis of the rapidly cooled volcanogenic samples with a relative simple thermal history, Spiegel et al. (2009) proposed implantation of \(^4\text{He}\) into the apatite from nearby minerals to explain the erroneously old ages. As they pointed out, however, the effect of apatite He implantation is most pronounced for apatites with low eU concentrations (<5 ppm). The eU concentrations of our samples range from 9 to 119.1 ppm, with an average eU of 46.5 ppm (table S2). Therefore, we conclude that He implantation is not a principal concern in our samples. Shuster et al. (2006) and Flowers et al. (2009) proposed that the accumulation of radiation damage associated with U and Th decay can modify the diffusivity of He in apatite and thus modify the effective closure temperature. Despite the large eU variability, there is no systematic correlation between eU and AHe date, implying that radiation damage does not play a significant role in the variations of single-grain ages (Flowers et al. 2009).

To extract information on the exhumation history of the study area, we utilized both AERs and multisystem ther-mochronometers. AERs permit the determination of the apparent exhumation rate without any information on the geothermal gradient (e.g., Braun 2002). Such rates can be obtained from the slope of the linear regression of the sample elevation versus age. Within analytical uncertainty, ZHe ages of the seven samples show a steep AER, indicating rapid exhumation during the 18–22-Ma interval (fig. 6). Linear regression of AHe sample ages with respect to elevation yields a slope of 0.41 km/Ma \((R^2 = 0.32)\) from \(\sim 11.3\) to 8.1 Ma (fig. 6) with no observable inflection points in the AHe data. The extremely low \(R^2\) value indicates that this exhumation rate might not represent the real exhumation rate. Therefore, this exhumation rate will not used in the next discussion. However, the steep AER of AHe probably implies that the Gang-
Figure 7. Plot of closure temperature versus age for multisystem thermochronometers of the Gangdese Batholith. Zircon U-Pb ages of ~46–48 Ma for samples XC01 and XC07, combined with biotite Ar-Ar ages of 46–48 Ma, suggest rapid cooling in the Early Eocene. Ar-Ar ages are from Tang et al. (2009).

Gangdese Batholith experienced relatively high exhumation rates from 11.3 to 8.1 Ma. Zircon U-Pb and biotite ⁴⁰Ar/³⁹Ar ages andapatite and zircon (U-Th)/He ages were utilized for constraining the entire thermal history since emplacement because these thermochronometers have distinct closure temperatures (800°–900°C for zircon U-Pb, ~300°–280°C for biotite ⁴⁰Ar/³⁹Ar, ~170°–190°C for ZHe, and ~45°–75°C for AHe; Harrison et al. 1985; Wolf et al. 1996; Farley 2000; Reiners et al. 2004). Both the Eocene biotite granodiorite and the Jurassic hornblende diorite yielded consistent biotite ⁴⁰Ar/³⁹Ar plateau ages of 46–48 Ma (Tang et al. 2009), therefore, biotite ⁴⁰Ar/³⁹Ar ages were also used in the time-temperature history. The early cooling histories of Eocene biotite granodiorite and Jurassic hornblende diorite porphyry are different, indicating temporal and spatial heterogeneity in uplift and denudation. One representative Jurassic sample (XC18) demonstrates a relatively slow cooling rate of ~4.5°C/Ma during ~170–48 Ma, while Eocene samples XC01 and XC07 show very fast cooling at ~46–48 Ma (fig. 7). Both Jurassic and Eocene samples exhibit similar thermal histories since the Early Eocene and relatively slower cooling rates of 3.2°–4.2°C/Ma during the interval 48–22 Ma, followed by accelerated cooling (~22.4°–9.8°C/Ma) during the Miocene, consistent with steep AERs of ZHe and AHe. After this period of rapid cooling, the cooling rates of the Gangdese Batholith have decreased since 8 Ma (fig. 7).

Discussion

Our new apatite and zircon (U-Th)/He data, combined with previously published ⁴⁰Ar/³⁹Ar [biotite and feldspar] andapatite fission-track ages (figs. 2, 3; Copeland et al. 1987, 1995; Richter et al. 1991; Pan et al. 1993; Chen et al. 1999a, 1999b; Yuan et al. 2002, 2009) and regional geological events (Murphy et al. 1997; Ding and Lai 2003; Wang et al. 2012), allow us to constrain the cooling and ex-
humation history of the Gangdese Batholith. The thermochronological data show that the batholith experienced a multiphase cooling history throughout the Cenozoic with three episodes of relatively rapid cooling and exhumation during the Early Paleogene, Early Miocene (∼22–18 Ma), and Late Miocene (11–8 Ma; figs. 2, 7).

**Cretaceous–Paleogene (∼140–46 Ma).** The Early Paleogene cooling history of the Gangdese Batholith was constrained by zircon U-Pb crystallization ages and biotite ⁴⁰Ar-³⁹Ar ages (fig. 7). This pulse of rapid exhumation is consistent with the occurrence of Eocene Daqin (Yan et al. 2005) and Lajiazi (Wan et al. 2001) conglomerate in the western Xigaze forearc basin (fig. 1b). The Jurassic samples show a low exhumation rate from 170 to 48 Ma, which conflicts with the abundant Cretaceous–Early Paleogene sediments in the Xigaze forearc basin that derived from the Gangdese Batholith (e.g., Wang et al. 2012). The possible reason for this inconsistency is that the exhumation of the Gangdese Batholith is heterogeneous. Most of the Mesozoic plutonic rocks were eroded and deposited in the Xigaze forearc basin during the Cretaceous; thus, their cooling histories cannot be recorded by thermochronometers in the Gangdese Batholith. Other geological observations also suggest that the Gangdese Batholith experienced rapid exhumation during the Cretaceous. Geological mapping and geochronology of granitoids related to faulting in the Coqin area of the northern Gangdese Batholith (fig. 1b) show that ∼60% crustal shortening occurred during the Early Cretaceous (Murphy et al. 1997). Previous studies reported the presence of leucogranites in the Chazi and Wenbu area, central-northern Gangdese Batholith (Ding and Lai 2003; fig. 1b). The geochemical compositions of the Gangdese leucogranites resemble those of the High Himalaya leucogranites that formed during large-scale crustal shortening. The monazite Th-Pb ages of Chazi leucogranites were around at 140 Ma and were believed to represent timing of crystallization. Muscovite ∼130 Ma ⁴⁰Ar/³⁹Ar ages of Chazi and Wenbu leucogranites were interpreted to reflect their rapid cooling during rapid crustal thickening, surface uplift, and denudation in the Gangdese Batholith (Ding and Lai 2003). This period of rapid exhumation may result from both the northern subduction of the Neo-Tethys (Ding and Lai 2003) and the collision between the Lhasa and Qiangtang blocks (Murphy et al. 1997).

**Early Miocene (∼22–18 Ma).** The exhumation history of the Gangdese Batholith during the early Miocene is clearly demonstrated by the ZHe ages from our study area and the combined study from biotite ⁴⁰Ar/³⁹Ar and apatite fission track on the Quxu pluton (near Lhasa; Copeland et al. 1987, 1995), which reveals that rapid exhumation of the Eocene Quxu pluton occurred at 26.8–15 Ma.

Thermochronological data can be influenced by tectonic processes that cause rock cooling (e.g., Ehlers and Farley 2003; Reiners and Brandon 2006). Although the tectonics of the Tibetan Plateau have been characterized by north-south shortening since the collision between Asia and India in the Eocene (Dewey and Burke 1973; Li et al. 2012), there is limited evidence for significant Tertiary crustal shortening in the Gangdese Batholith (e.g., Harrison et al. 2000), possibly because the north-south crustal shortening of the Gangdese belt had been completed prior to the India-Asia collision (Murphy et al. 1997). The most prominent structural feature of the Gangdese Batholith is the north-dipping Gangdese Thrust system along its southern edge (fig. 3a; Yin et al. 1994; Harrison et al. 2000). Structural and thermochronological studies reveal the timing of slip on the Gangdese Thrust to be 27–23 Ma (Yin et al. 1994). These ages are slightly older than the first stage of accelerated exhumation of the Gangdese Batholith (∼22–18 Ma; fig. 8) but much older than the AHe ages. Considering that there is a time lag between establishing the high topography caused by the Gangdese Thrust and ZHe cooling at depths of 4–6 km, the Gangdese Thrust might have influenced this stage of exhumation of the Gangdese Batholith. Another structure proximal to our transect is the Renbu-Zedong Thrust (fig. 3a). However, this south-dipping fault is north directed, resulting in burial rather than exhumation of the Gangdese Batholith (Yin et al. 1994). Consequently, the Gangdese Thrust was the possible mechanism for this period of rapid cooling by exhuming the hanging wall to the surface through erosion (Copeland et al. 1995).

Lithospheric delamination can exert a strong influence on the topography of an orogen (e.g., Molnar et al. 1993) and thus can lead to exhumation via erosion. Lithospheric delamination was initially estimated to have occurred at ∼8 Ma, on the basis of the initiation of orogen-perpendicular normal faulting (Molnar et al. 1993; Harrison et al. 1995). However, recent geochemistry and geochronology studies of the adakitic, ultrapotassic, and shoshonitic rocks in the Lhasa terrane have refined the ages of this event significantly (Chung et al. 2003, 2009; Zhao et al. 2009; Chen et al. 2012). The Lhasa block adakites were emplaced from ∼30 to 10 Ma and were generated by melting of eclogites and/or garnet amphibolites in the lower part (≥50 km) of thickened crust according to their geochemical
characteristics. Upwelling asthenosphere resulting from delamination of the thickened lithospheric mantle in Late Oligocene time is required to generate lower-crustal melting (Chung et al., 2003, 2009). Lithospheric delamination is also needed to generate ultrapotassic rocks and associated potassic rocks of ~8–24 Ma in the Lhasa block (Zhao et al., 2009). These observations suggest that delamination of the lower lithosphere beneath the Gangdese Batholith began as early as ~30 Ma and ended at ~10 Ma (fig. 8; Chung et al., 2003, 2009; Zhao et al., 2009). The upwelling of the asthenosphere could have produced dynamic uplift of the surface over a broad region (e.g., Molnar et al., 1993; Turner et al., 2005).
In turn, this uplift could drive an increase in the erosion rate, given that several north-south-trending fluvial networks maintained a connection to Indian foreland base level during the Late Eocene to Early Miocene in southern Tibet (Liu-Zeng et al. 2008). Even though the lithospheric delamination model is hypothetical and debated, the excellent correlation between the timing of delamination and the Early Miocene rapid exhumation suggests that lithospheric delamination might be the driver of this period of exhumation. In summary, we cannot identify either the Gangdese Thrust or the lithospheric delamination as the dominating driver of the Early Miocene exhumation.

**Late Miocene (~11–8 Ma).** The apatite fission-track data in previous studies and our AHe data indicate a Late Miocene episode of rapid exhumation of the Gangdese Batholith (fig. 2; Pan et al. 1993; Copeland et al. 1995; Yuan et al. 2002, 2009). All apatite samples with this age range from previous studies are located within the Yadong-Gulu rift (fig. 3a). Normal faults are prevalent throughout the Tibetan Plateau (fig. 3a; Molnar and Tapponnier 1978; Taylor and Yin 2009). The ages of these faults are constrained to be 14–5 Ma across the whole Tibetan Plateau and Himalayas (Harrison et al. 1992; Pan and Kidd 1992; Coleman and Hodges 1995; Blisniuk et al. 2001; Lee et al. 2011). In our study region, the most prominent normal fault is located in the Yadong-Gulu rift (fig. 3a). 40Ar/39Ar thermochronology reveals the timing of significant motion on this fault to be 8 ± 3 Ma (Harrison et al. 1992, Pan and Kidd 1992; Harrison et al. 1995). Our study transect is ~200 km away from the Yadong-Gulu rift; thus, influence from this rift can be ruled out (fig. 3a). But Late Miocene apatite fission-track ages of previous studies should be controlled by this normal faulting (Pan et al. 1993; Copeland et al. 1995). On the basis of topographic characteristics, however, we propose that the normal fault developed in the Xainza north-south graben (figs. 3a, 4a). Our study transect is located in the footwall, and this faulting could result in the exhumation and erosion of our transect. The age of this fault was ~14 Ma (Lee et al. 2011), broadly consistent with our AHe ages. Consequently, this period of rapid exhumation might be affected by activity on this fault.

The helium partial retention zone (PRZ) temperature for apatite is ~45°–75°C (Wolf et al. 1996; Farley 2000). Given the continental geothermal gradients of 25°–30°C/km and surface temperatures of ~10°C, the PRZ of apatite should correspond to depths of ~1.2–2.8 km. The shallow closure depth of the AHe makes it a sensitive indicator for deciphering the effect of protracted surface processes, such as river incision. Detrital zircon U-Pb and Lu-Hf isotopic analyses from the eastern Himalayan Neogene foreland basin indicate the presence of abundant detrital zircons derived from the Gangdese Batholith (Cina et al. 2009). These observations led to the proposal that the Yarlung Zangbo gorge was captured by the Subanisri River at ~10 Ma. Similarly, Liang et al. (2008) proposed that the Yarlung Zangbo was connected with the Irrawaddy no later than the Late Miocene, on the basis of studies of Upper Miocene sandstone in the Inner-Burma Tertiary Basin. Regardless of the connected rivers, these studies imply that the Yarlung Zangbo gorge was connected to the external drainage system by at least ~10 Ma. Before this connection, the Yarlung Zangbo might have been an internal drainage system with a high base level; thus, this connection should result in a base-level fall of several kilometers. Both laboratory and field studies have shown that rapid base-level fall can cause rapid river incision (e.g., Heller et al. 2001; Reinhardt et al. 2007; Bowman et al. 2010). Our AHe ages of samples from the Yarlung Zangbo gorge document a rapid exhumation from 11 to 8 Ma (fig. 6). These observations suggest that river incision is likely another mechanism responsible for Late Miocene exhumation.

In addition to the base-level fall, increased precipitation also has had important synergistic effects for the rapid incision of the Yarlung Zangbo gorge (Clark et al. 2005). The Asian monsoon is active in southern Tibet, as evidenced by the fact that precipitation in the Lhasa area during the rainy season is depleted in 18O by >6.3‰ with respect to winter rainfall (e.g., Araguás-Araguás et al. 1998). Moreover, oxygen isotopic studies from carbonates indicate that the climate of southern Tibet has been dominated by the Asian monsoon since Late Oligocene times (e.g., DeCelles et al. 2007). Stable isotopic studies from sediments in the Siwalik basin indicate that a dramatic environmental shift from C3 to C4 plants began as early as 11–7 Ma, which is interpreted to represent the intensification of the Asian monsoon at that time (Quade et al. 1989; Sanyal et al. 2010). This interpretation was sustained by records of aeolian sediments from China and marine sediments from the Indian and North Pacific oceans, all of which suggest the onset of the Indian and east Asian monsoon at ~9–8 Ma (An et al. 2001). Such drastic strengthening of the Asian monsoon (see Molnar et al. 2010 for detailed reviews) would introduce more precipitation onto the southern Tibetan Plateau and enhance the effi-
Figure 9. Geodynamical evolution of the Gangdese Batholith, southern Tibetan Plateau, from the Cretaceous to the Miocene. This geodynamical evolution invokes many geological events—including the northward subduction of the Neo-Tethys, the collision between the Lhasa and Qiangtang blocks, the lithospheric delamination, the Gangdese Thrust, and the Yarlung Zangbo incision—to explain the exhumation history of the Gangdese Batholith. See the text for details. MFT = Main Frontal Thrust, MBT = Main Boundary Thrust, MCT = Main Central Thrust, STDS = South Tibet Detachment System, XFB = Xigaze forearc basin.
ciency of fluvial erosion, thereby increasing exhumation rates along rivers. Our studies are also consistent with studies from the eastern Tibetan Plateau, where river incision prevailed from 13 to 9 Ma (Clark et al. 2005; Ouimet et al. 2010).

In summary, either the normal fault or the incision of the Yarlung Zangbo gorge might play a key role in controlling the Late Miocene exhumation of the Gangdese Batholith. Increased precipitation resulting from intensification of the South Asian monsoon might also strengthen this period of exhumation.

**Integrated Tectonic Model.** The Cretaceous and early Cenozoic exhumation of the Gangdese Batholith is recorded by the Xigaze forearc basin sediments. Since at least the Early Cretaceous, the Gangdese Batholith has operated as the source area for synorogenic sediments in the Early Cretaceous to Paleogene Xigaze Group (e.g., Dürr 1996; Wu et al. 2010, Wang et al. 2012). Detrital zircon ages of the Xigaze sediments exhibit two modes, 130–80 Ma and a subordinate 190–150 Ma, which are rare in the exposed bedrock of the Gangdese Batholith (Wu et al. 2010). These observations, in combination with Cretaceous exhumation of leucogranites in the central-northern Gangdese (Ding and Lai 2003), Cretaceous crustal thickening from geological mapping in the Coqin area (Murphy et al. 1997), and rapid Early Paleogene exhumation revealed by Eocene biotite granodiorite samples (fig. 7), suggest that significant erosion occurred during the deposition of Xigaze forearc basin sediments (fig. 9a).

After the early exhumation of the Gangdese Batholith, the second regional surface uplift and subsequent rapid exhumation should have occurred 22–18 Ma, probably because of the activity of the Gangdese Thrust, lithospheric delamination, or both. The eroded sediments were transported to the Siwalik foreland basin (fig. 9b). The Himalayas had already achieved their present elevation, based on the estimates from paleoelevation studies, at ~11–9 Ma (Garzione et al. 2000; Rowley et al. 2001; Saylor et al. 2009; Quade et al. 2011). Therefore, most rivers in southern Tibet became internal drainage systems. The base-level fall caused by the capture of an external river (Liang et al. 2008; Cina et al. 2009) and the increase in precipitation resulting from the intensification of the South Asian monsoon (Quade et al. 1989; An et al. 2001; Molnar et al. 2010, Sanyal et al. 2010) induced the Yarlung Zangbo to dissect the southern Tibetan Plateau during the Late Miocene (11–8 Ma; fig. 9c). We should point out, however, that normal faults also influenced the Late Miocene exhumation within the north-south grabens. As discussed earlier, the exhumation rate became relatively slow from the Late Miocene to the present. This type of geodynamic evolution indicates that the exhumation of the Gangdese Batholith was controlled by several drivers. Clearly, far more data on the spatial and temporal distribution of the exhumation across the Gangdese Batholith, particularly within the western part of the batholith, are needed to further evaluate this model.

Interestingly, thermochronometric studies from the Ladakh Batholith in western Transhimalaya indicate that its southern and northern margins experienced different exhumation histories. The significant exhumation of the southern margin of the Ladakh Batholith occurred in the Oligocene (~26 Ma), while exhumation of the northern margin occurred later, in the Mid- to Late Miocene (~11–8 Ma; Kirstein et al. 2006, 2009; Kirstein 2011). Northward tilting that resulted in elevated topography along the southern margin of the Ladakh Batholith contributed to the southern exhumation, and the resultant sediments and north-directed thrusting of the Indus Molasse potentially blanketed the southern Ladakh Batholith. The northern margin was exhumed during the Mid- to Late Miocene (Kirstein 2011). Mechanisms for the exhumation of the Ladakh Batholith are distinct from those of the Gangdese Batholith.

**Conclusion**

Paired apatite and zircon (U-Th)/He thermochronological investigations of the Yarlung Zangbo gorge provide new constraints on the exhumation history of the Gangdese Batholith. AERs and multisystem thermochronometers reveal three stages of rapid exhumation (~46–48, ~22–18, and ~11–8 Ma). On the basis of previously published thermochronological ages synthesized with regional geological events, we can make the following conclusions: (1) the Cretaceous–Early Paleogene exhumation of the Gangdese Batholith was probably caused by both the northward subduction of the Neo-Tethys and the collision between the Lhasa and Qiangtang blocks; (2) the Early Miocene rapid exhumation might be a response to shortening caused by the Gangdese Thrust or to erosion driven by dynamic uplift following lithospheric delamination; (3) the Late Miocene exhumation is coincident with both the proposed capture of the Yarlung Zangbo gorge by a foreland-draining catchment and the intensification of the Asian monsoon, as well as normal faulting—hence, the latest stage of exhumation might be attributed to the incision of the Yarlung Zangbo gorge or the activity...
of a north-south fault; and (4) the drivers of exhumation of the Gangdese Batholith are clearly different from those of the Ladakh Batholith.

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REFERENCES CITED


Liu-Zeng, J.; Tapponnier, P.; Gaudemer, Y.; and Ding, L.


Tafti, R.; Mortensen, I. K.; Lang, J. R.; Rebagliati, M.; and Oliver, J. L. 2009. Jurassic U-Pb and Re-Os ages for the newly discovered Xietongmen Cu-Au porphyry district, Tibet, PRC: implications for metallogenic ep-