Peneplain formation in southern Tibet predates the India-Asia collision and plateau uplift

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ABSTRACT

The uplift history of Tibet is crucial for understanding the geodynamic and paleoclimatologic evolution of Asia; however, it remains controversial whether Tibet attained its high elevation before or after India collided with Asia ~50 m.y. ago. Here we use thermochronologic and cosmogenic nuclide data from a large bedrock peneplain in southern Tibet to shed light on the timing of the uplift. The studied peneplain, which was carved into Cretaceous granitoids and Jurassic metasediments, is located in the northern Lhasa block at an altitude of ~5300 m. Thermal modeling based on (U-Th)/He ages of apatite and zircon, and apatite fission track data, indicate cooling and exhumation of the granitoids between ca. 70 and ca. 55 Ma, followed by a rapid decline in exhumation rate from ~300 m/m.y. to ~10 m/m.y. between ca. 55 and ca. 48 Ma. Since then, the peneplain has been a rather stable geomorphic feature, as indicated by low local and catchment-wide erosion rates of 6–11 m/m.y. and 11–16 m/m.y., respectively, which were derived from cosmogenic ^{10}Be concentrations in bedrock, grus, and stream sediment. The prolonged phase of erosion and planation that ended ca. 50 Ma removed 3–6 km of rock from the peneplain region, likely accomplished by laterally migrating rivers. The lack of equivalent sediments in the northern Lhasa block and the presence of a regional unconformity in the southern Lhasa block indicate that the rivers delivered this material to the ocean. This implies that erosion and peneplanation proceeded at low elevation until India's collision with Asia induced crustal thickening, surface uplift, and long-term preservation of the peneplain.

INTRODUCTION

The growth of the Tibetan Plateau, the highest plateau on Earth, with a mean elevation of 5 km above sea level (Fielding et al., 1994), has long been attributed to India's collision with Asia (Argand, 1924; Dewey et al., 1988; Tapponnier et al., 2001), which started ca. 50 Ma (Patriat and Achache, 1984; Rowley, 1996; Najman et al., 2010). However, the preceding accretion of continental terranes to Asia (e.g., Dewey et al., 1988) raises the possibility that crustal thickening, and hence surface uplift, occurred much earlier. It has been argued that the collision between the Lhasa block and the Qiantang terrane (Fig. 1A, inset) resulted in crustal shortening, which may have raised southern Tibet to an elevation of 3–4 km during the Cretaceous (Murphy et al., 1997; Kapp et al., 2005, 2007). However, the following observations suggest that crustal shortening in several regions of the Lhasa block and the Qiangtang terrane does not necessarily imply that southern Tibet as a whole reached a high elevation and remained high until the onset of the India-Asia collision. First, marine limestones document that many regions of southern Tibet remained close to sea level until the Albian (ca. 100 Ma) or Cenomanian (ca. 95 Ma) (Marcoux et al., 1987; Leeder et al., 1988; Yin et al., 1988). Second, thrust fault systems interpreted to have caused considerable north-south shortening in the Lhasa block and the Qiangtang terrane at long 85°E are crosscut by undeformed granitoids dated at ca. 99 Ma, ca. 113 Ma, and ca. 153 Ma (Murphy et al., 1997). Likewise, shortening at 87°E occurred before ca. 118 Ma and there is no evidence for deformation between the Cenomanian (ca. 95 Ma) and the early Tertiary (Kapp et al., 2007). Hence, the thickened crust was subject to erosion for tens of millions of years before the collision of India, which may have reduced the crustal thickness substantially before the India-Asia collision started. The detritus derived from the erosion of the Early Cretaceous orogen is partly preserved in the mid-Cretaceous Takena Formation of the Lhasa block (Dewey et al., 1988; Leeder et al., 1988), but was also transported farther south and deposited in the Xigaze forearc basin (Dürr, 1996) located just north of the Indus-Yarlung suture (Fig. 1A, inset).

Here we apply an independent approach to constrain the early uplift of southern Tibet, which is based on quantifying the age and geomorphic evolution of a large bedrock peneplain using low-temperature thermochronology and cosmogenic nuclides. We use the term peneplain to denote a nearly featureless, gently undulating land surface of considerable area, which has been produced by erosion almost to base level (cf. Jackson, 1997).

STUDY AREA

The investigated bedrock peneplain is located in the northern Lhasa block (Fig. 1A, inset) and was carved into Cretaceous granitoids and very low grade metamorphic sediments of Jurassic age. Field investigations and the analysis of digital elevation models show that originally the peneplain extended for at least ~150 km east-west and ~75 km north-south. Streams that incised the original erosion surface have generated a local relief of as much as a few hundred meters and divide the peneplain into different well-preserved parts that are at similar elevations of ~5200 m to ~5400 m (Strobl et al., 2010). The best preserved portion of the original planation surface occurs near the town of Bangoin, where it was eroded into granitoids that intruded Early Cretaceous sediments (Fig. 1; see the GSA Data Repository[1] for a description of geomorphology and field photographs). Locally, the granitoids underneath the peneplain are overlain by continental red beds of Eocene age (Qu et al., 2003) along a gently dipping unconformity (Fig. 1). These red beds contain abundant granitic detritus, indicating that the granitoids had been exhumed to the surface by Eocene time. Field observations show that the peneplain exposes bedrock or is covered by block fields generated by frost weathering of the granitoids (Fig. DR2A in the Data Repository). Where present, the soil between the blocks is thin (<30 cm) and contains large amounts of granite grus.

METHODS AND RESULTS

We dated the emplacement age and the cooling history of the granitoids in the Bangoin region with U/Pb geochronology and low-temperature thermochronological methods (Table 1; Tables DR1–DR5). Five U/Pb ages reveal that the granitoids intruded their sedimentary host rock between ca. 120 and ca. 110 Ma. The subsequent cooling history is constrained by seven

[1]GSA Data Repository item 2011287, geomorphic description of peneplain, details of geochronologic and cosmogenic radionuclide samples, and analyses, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

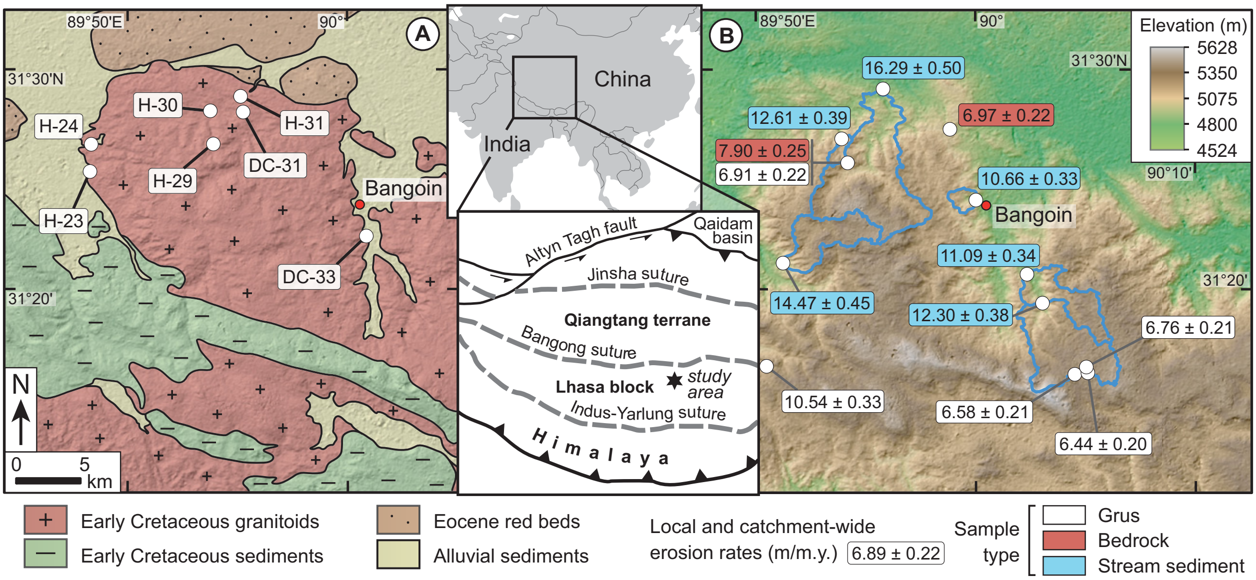

Figure 1. A: Geologic map of peneplain region in northern Lhasa block near town of Bangoin and sample locations. U/Pb dating and thermochronology performed on granitoid samples revealed their intrusion ages and their subsequent cooling history. Inset maps show continental terranes of Tibetan Plateau, bounded by suture zones, and depict their location in Central Asia. B: Digital elevation model (30 m resolution) of study area with local and catchment-wide erosion rates (m/m.y.) quantified from concentrations of cosmogenic ^{10}Be in quartz. Peneplain is in brown.

TABLE 1. U/Pb AND THERMOCHRONOLOGICAL AGE DATA

Sample number	U/Pb age*† (Ma)	(U-Th)/He zircon age§ (Ma)	Apatite fission track age§ (Ma)	(U-Th)/He apatite age§ (Ma)
H-23	117.0 ± 2.8	77.1 ± 7.9	59.4 ± 2.3	56.2 ± 0.9
H-24	–	80.2 ± 5.0	58.5 ± 3.3	56.3 ± 0.7
H-29	111.7 ± 1.6	75.1 ± 6.6	56.8 ± 2.8	53.6 ± 1.2
H-30	112.8 ± 2.3	94.1 ± 9.1	58.2 ± 3.0	59.0 ± 3.6
H-31	–	66.7 ± 3.2	68.4 ± 3.9	55.4 ± 5.7
DC-31	117.5 ± 3.9	85.1 ± 4.7	58.8 ± 3.0	55.1 ± 3.3
DC-33	111.6 ± 0.5	74.8 ± 1.7	59.6 ± 2.4	52.0 ± 0.2

*Ages were obtained using laser inductively coupled plasma–mass spectrometry dating of zircon.
†Reported error limits are 2σ.
§Reported error limits are 1σ.

pairs of zircon and apatite (U-Th)/He ages and seven apatite fission track ages that demonstrate that the rocks cooled from ~180 °C to ~60 °C between 90 and 75 Ma and ca. 55 Ma (Table 1). Thermal modeling based on apatite fission track data, (U-Th)/He constraints, and the Eocene age of the red beds overlying the granitoids demonstrates a rapid cooling from ~130 °C to near-surface temperatures between ca. 65 and ca. 48 Ma (Fig. 2) (for details, see the Data Repository), reflecting the exhumation of the granitoids forming the peneplain. We infer that the planation process was synchronous with the waning stage of exhumation and was completed ca. 50 Ma.

To evaluate the stability of the peneplain we determined erosion rates from concentrations of in situ–produced cosmogenic ^{10}Be (Table 2; Table DR6). We used granite grus and bedrock samples for quantifying local erosion rates, whereas spatially integrated erosion rates for six catchments were derived from sediment samples taken in streams that are incising and eroding headward into the peneplain (Fig. 1B; Figs. DR2B and DR2C). All samples except one yield local erosion rates of only 6–8 m/m.y. (Table 2), demonstrating that the bedrock peneplain constitutes a stable landform. The catchment-wide erosion rates are only slightly higher than the local erosion rates, i.e., 11–16 m/m.y., indicating that incision of the peneplain by the small streams proceeds at low rates. We note that erosion rates measured with cosmogenic nuclides integrate over the time that is needed to remove ~60 cm of rock (Lal, 1991), i.e., a period of 40–90 k.y. for our samples. As this time scale roughly spans the last glacial-interglacial cycle, we consider the erosion rates to be representative for the Quaternary Period. Extrapolation further back in time is more uncertain, because climate conditions during the Tertiary, and hence erosion rates, were presumably different from those today. On the flat peneplain, where a thin veneer of soil is present between bedrock blocks in most areas, a warmer and more stable climate in the Tertiary may have caused soils to be thicker than today. Since the soil production rate (i.e., the rate at which bedrock is transformed to soil by processes such as freeze-thaw or burrowing) decreases with increasing soil thickness (Heimsath et al., 1997), erosion in the Tertiary may have proceeded at a lower rate compared to the Quaternary. However, since it is not possible to quantify the effect of a warmer climate, we assume that the local erosion rates of 6–8 m/m.y. are at least roughly representative for the past 50 m.y. This suggests that the peneplain was lowered by 300–400 m during that period.

DISCUSSION AND CONCLUSIONS

The amount of rock that was removed during the exhumation of the granitoids and the generation of the peneplain in the Bangoin area can be estimated from the mean cooling rate of ~10 °C/m.y. between 65 and 50 Ma, a rate derived from the time-temperature history (Fig. 2). Combining this cooling rate with a conservative estimate for the paleogeothermal gradient of 25–50 °C/km yields an exhumation rate of 200–400 m/m.y. Thus, within 15 m.y., ~3–6 km of rock was removed from the peneplain region, which requires an efficient agent of erosion able to erode bedrock uniformly over a large area (>10,000 km^2). We infer that erosion and exhumation of the granitoids were

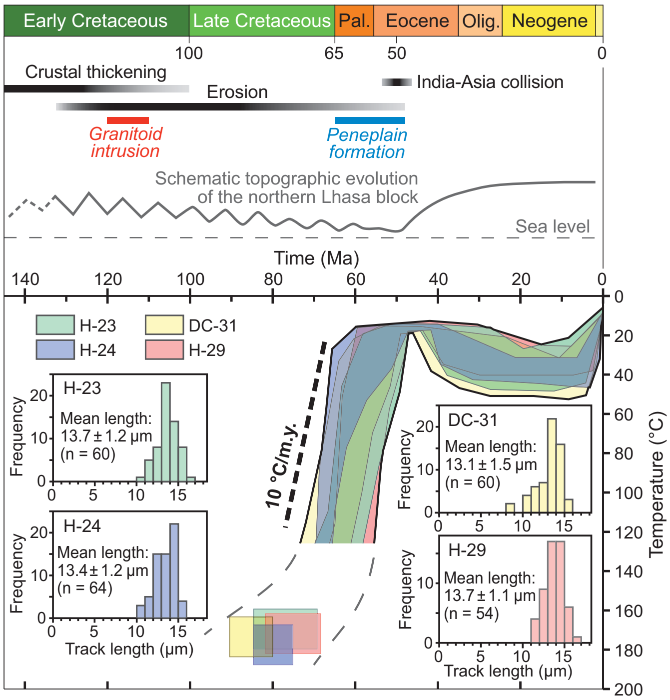

Figure 2. Cooling history of Cretaceous granitoids forming peneplain and geologic events in southern Tibet. Lower part of figure shows cooling histories of four samples based on thermal modeling of zircon and apatite (U-Th)/He ages, apatite fission track data, age of Bangoin intrusives, and Eocene age of overlying red beds. Boundaries of mutual cooling path encompass all path envelopes of acceptable fit obtained for four samples using merit value of 0.05 in HeFTy software (Ketcham, 2005). Boxes are defined by zircon (U-Th)/He ages of samples and their respective closure temperatures (calculated with software CLOSURE; Ehlers et al., 2005). Box size represents 1σ errors. Inset diagrams depict track length distributions and numbers of confined fission tracks in apatite from the four granitoid samples. Upper part of figure illustrates timing of important geologic events in southern Tibet, shown by horizontal bars below geologic time scale (Pal.—Paleocene; Olig.—Oligocene). Gray line sketches topographic evolution of northern Lhasa block through time. After period of crustal thickening during Early Cretaceous (Murphy et al., 1997; Kapp et al., 2005, 2007) and intrusion of granitoids (red bar), crust was thinned by erosion in Late Cretaceous and Paleocene. Exhumation of granitoids and formation of bedrock peneplain (blue bar) ended ca. 50 Ma with onset of India-Asia collision. Subsequent underthrusting of Indian continental crust beneath Lhasa block is thought to be responsible for rapid surface uplift, and by ca. 35 Ma southern Tibet had reached an elevation of at least ~4 km (Tapponnier et al., 2001; Rowley and Currie, 2006; van der Beek et al., 2009).

TABLE 2. EROSION RATES FROM COSMOGENIC ^{10}Be

Sample number	^{10}Be concentration* (10^4 at/g)	Erosion rate† (m/m.y.)
Grus samples		
08T10	912 ± 27	6.58 ± 0.21
08T12	906 ± 27	6.76 ± 0.21
08T13	951 ± 29	6.44 ± 0.20
08T20	534 ± 16	10.54 ± 0.33
08T24	838 ± 25	6.91 ± 0.22
Bedrock samples		
08T16	714 ± 21	6.97 ± 0.22
08T25	709 ± 21	7.90 ± 0.25
Stream sediment samples		
08T21	346 ± 10	16.29 ± 0.50
08T23	487 ± 15	10.66 ± 0.33
08T26	441 ± 13	12.61 ± 0.39
09T21	408 ± 12	14.47 ± 0.45
09T26	479 ± 14	12.30 ± 0.38
09T27	522 ± 16	11.09 ± 0.34

*Blank-corrected ^{10}Be concentrations with 1σ error limits.
†Erosion rates reported with 1σ error limits (internal uncertainty) were calculated with the CRONUS-Earth ^{10}Be–^{26}Al web calculator, version 2.2.1 (http://hess.ess.washington.edu), using the constant production rate scaling model of Lal (1991) and Stone (2000).

accomplished by major rivers that migrated laterally over the future peneplain area.

Two arguments suggest that the large volumes of sediment that were produced during exhumation and peneplain formation were not deposited on the Lhasa block, but were transported to a basin near global base level. First, siliciclastic sediments of Paleocene to Early Eocene age (65–48 Ma) are scarce in the Lhasa block (e.g., Leeder et al., 1988). Second, in the southern Lhasa block an erosional unconformity extends for ~1000 km east-west and ~200 km north-south at the base of the Linzizong Formation (Burg et al., 1983; Lee et al., 2009). This regional unconformity separates folded Early Cretaceous sediments from nearly undeformed volcanic rocks of the Linzizong Formation (Burg et al., 1983; Lee et al., 2009), erupted mainly between ca. 60 and ca. 40 Ma (Yin and Harrison, 2000; Wen et al., 2008; Lee et al., 2009). As the deformed Cretaceous rocks must have undergone a phase of erosion before the deposition of the Linzizong Formation, the southern Lhasa block was not able to act as a depocenter for the clastic sediments produced in the peneplain region. Hence, these sediments were presumably transported to the ocean by large rivers. At least a part of the erosional debris may be preserved in the Late Paleocene to Eocene Qiuwu Formation (Qian, 1985; Einsele et al., 1994), which was deposited at the southern margin of the Lhasa block and originally had a much larger extent (Einsele et al., 1994). Alternatively, the sedimentary material from the peneplain region may have been transported northward and deposited at the northern margin of the Qiangtang terrane, where there are sedimentary basins with Paleocene and Eocene sediments (Liu and Wang, 2001; Spurlin et al., 2005). We prefer the former interpretation, because the topography produced by the collision between the Lhasa and Qiantang terranes in the Early Cretaceous may still have been partly preserved, which would have prevented a northward flow of rivers originating in the peneplain region. Future provenance studies using fission track and U-Pb dating of detrital apatite and zircon will likely identify the source areas of early Tertiary deposits in Tibet and adjacent regions and decipher the pathways of the material removed from the peneplain region. If our preferred interpretation is correct and the rivers draining the northern Lhasa block were connected to the sea, the peneplain must have formed at rather low elevation, because otherwise the rivers would have merely incised the bedrock, and lateral migration and erosion over large distances (required for peneplanation) would have been inhibited. Although it is difficult to quantify the paleoelevation of the northern Lhasa block, we suggest that the peneplain formed at least 3–4 km beneath its current elevation of ~5300 m. Taken together, our results indicate that the formation of the peneplain at low elevation was completed by ca. 50 Ma and that the resistant bedrock surface has undergone only very slow erosion since then. Combined with the results of previous studies, which used paleoaltimetry (Rowley and Currie, 2006), geomorphology and thermochronology (van der Beek et al., 2009), and geologic data (Tapponnier et al., 2001) to show that southern Tibet had reached an elevation of at least 4 km by ca. 35 Ma, this implies that the Tibetan Plateau grew rapidly in height between ca. 50 and ca. 35 Ma, i.e., early in the ongoing history of the India-Asia collision, and retained its high elevation (Spicer et al., 2003; Rowley and Currie, 2006; DeCelles et al., 2007).

Our study demonstrates that the age and geomorphic evolution of bedrock peneplains can be deciphered using a combination of thermochronologic and cosmogenic nuclide analyses. Dating the formation of these remarkable features has hitherto been a major obstacle, hampering their use as geomorphic markers tracking the uplift of mountains through space and time. If peneplains are developed in resistant bedrock, they can be preserved for tens of millions of years, even at high altitude, and may provide important constraints on the paleoelevation history of Cenozoic mountain belts.

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Early Tibetan Plateau uplift history eludes

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The elevation history of Tibet, the world's highest and most extensive plateau, offers a testing ground for ideas concerning the geodynamics of continental collision, the effect of large orogens on climate, and the interactions between the two. Included in the understanding of the evolution of modern Tibet is the elevation of the proto-plateau, or Asian margin, prior to its collision with India ~50 m.y. ago. Although most assume that post-collision convergence created much of the current high topography and doubled the thickness of the crust, many studies document crustal shortening or rapid cooling histories during Jurassic and Cretaceous time across Tibet, which raises the possibility of elevated topography prior to continental collision with India.

The rock that comprises Tibet had amalgamated by late Jurassic to early Cretaceous time, and most believe that an elevated Lhasa Block represented a wide Andean-type margin that bound southern Asia prior to collision (Fig. 1). But quantifying the contribution of pre-Eocene deformation to the modern crustal thickness and elevation is difficult. Where estimates are made on the basis of surface shortening, assumptions regarding the mechanisms of lower crustal and mantle lithosphere shortening drastically affect predicted altitudes. Erosion, foundering of mantle lithosphere, and lateral flow of ductile lower crust also affect the longevity of topography, but are rarely quantifiable. So, whether or not high elevations accompanied pre-Eocene deformation in Tibet, and were sustained for tens to hundreds of millions of years prior to India's collision, remains an open question.

Hetzel et al. (2011, p. 983 in this issue of *Geology*) challenge a widely accepted view that the southern margin of Asia was at high elevation prior to collision with India (e.g., England and Searle, 1986; Kapp et al., 2007a, and references therein). Using low-temperature thermal histories from granitoids in the northern Lhasa block, Hetzel et al. document rapid cooling between 65 and 48 Ma that occurred at rates of ~10 °C/m.y. (0.2–0.4 mm/yr) and exhumed up to 6 km of rock. They interpret rapid denudation rates to reflect planation by laterally migrating rivers that created the observed low-relief land surfaces. By relating these rivers to sea level, they propose that the landscape was reduced to low elevations prior to the continental collision of India. Slow erosion rates (0.006–0.016 mm/yr) averaged over the past 40–90 k.y. from ^{10}Be ages, combined with extrapolation of the low-temperature histories to modern time, suggest little modification of these surfaces since collision and uplift to their modern altitude near 5300 m.

Hetzel et al.'s study highlights the use of low-relief surfaces as passive markers in continental tectonics, a practice that has regained momentum in the past decade (e.g., Clark et al., 2005, 2006; Bishop, 2007; Calvet and Gunnell, 2008; van der Beek, et al., 2009). As ~70% of the Earth's continental surfaces lie at altitudes of <1 km, most landscapes undergo very little relief change over long periods of time. Erosion surfaces, more aptly termed "relict landscapes," represent low-relief remnants of fluvially sculpted, and sometimes glacially modified, landscapes that can develop at relatively low altitude where rivers are externally drained to or near sea level (planation surfaces) or alternatively, at high altitudes where rivers are internally drained to high-elevation basins (altiplanation surfaces). Once reduced to low relief, the stability of these landforms is demonstrated by long periods (more than tens of millions of years) of low erosion rates (e.g., Hetzel et al., 2011), which can be shown to be out of equilibrium

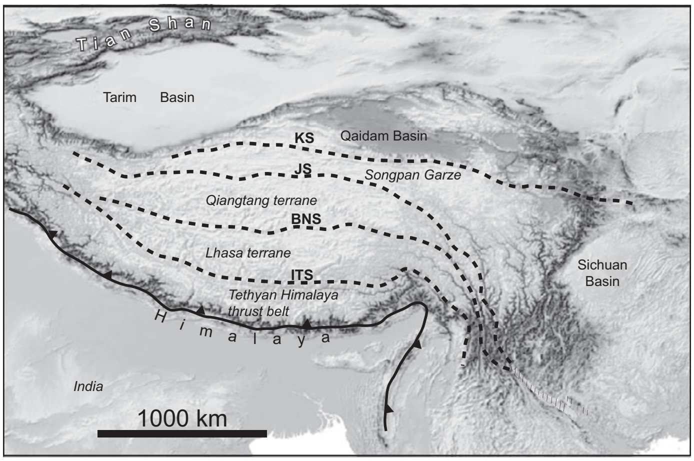

Figure 1. Location map of India-Asia collision zone. ITS—Indus-Tsangpo suture (created by the India-Asia collision); BNS—Bangong-Nujiang suture; JS—Jinsha suture; KS—Kunlun suture.

with parts of the landscape responding to recent tectonic forcing, climate change, or drainage integration (e.g., Clark et al., 2005). These artifacts seem to be commonly preserved in active landscapes to greater or lesser degrees. Where base level can be determined, these planar landscape remnants present opportunities to measure local and regional surface elevation change, and the timing of their disruption can represent climate or tectonic forcing on the landscape.

The Eocene low-relief surfaces described by Hetzel et al. likely correlate with the basal unconformity of the Linzizong volcanics (magmatic flare-up between 68 and 49 Ma), a gently-dipping contact at similar elevations across the Lhasa terrane. This unconformity surface has been previously interpreted as a part of a high-elevation, Altiplano-like landscape (Kapp et al., 2007b), which would have formed by an isolated (internally drained) river system and would not necessitate a near-sea-level interpretation. A critical difference in Hetzel et al.'s argument is the formation of a low-relief landscape by a southward-flowing fluvial system that drained to sea level. While south-draining rivers are a likely inference, the connection to global base level (i.e., sea level) is a crucial part of the puzzle that awaits confirmation or rejection by provenance studies or fluvial reconstructions.

Rapid underthrusting and elevation increase following lithosphere removal from 90 to 50 Ma (Kapp et al., 2007b) are also consistent with the rapid erosion rates inferred by Hetzel et al. between 65 and 48 Ma. This period of erosion acted on potentially high-elevation topography created by thrust faulting associated with the accretion of the Lhasa Block between 125 and 118 Ma, continued convergence, and mantle foundering thereafter (e.g., Kapp et al., 2007a and 2007b, and references therein). An estimate of 50% shortening may account for 3–4 km of elevation gain if pure shear of the entire crust and Airy isostasy are assumed (Murphy et al., 1997). Preservation of Eocene age low-relief surfaces, if they drained southward to sea level, would suggest reduction of that topography prior to the time of collision (Hetzel et al., 2011).

Once collision commenced, the area over which crustal thickening began may have been much larger than previously thought. The development of the northeastern plateau, typically considered to be the youngest part of the orogen (e.g., Meyer et al., 1998), has been occurring since roughly collision time (e.g., Dupont-Nivet et al., 2004; Yin et al., 2008; Wang et al., 2008; Clark et al., 2010; Duvall et al., 2011). As such, a stable northern boundary would imply that the north-south extent of Tibet has grown narrower, not wider, since collision. While Eocene thrust faulting does not necessarily imply achievement of modern elevations at that time, it does suggest that the northern boundary of Tibet was established early and has not propagated despite >2000 km of subsequent convergence of India with Eurasia.

In the recent decade, quantitative paleo-elevation records for Tibet derived from light stable isotopes offer elevation constraints that are independent of deformation, erosion, and assumptions therein. Greater confidence exists in younger histories from southern Tibet where the isotopic composition of modern meteoric waters conforms to a simple thermodynamic model of isotopic fractionation of water vapor traveling over a high-elevation landmass. These records suggest that southern Tibet has been high since at least 26 Ma (e.g., Quade et al., 2007), but estimates from northern Tibet and older rocks are not definitive (e.g., Quade et al., 2011). Complexities in past moisture sources, evaporation, and surface-water recycling are thought to effect the isotopic composition of meteoric water from the interior of Tibet. Our current understanding of how these processes have interacted in the past limits the quantitative interpretation of paleo-elevation there (e.g., Polissar et al., 2009; Quade et al., 2011). A better understanding of the proxy record from climate simulations, that include the prediction of isotopic values in precipitation, is an area of active research.

Studies in Tibet illustrate the current need to reconcile conflicting views of paleo-elevation derived from erosion histories, reconstructions of surface shortening, and estimates from geochemical proxies in active orogens. As a clearer picture of widespread deformation prior to and overlapping with the beginning of continental collision emerges, the record of paleo-elevation remains critical to the dynamic understanding of how the world's largest plateau came to be. Recognition of stable landforms and their connection to sea level may be an integral part of our overall understanding of plateau evolution. Where surfaces can be related to sea level through fluvial systems or their deposits, they become a useful passive marker to elevation change and long-wavelength deformation.

Surfaces of late Jurassic to Eocene age have been recognized across Tibet and within the Himalaya, and even north into Mongolia. So it is interesting to speculate whether these surfaces may represent a vast, large-scale ancient surface that has been disrupted at different times, or may have formed independently at a range of altitudes. Advances in our ability to quantify the most recent history of these landforms through new lower-temperature methods in thermochronometry (<60 °C), and application of stable cosmogenic isotopes to dating of surfaces, promises to enhance interpretation of the origin, age, and geodynamic significance of these long-lived landscape relicts. Why old landscapes are often preserved in tectonically active regions is enigmatic; but the fortunate preservation of these ancient remnants may be an important clue to the tectonic and climatic conditions that governed the plateau during and just prior to continental collision.

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