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

Ralf Hetzel1, István Dunkl2, Vicky Haider2, Marcus Strobl1, Hilmar von Eynatten2, Lin Ding3, and Dirk Frei4
1Institut für Geologie und Paläontologie, Westfälische Wilhelms-Universität Münster, Corrensstraße 24, 48149 Münster, Germany
2Geowissenschaftliches Zentrum der Universität Göttingen, Abteilung Sedimentologie/ Umweltgeologie, Goldschmidtstraße 3, 37077 Göttingen, Germany
3Institute of Tibetan Plateau Research and Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
4Department of Earth Sciences, Stellenbosch University, Private Bag X1, 7602 Matieland, South Africa

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 uplifting. 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 10Be concentrations in bedrock, grus, and stream sediments. 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 Acluche, 1984; Bowley, 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 Qiangtang 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 was 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 (Diirr, 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 peneplain surface occurs near the town of Bangoin, where it was eroded into granitoids that intruded Early Cretaceous sediments (Fig. 1; see the GSA Data Repository1 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

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1GSA 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.
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 cosmogenic 10Be in quartz. Peneplain 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 km²). We infer that erosion and exhumation of the granitoids were

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**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 climate conditions during the Tertiary, and 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.

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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 Linzing Formation (Burg et al., 1983; Lee et al., 2009). This regional unconformity separates folded Early Cretaceous sediments from nearly undeformed volcanic rocks of the Linzing 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 Linzing 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 Palaeocene to Eocene Qiwu 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 Qiangtang 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 (Tapponnier et al., 2001; Rowley and Currie, 2006; van der Beek et al., 2009).

![Figure 2. Cooling history of Cretaceous granitoids forming peneplain and geologic events in southern Tibet.](image)

**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). Box sizes 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., 1987; 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).

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**TABLE 2. EROSION RATES FROM COSMOGENIC 10Be**

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

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