**Pulsed exhumation of interior eastern Tibet: Implications for relief
generation mechanisms and the origin of high-elevation planation
surfaces**

Huiping Zhang^{1*}, Michael E. Oskin^{2*}, Jing Liu-Zeng¹, Peizhen Zhang¹, Peter W.
Reiners³, Ping Xiao¹

¹State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake
Administration, Beijing, 100029 China

² Department of Earth and Planetary Sciences, University of California, Davis,
California 95616, USA.

³ Department of Geosciences, University of Arizona, Tucson, Arizona 85271, USA

* huiping@ies.ac.cn (H.Z.); meoskin@ucdavis.edu (M.O.)

Abstract

River incision into a widespread, upland low-relief landscape, and related patterns of
exhumation recorded by low-temperature thermochronology, together underpin
geodynamic interpretations for crustal thickening and uplift of the eastern Tibetan
Plateau. We report results from a suite of 11 (U-Th-Sm)/He cooling-age samples. Eight
samples comprise a 1.2 km relief section collected from elevations up to 4800 m in the
Jiulong Shan, an elevated, rugged region located in the hinterland of the
Yalong-Longmen Shan Thrust Belt, and surrounded on three sides by upland low-relief
landscape surfaces. Zircon and apatite cooling ages record two episodes of rapid
exhumation in the early Oligocene and late Miocene, that were separated by a period

of stability from ~30 to 15 Ma. The first episode is consistent with a similar pulse evident from the Longmen Shan. The second episode is ongoing, and when integrated with adjacent cooling-age data sets, shows that doming of the Jiulong Shan has resulted in 2 to 4 km of differential exhumation of the plateau interior. We show from a compilation of glacial landform-mapping that the elevation of the plateau surface closely tracks global last glacial maximum equilibrium line altitude. We hypothesize that smoothing of highlands by efficient glacial and periglacial erosion, coupled with potential river captures and conveyance of sediments via external drainage, can yield an apparently continuous low-relief plateau landscape formed diachronously at high elevation.

Keywords: Low-temperature thermochronology, Pulsed exhumation, Eastern Tibet, Low-relief surfaces, Landscape evolution

1 Introduction

The uplift history and development of Tibetan Plateau is crucial for understanding the geological evolution of Asia, and serves as a prototype for the culmination of continent-continent collision (Fig. 1a). High-elevation and low topographic relief of central Tibet contrasts with high relief along most of the plateau edge, except for its southeastern and northeastern margins, which descend gradually to low elevations (Fig. 1b, Clark and Royden, 2000). The evolution of this plateau topography, and its relationship to the spatio-temporal pattern of upper crustal deformation, remains at the center of debates over the links between plateau growth and geodynamic processes (Clark and Royden, 2000; Clark et al., 2005, 2006; Royden et al, 1997, Hetzel et al.,

2011; Liu-Zeng et al., 2008; van der Beek et al., 2009; Yin, 2010; Yin and Harrison, 2000).

At high-elevation (>3500 m), samples from eastern Tibet typically yield Mesozoic to Early Cenozoic apatite fission-track (AFT) and apatite-helium (AHe) ages (Clark et al., 2005), indicating prolonged, slow rates of exhumation. However at lower elevations, within river gorges, Late Miocene and younger cooling ages (Figs. 2 and 3) suggest a widespread exhumation event, starting ~ 10 -12 Ma, associated with major river incision into an elevated, low-relief planation surface (Clark et al., 2005; Ouimet et al., 2010; Duvall et al., 2012). This event is hypothesized to record expansion of the Tibetan Plateau to the southeast as a result of flow of lower crust from the hot, overthickened region of central Tibet (Clark and Royden, 2000; Royden, et al. 1997).

A key contention of the lower crustal flow and surface uplift model is that low-relief, highland landscapes initially formed at low elevation (Clark et al., 2005; Liu-Zeng et al., 2008). Even modest rates of uplift and fluvial erosion (~ 200 m/Ma) should be accompanied by the presence of a mountainous landscape (e.g. Wang et al., 2012). River capture events may also leave behind low-relief surfaces formed by underfit valleys, as has been both documented (Clark et al., 2006) and inferred from stream-network geometry (Yang et al., 2015) in eastern Tibet. An important test of the surface uplift hypothesis is that the eastern Tibetan Plateau inherited a landscape formed earlier under prolonged, low rates of erosion-driven exhumation. Detrital thermochronology supports this case for over much of eastern Tibet (Duvall et al., 2012). Notable exceptions do occur, including the steep plateau margin of the Longmen Shan, where zircon fission track data indicate relatively rapid cooling during the mid-Tertiary, between ~ 38 and 10 Ma (Arne et al., 1997). Wang et al. (2012)

75 subsequently showed, using a suite of low-temperature thermochronometers, that the
76 central Longmen Shan experienced two phases of rapid exhumation, ~30 – 25 Ma and
77 ~15 – 0 Ma (Fig. 2). Deep exhumation starting at ca. 30 Ma is also observed in the
78 southern Longmen Shan, with a second stage of rapid exhumation commencing later
79 than at other sites, ca. 3–5 Ma (Tan et al., 2014).

80 Here we examine the relationship between exhumation and glacial landscape evolution
81 at high elevation within the interior of eastern Tibet. Though glacial erosion and related
82 periglacial processes have been proposed to modulate plateau landscape evolution
83 elsewhere (Brozovic et al., 1997; Hales et al., 2005), its impact on formation of the
84 widespread plateau surface of eastern Tibet has not been explored. We focus on a
85 transect between the Jaggai (Liqiu) plateau surface of Clark et al. (2005), where AHe
86 dates yield late Cretaceous cooling ages, and the Yalong Thrust Belt, where Late
87 Cenozoic reactivation involves Eocene strata (Fig. 2b; BGMR Sichuan, 1991; BGMR
88 Yunnan, 1990), and may be contemporaneous with reactivation of the Longmen Shan
89 Thrust Belt (Wang et al., 2012). Within this transect, Ouimet et al. (2010) found that
90 AHe and zircon-helium (ZHe) recorded anomalously rapid (~330 m/Ma) exhumation
91 from at least 14 Ma to the present (Figs. 2 and 3). Rapid cooling, beginning during the
92 Early Miocene (~22 – 15 Ma), is also observed nearby at Daocheng (Fig. 2; Tian et al.,
93 2014). This early, and in some cases, substantial, and ongoing exhumation calls into
94 question whether the plateau landscape in this area necessarily formed as a result of
95 lowland fluvial erosion, and then uniformly uplifted in time as it was incised.

96 In order to define the extent and impact of rapid exhumation at high elevations within
97 this transect, we present AHe and ZHe thermochronology results from a suite of 11
98 additional samples from the hanging wall of the Yalong Thrust Belt: Three from the

margin of the Jaggai plateau surface (Clark et al., 2005), and eight from a relief transect within the adjacent Jiulong Shan – a mountainous, glaciated region surrounded on three sides by mapped low-relief plateau surfaces at 4000-4200 m elevation (Figs. 3 and 4). Through synthesizing our results with previous published thermochronology from Clark et al. (2005) and Ouimet et al. (2010), we show that a ten-fold north-south gradient in exhumation rate occurs within this portion of interior eastern Tibet (Figs. 3 and 4). Over a distance of 100 km, exhumation rates increase from ~50 m/Ma in the center of the Jaggai plateau surface, to ~560 m/Ma within the Jiulong Shan (Fig. 3). In addition, ZHe results from the Jiulong Shan document a distinctly separate, early Oligocene exhumation event (Fig. 4). Together these events account for over 6 km of exhumation from above 4800 m elevation, half of which has taken place since 10 Ma.

Considering this Late Cenozoic exhumation gradient, we examine how a ten-fold increase in erosion rate is expressed in this high-elevation plateau landscape.

Previously, Ouimet et al. (2010) showed that a subtle gradient exists in average and peak elevations between the Jaggai plateau surface and the Jiulong Shan. On the basis of new and previously published paleoglaciation reconstructions (Fu et al., 2013a,b), and as originally hypothesized by Ouimet et al., (2010), we argue that glacial and periglacial erosion is presently responsible for limiting the elevation of the Jiulong Shan and other areas of anomalously high exhumation rate within the plateau interior. We further show that the imprint of glaciation, as evidenced by distinctive erosional and depositional patterns produced by ice caps and valley glaciers during global Last Glacial Maximum (gLGM), is widespread across areas previously identified as uplifted planation surfaces (Clark et al., 2006; Fig. 1). We conclude that glacial erosion in eastern Tibet may have kept pace with rapid rates of rock uplift, smoothing the local relief by vigorous periglacial hillslope processes, and consequently setting the stage for

development of a low-relief plateau surface.

2 Background

Much of the high, flat portion of the eastern Tibetan plateau is underlain by the Songpan – Garze terrane (Clark et al., 2006), which consists predominately of thick middle and upper Triassic flysch deposits (Fig. 2a; BGMR Sichuan, 1991; Burchfiel et al., 1995). Cenozoic strata, where present, are mostly Pliocene – Quaternary glacial-fluvial deposits (Burchfiel et al., 1995). The terrane was intruded by Late Triassic – Jurassic granitoids (Roger et al., 2004, 2010). Shallow pluton emplacement, and preservation of Triassic shallow basin sediments in the eastern Songpan – Garze terrane, limit the total post-Jurassic erosion, in general, to less than about 10 km (Burchfiel et al., 1995). The eastern Songpan – Garze terrane probably existed as a low-relief erosional highland to the west of the Longmen Shan because it has been a source of sediment in the Sichuan Basin since Jurassic time (Burchfiel et al., 1995). The plutons remain largely undeformed except by late Miocene – early Pliocene strike-slip faulting, indicating little post – Triassic contractional deformation, consistent with structural evidence at the eastern and western margins of the terrane (Reid et al., 2005).

The Longmen Shan and Yalong Thrust Belt define the southeastern boundary of the Songpan – Garze terrane (Fig. 2a). Metamorphosed passive margin sedimentary sequences of Proterozoic through Paleozoic age and Proterozoic granitic basement rocks were thrust eastward in late Triassic – early Jurassic time (Burchfiel et al., 1995; Dirks et al., 1994; Wallis et al., 2003). The Longmen Shan thrust belt was reactivated

in the Cenozoic, but Cenozoic shortening was probably limited to a few tens of kilometers (Dirks et al., 1994; Burchfiel et al., 1995). Unlike the Longmen Shan, the Yalong Thrust Belt does not coincide with a steep topographic escarpment. However this belt remains evident as a 200 – 250 km wide NE – trending topographic step across the present low-relief plateau surface (Fig. 1b; Liu-Zeng et al., 2008). More broadly, the gradient of the plateau surface increases across Yalong Thrust Belt; mean elevation decreases southeastward from 4 – 5 km to 2– 3 km (Fig. 1b; Liu-Zeng et al., 2008).

Cenozoic sediment is preserved between splays of the Yalong Thrust Belt (Fig. 2a; BGMR Sichuan, 1991; BGMR Yunnan, 1990). The oldest sediments are mapped as Eocene – Oligocene and consist of fluvial sandstones and conglomerates (BGMR Sichuan, 1991; BGMR Yunnan, 1990). Between the Longmen Shan and Yalong Thrust Belt, along the eastern segment of the Xianshuihe fault zone, deformed and undeformed middle Miocene age granites are exposed near the Konggar massif (Fig. 2; Li and Zhang, 2013; Roger et al., 1995). A regional study of apatite fission track ages along the Xianshuihe fault (Xu and Kamp, 2000) concluded that much of the region was cooling slowly between circa 130 Ma and circa 22 Ma. Li and Zhang (2013) further inferred that the Xianshuihe fault zone and Konggar massif was intruded by magma during the Miocene (in 18 – 12 Ma), and finally, sinistral shearing began to occur at about 10 Ma and continues to present-day.

The topography of the eastern Tibetan Plateau is characterized by landscapes with low local relief (generally less than 600 m of relief at 4000 – 5000 m elevation) and slow erosion independent of lithology (Clark et al., 2006). Isotopic ages indicate regional slow cooling and probably slow erosion (1 – 3°C/Ma) from Jurassic time until at as recently as Late Miocene time (Kirby et al., 2002; Tian et al., 2014a, b).

Low-temperature thermochronometry yields apparent exhumation rates between 10 – 30 m/Ma since Cretaceous time (Clark et al., 2005; Xu and Kamp, 2000). ^{10}Be concentrations from fluvial sediment also indicate low (~20 m/Ma) erosion rates, consistent with long-term stability of the plateau surface (Ouimet et al., 2009). Overall, the presence of an intact, low-relief relict landscape draping the gently inclined surface of the southeastern Tibetan Plateau suggests that this area has experienced little to no surface shortening or exhumation during the Cenozoic (Clark et al., 2005).

Though the high-elevation planation surface of eastern Tibet has been argued to have formed at low elevation by lowland river erosion (e.g., Clark et al., 2005), high elevation planation surfaces elsewhere have been argued instead to have formed *in situ* as a result of glacial and periglacial erosion (Brozovic et al., 1997; Hales and Roering, 2009). Glacial erosion is most effective near the glacial equilibrium line altitude (ELA), where net ice accumulation and melting are balanced, and the flux of ice transported by glacial sliding reaches its maximum (Kessler et al., 2006). Though vigorous glacial erosion produces striking local relief between sharp peaks and U-shaped valleys, in many locations its main effect is to remove topography above the ELA, reducing relief (Egholm et al., 2009; Oskin and Burbank, 2005). In southern and eastern Tibet, glacial erosion should be most effective near the margins of the plateau, where more summer monsoon moisture is available to feed glacial accumulation, and ELAs are consequently depressed by several hundred meters (Heyman, 2014; Shi, 2002).

Conversely, periglacial frost-cracking is an effective geomorphic agent throughout the plateau, much of which is underlain by permafrost (Vandenberghe et al., 2014) with summer temperatures that regularly fluctuate around freezing (Hijmans et al., 2005). Here we evaluate the imprint of glacial erosion across a portion of eastern Tibet, and its relationship to gradients in exhumation defined using published data and new

measurements, in order to assess the role that glaciers, and associated periglacial process could play in producing the observed high-elevation planation surfaces.

3 Methods

3.1 U-Th-Sm/He dating

Similar to previous thermochronologic studies in eastern Tibet, we use low-temperature systems to explore cooling history and its relationship to mechanism of deformation and the generation of topographic relief (Fig. 2). We focus on (U-Th-Sm)/He thermochronometry in apatites (AHe) and zircons (ZHe), which reflect rock cooling and exhumation through the ~ 70 °C and ~ 180 °C isotherms, respectively (Farley, 2002; Reiners et al., 2005). Assuming a geothermal gradient of ~ 25 - 30 °C/km, the respective closure isotherms for AHe and ZHe are ~ 2.5 - 3.0 km and ~ 6 - 7.2 km beneath a surface with mean annual temperature near 0 °C. In total, we report ZHe and AHe results from 11 granitoid samples (Figs. 3 and 4, Tables 1 and S1-2). Two samples (MEO12-01, MEO12-02) were collected from the upper Liqiu river valley (Jaggai; JG) where low-relief surfaces were identified and early Cenozoic AHe cooling ages were previously reported by Clark et al. (2005) (Fig. 3; Table 1). A third sample (MEO12-04) is reported from an intermediate position, within a canyon incised below the low-relief plateau surface, at an elevation of $\sim 3,500$ m (Fig. 3; Table 1). Our remaining eight samples (MEO12-10 to 17) define a $\sim 1,200$ m age-elevation relief transect between $3,600$ and $4,800$ m, located near the town of Jiulong (JL) and ~ 30 km southeast of the confluence of the Liqiu and Yalong rivers (Figs. 3 and 4). These samples were collected within 2 km in map-view, adjacent to a rugged, glaciated canyon, to limit the influence of topography on estimated exhumation rates.

All samples were crushed, and apatite and zircon were extracted using standard magnetic and heavy-liquid techniques. (U-Th)/He thermochronometry was performed at the University of Arizona (Tables S1-2). Preparation included selection of euhedral grains larger than $60 \times 150 \mu\text{m}$ in dimension and, in the case of apatite, absence of visible microinclusions. Apatite and zircon grain dimensions were measured using digital images taken under $210\times$ magnification and dark-field illumination. Five single-crystal apatite and three single-crystal zircon aliquots per sample were loaded into Nb tubes, degassed by laser heating, and analyzed for He using ^3He isotope dilution, cryogenic purification, and quadrupole mass spectrometry. Degassed aliquots were dissolved and U and Th concentrations were measured by isotope dilution using a sector inductively coupled plasma-mass spectrometer. An α -ejection correction was applied to derive the corrected (U-Th)/He age (Farley, 2002; Reiners, 2005). Shards of Durango apatite and euhedral zircon crystals of Fish Canyon Tuff were analyzed with the samples as age standards. Mean values of individual sample were determined using all grain ages ($n = 3$ or 5 in all cases) and propagating all uncertainties.

Exhumation rates were calculated for the Jiulong and Liqui transects, considering AHe and ZHe results independently (Fig. 4). Following the rationale to determine exhumation rates using the slope of the age-elevation arrays, we quantified exhumation rates for the Jiulong transect, as well as for the previously published Liqui transect (Ouimet et al., 2010) by least-square fitting of age versus elevation, weighted by measurement errors of individual grains (Fig. 5). Given that the geotherm itself changes with exhumation, increasing as heat is advected toward the surface, the geothermal gradient will become non-linear and compressed in the shallow crust. To account for multiple chronometers within elevation transects, and to allow for non-steady cooling, we used the transdimensional monte-carlo simulation software,

QTQt v5.4.3 (Gallagher, 2012) to infer cooling histories (Fig. 6). Additional geological constraints used to constrain the model were a present-day surface temperature of 0 °C, initial time-temperature constraint of 300 ± 50 °C at 120 ± 10 Ma from published biotite Ar/Ar age from plutons at Jaggai and other nearby sites (Wallis et al., 2003; Reid et al., 2005), and an initial prior condition for the model domain of 0 to 300°C from 60 to 0 Ma. These model constraints were selected to give the modeling algorithm sufficient freedom to search for data-constrained cooling histories.

3.2 Glacial landscape mapping and ELA determination

We refined and expanded upon previously published glacial landform mapping in eastern Tibet (Fu et al., 2013a,b; Heyman, 2014) by interpreting glaciated features (cirques, arête) and deposits (lateral and terminal moraines), using high-resolution imagery available in Google Earth and the 90 m Shuttle Radar Topography Mission digital elevation model (Farr et al., 2007). Glacial extents were mapped on the basis of diagnostic landforms, such as U-shaped valleys, cirques, cirque-floor lakes, and lateral and terminal moraines (Fig. 7). For example, marginal and recessional moraines can be usually identified and traced from Google Earth images (Fig. 7). Where available, the centerlines of maximum-extent marginal moraine ridges were delineated as the boundary of former glaciers. Slope and shaded relief maps were overlain semi-transparently on the color-coded digital elevation to enhance and distinguish the visual impression of the fluvial V-shaped and glacial U-shaped valley topography. Mapping results were then double-checked against our own field investigation and earlier geomorphological mapping (Fu et al., 2013a, b).

Glacial maximum equilibrium line altitudes (ELAs) were estimated for the combined data set using an average of individual estimates obtained from two techniques:

accumulation area ratio ($AAR = 0.65$), and toe-headwall altitude ratio ($THAR = 0.40$) (Benn et al., 2005). Both measures were calculated from the hypsometry extracted from beneath each glacier outline. These measures nominally underestimate the true ELA because the thickness of the ice is not reconstructed. For previously mapped paleo-glaciers (Fu et al., 2013a, b), ELAs were determined for those with less than 10 km^2 surface area; larger ones tend to be fed by multiple tributary glaciers, and may have multiple outlets (Fig. 1b).

4 Results

4.1 Thermochronology

Along upper Liqiu river valley (Jaggai; JG), our results for two samples (MEO12-01/02) were dated as ~ 60 and 73 Ma (Fig. 3; Tables 1 and S1-2), and replicate early Cenozoic and Late Cretaceous AHe cooling ages previously published (Clark et al., 2005). The third sample (MEO12-04) from an elevation of $\sim 3,500 \text{ m}$ yielded a mean AHe age $37.3 \pm 2.6 \text{ Ma}$ (Figs. 3 and 5; Tables 1 and S1-2). Adjacent to the lower Liqiu river, near its confluence with the Yalong river (Fig. 3), Ouimet et al. (2010) reported that AHe ages span 1.7 Ma to 5.6 Ma over an elevation range of $2,800$ to $4,000 \text{ m}$, and ZHe ages for the Liqiu transect are as young as Late Miocene, ranging from $7.7 \pm 0.3 \text{ Ma}$ to $14.1 \pm 0.6 \text{ Ma}$ (Table 1; LQ: Figs. 4 and 5). With exception of one anomalously old sample (MEO12-13), cooling ages from our new Jiulong transect are tightly clustered (Fig. 4) for both ZHe ($30.2 \pm 1.5 \text{ Ma}$ to $33.3 \pm 8.5 \text{ Ma}$) and AHe ($6.5 \pm 1.1 \text{ Ma}$ to $9.6 \pm 0.7 \text{ Ma}$). Inverse correlation between single grain ZHe dates and effective uranium (eU) concentrations was observed for both the Jiulong and Liqiu sections (Fig. 8). We speculate that the effective closure temperature of the Liqiu

transect samples may be lowered due to radiation damage from the high U content (Guenther et al., 2014), and partially helps to explain the differences between Liqiu and Jiulong ZHe data sets. This further may have led to the less separation of ZHe and AHe ages at the Liqiu-Yalong confluence compared with those at Jiulong transect (Fig. 5). A conservative interpretation of the Liqiu ZHe ages is that these ages record rapid exhumation ca 10 Ma, though the amount of exhumation implied by the ZHe dates requires further analysis that is beyond the scope of this paper. Overall, depth of Late Miocene and younger exhumation at both the Liqiu (LQ) (Ouimet et al., 2010) and Jiulong (JL) (our study) require removal of several kilometers of rock from above the present elevation of the plateau surface (Fig. 4), and the depth of Late Miocene and younger exhumation implied is greatest at the Yalong-Liqiu confluence, whereas the older ZHe ages at Jiulong reveal an earlier, Oligocene exhumation event.

Along upper Liqiu River valley (Jaggai; JG), Cenozoic cooling rate of the low-relief surface region has been suggested to be low at $<1^{\circ}\text{C}/\text{Ma}$ (Clark et al., 2004). Results from both our new samples (MEO12-01/02/04) and Clark et al. (2005) support a slow average Cenozoic exhumation rate of 30 to 70 m/Ma, assuming a geothermal gradient of 20 – 30 $^{\circ}\text{C}/\text{km}$. South of the preserved low-relief surfaces, the slope of the age-elevation relationship from Liqiu transect (Ouimet et al., 2010) yields a best-fit exhumation rate that is up to ten times higher, at ~ 330 m/Ma (~ 270 – 420 with 95% confidence) (Figs. 3 and 4). Zircon-helium (ZHe) ages from these same samples also yield a high exhumation rate of ~ 250 m/Ma (180 – 420 with 95% confidence). The Jiulong transect reveals yet higher rates of exhumation, with a best fit age-elevation relationship of ~ 500 m/Ma (~ 200 – $>1,000$ m/Ma) (Figs. 4 and 5).

Our thermal history modeling for both AHe and ZHe cooling ages from Jiulong (Fig.

6a-c) and Liqiu (Ouimet et al., 2010; Fig. 6d-f) transects confirms that the Cenozoic cooling rate of the downstream Liqiu transect region was ten times higher ($\sim 10^{\circ}\text{C}/\text{Ma}$) than that of the low-relief surface region. This sharp cooling gradient coincides well with the estimation of the exhumation rates from age-elevation relationships (Fig. 5). Our Jiulong (JL) samples also reveal a pulsed cooling history during the Cenozoic, expressed by two stages of relatively rapid cooling during late Eocene-early Oligocene and late Miocene to present, with slowing of exhumation rate during the early Miocene (Fig. 6a-c). More specifically, the first stage of rapid cooling can be tightly constrained to have occurred in the early Oligocene, or perhaps the latest Eocene, between $\sim 35\text{-}30$ Ma, and the second stage occurred in the late Miocene, $7\text{-}8$ Ma (Fig. 6a-c). A decrease of cooling after $7\text{-}8$ Ma is also indicated by the cooling history modeling, but without thermal constraints at less than $\sim 60^{\circ}\text{C}$, a confident conclusion cannot be drawn at present. Different from the Jiulong transect, model results from the Liqiu (LQ) relief transect (Ouimet et al., 2010) revealed an increase of cooling rate in the early Miocene, ca. ~ 20 Ma (Fig. 6d-f), followed by an accelerated cooling at ~ 8 Ma (Fig. 6a-c).

4.2 Glacial mapping

Glacial landform mapping reveals that glaciers once mantled the higher ridgelines of the Jiulong and Liqiu areas (Figs. 3 and 4). Abundant glacial landforms are found on the present mostly ice-free areas, including distinctive patterns of glacial cirques, valleys, lakes and marginal/terminal moraines (Fig. 7). Glacial cirques are either isolated or connected downstream with glaciated U-shaped valleys (Fig. 7). Numerous marginal moraines are present, including arc-shaped lateral or lateral-terminal moraines in valleys and sinuous moraines on the plateau surface. In total, 3,661 valley

and cirque glacier polygons were outlined and interpreted, ranging from 0.1 to 175 km² in area (Fig. 3). Our combined glacial mapping result reveals ubiquitous glacial erosion along ridgelines separating low-relief plateau surfaces from deeply incised river gorges (Fig. 3). Fig. 4 shows the mean elevations of previously mapped relict surfaces (Clark et al., 2006; Ouimet et al., 2010) and ELA determinations along 70 km-wide, 250 km-length topographic swath across the exhumation-rate gradient. We find that mean ELAs in eastern Tibet lie near ~4,400 – 4,500 m altitude, 0 to 200 m above the mean elevation of the interpreted plateau surface (Clark et al., 2006) (Fig. 4).

5 Discussion and implications

Mid- to Late-Cenozoic exhumation history and magnitude across eastern Tibet show greater variation southwest of the Xianshuihe fault than to the northeast (Fig. 2b). To the southwest, evidence for pre-mid Miocene and earlier onset of deformation include multiple angular unconformities of the Eocene-Oligocene strata within the Yalong Thrust Belt (YLTB) (BGMR Sichuan, 1991; BGMR Yunnan, 1990), early Miocene cooling at Daocheng (DC) (Tian et al., 2014), and Liqiu (LQ) (Fig. 5d-f; Ouimet et al., 2010), and an Oligocene cooling evident from our ZHe cooling results from Jiulong Shan.

Evidence for early-middle Cenozoic exhumation may be widespread within the hinterland of the Yalong-Longmen Shan Thrust Belt (Fig. 2b). Oligocene cooling of Jiulong Shan is similar to the timing of cooling of the central and southern Longmen Shan (Tan et al., 2014; Wang et al., 2012). Protracted Oligocene metamorphism at ~ 32 – 27 Ma is also suggested by growth rims of zircons from the melanosome and the leucosome samples from the Konggar massif (Li and Zhang, 2013). Although zircons

can grow (under certain fluid compositions) at temperatures below the partial melting temperature for granite, the most likely explanation is that those rocks were at 650° or greater in Oligocene time (Li and Zhang, 2013). If correct, that requires crust along this plateau margin must have been thickened, likely following an Oligocene shortening event. Early-middle Cenozoic deformation could have been more widespread and variable within southeast Tibet, but this history may not yet be completely revealed because of absence of higher-temperature thermochronological data. Northeast of the Xianshuihe fault, cooling ages from Longmen Shan Thrust Belt (LTB, Cook et al., 2013; Godard et al., 2009; Kirby et al., 2002; Wang et al., 2012), Dadu river canyon (DD, Clark et al., 2005; Ouimet et al., 2010), Lianghekou (LH) and Heishui (HS, Tian et al., 2015), and Min Shan (MS, Kirby et al., 2002) indicate a more uniform pattern of exhumation commencing largely at 10-12 Ma (Fig. 2b).

Overall, the available data summarized here reveal a non-uniform exhumation history across the eastern Tibet (Fig. 2b). Both earlier onset of the current phase of exhumation, and evidence for earlier pulses of exhumation, are found in about half of sites where suitable data exist. Though the elevation of low-relief plateau surfaces shows remarkable continuity, the evidence for heterogeneous exhumation timing and depth suggests that this surface may not reflect a single generative mechanism. For example, regions uplifted within the Longmen Shan-Yalong Thrust Belt were probably more mountainous during the late Eocene - early Oligocene and early Miocene than areas, such as along the upper Dadu River, with a long Cenozoic history of slow cooling (Clark et al., 2005; Ouimet et al., 2010). As previously suggested by Wang et al. (2012) along the Longmen Shan, the exhumation rate of ~100 m/Ma determined by age-elevation trend of ZHe ages implies an order of ~750 – 1000 m topographic relief during Paleocene. Our ZHe ages from Jiulong section, however, would indicate almost

~3,000 m of topographic relief during late Eocene - early Oligocene, similar to today, and consistent with the relationship between relief and erosion rate for mid-latitude, temperate catchments (Ahnert, 1970).

Along a north-to-south transect of elevation, ELA, and exhumation rate from the upper Liqiu river to Jiulong (Figs. 3 and 7), the rate of Late Miocene and younger exhumation from samples residing at or above the ~4.2 to 4.5 km plateau-surface elevation increases from ~50 to >500 m/Ma, while both mean and maximum elevations increase only modestly (<500 m). Importantly, however, the surface area above the glacial ELA that fed glaciers during the Last Glacial Maximum increased substantially (Heyman, 2014; Shi, 2002). As a result, the effects of glacial erosion are far more widespread in the high exhumation-rate area surrounding the Liqiu-Yalong confluence. This evidence suggests an appealing mechanism to regulate plateau surface elevations and produce the continuity of the plateau surface evident today. At higher elevation, vigorous glacial erosion would be expected to occur, eroding and leveling the landscape. Though a relict plateau surface is not present within the Jiulong Shan, areas of low slope at high elevation are abundant within cirque basins above the ELA, and in low-gradient U-shaped valleys that are widely distributed above ~3,500 – 3,600 m (Fig. 9b). Much of the surrounding low-relief plateau surface, including the area of Jaggai, lies close to the last glacial maximum equilibrium line altitude (Figs. 4 and 9a-b), and is subject to similar regulation of topographic relief production by efficient glacial and periglacial erosion of ridges.

Smoothing of highlands by efficient glacial and periglacial erosion, coupled with potential drainage capture, and efficient conveyance of sediments via external drainage, may yield an apparently continuous low-relief plateau landscape with a diachronous origin at high elevation. Relief would be reduced by glacial erosion of ridgelines,

smoothed by vigorous periglacial hillslope processes, and suppressed by low-gradient, transport-limited streams (Liu-Zeng et al., 2008). Such a process of plateau-surface formation is evident today north of the Liqui-Yalong confluence, where the transition between areas of high- and low exhumation rates is associated with a decline in Late Pleistocene glacier cover and emergence of a plateau landscape with reduced upland relief. Drainage capture events, and the resulting isolation of low-gradient underfit valleys, may seed the formation of individual portions of the plateau surface, with glacial erosion providing the means to equalize the plateau elevation near the ELA. Though the impact of glacial and periglacial erosion within southeast Tibet area prior to the Late Quaternary is unknown, the present plateau landscape bears a strong imprint of these processes, which likely play an important role in rendering formerly mountainous landscapes into an apparently contiguous, high-elevation planation surface. Due to moisture availability, glacial erosion may be most effective near the plateau margin, such as exemplified by our study area. Whether the glacial and periglacial erosion could explain the generation of low-relief landscapes within the interior of the Tibetan Plateau remains to be tested.

The modest difference in mean elevation of glaciated landscapes in eastern Tibet, despite an approximately 10-fold difference in exhumation rate, suggests that a plateau surface could stabilize in ~10 Ma. Only ~200 m of surface lowering, or little more than 1 km of exhumation after accounting for isostatic compensation, is required to lower the average elevation of the high-exhumation-rate region at Jiulong to that of the low-exhumation-rate plateau landscape near Jaggai. This lies within the acceptable amount of Neogene exhumation of the nearby plateau interior permitted by AHe data. One kilometer of exhumation is not enough to expose the partial retention zone at the plateau surface (~2 – 3 km for a ~25°C geothermal gradient). Therefore, rocks with

early Cenozoic and older cooling ages could be readily preserved while periglacial transport and glacial erosion smoothed a formerly more rugged plateau landscape.

We conclude that glacial erosion of externally drained upland regions in eastern Tibet can keep pace with rapid rates of rock uplift, limiting mean elevation, and setting the stage for development of a low-relief plateau surface (Fig. 9c). The interpretation that low-relief plateau surfaces must have formed at low-elevation neglects that important role of glacial erosion in limiting mountain-range elevation (Brozovic et al., 1997; Egholm et al., 2009). More specifically, some previous studies proposed that the low-relief surfaces in Tibet and other orogens can be utilized to constrain amount of surface uplift (Clark et al., 2006; Hetzel et al., 2011), but if formation of at least some of these high-elevation, low-relief landscapes was glacially driven, then the validity of these relict surfaces as uplift markers needs to be reevaluated.

6 Conclusions

We report new U-Th-Sm/He cooling ages in the Jiulong mountains and adjacent regions of eastern Tibet. Zircon and apatite ages and age-elevation plots record episodes of rapid exhumation (~500 m/Ma) in the early Oligocene and late Miocene, respectively. This pulsed exhumation history within the interior plateau is similar to a cooling history observed along the marginal Longmen Shan, and thus supports the emerging view of a two phases of tectonism and uplift in eastern Tibet. Synthesis of available data from eastern Tibet revealed a heterogeneous pattern of Late Cenozoic uplift and exhumation of the plateau interior. Overall, the varied exhumation history of Eastern Tibet is inconsistent with the hypothesis of a uniformly graded low-relief

surface that was uplifted to form the plateau due to lower crustal inflation. Our compilation of glacial landform-mapping indicates that the elevation of the plateau surface closely tracks global last glacial maximum equilibrium line altitude. Though lowland fluvial erosion along major river systems could explain the present plateau surface in many areas, other features, such as intramontaine valley systems, and stream piracy, or glaciers could also play important roles in leveling the plateau landscape. We conclude that smoothing of highlands by efficient glacial and periglacial erosion, coupled with efficient conveyance of sediments via external drainage, can yield an apparently continuous, but diachronous low-relief plateau landscape.

Acknowledgements

This current research was supported jointly by the National Science Foundation of China (Grant no. 41172179, 41225010 and 41272196), and Strategic Priority Research Program of the CAS (XDB03020201); M.O. and P.R. were supported by NSF EAR-1050060. We gratefully acknowledge Eric Kirby, Editor An Yin and two anonymous reviewers for constructive reviews. We appreciate comments from Peter Molnar, Doug Burbank and Marin Clark on the early draft and Dr. Ping Fu for sharing their glacial landscape mapping data, and Alexis Ault, Uttam Chowdhury, Erin Abel for helping with apatite and zircon analyses.

References

- Ahnert, F., 1970. Functional relationships between denudation, relief, and uplift in large, mid-latitude drainage basins. *American Journal of Science* 268, 243-263.
- Arne, D., Worley, B., Wilson, C., Chen, S.F., Foster, D., Luo, Z.L., Liu, S.G., Dirks, P., 1997. Differential exhumation in response to episodic thrusting along the eastern

margin of the Tibetan Plateau. *Tectonophysics* 280, 239-256.

Benn, D.I., Owen, L.A., Osmaston, H.A., Seltzer, G.O., Porter, S.C., Mark, B., 2005. Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. *Quaternary International* 138–139, 8-21.

Brozovic, N., Burbank, D.W., Meigs, A.J., 1997. Climatic limits on landscape development in the northwestern Himalaya. *Science* 276, 571-574.

Burchfiel, B.C., Zhiliang, C., Yupinc, L., Royden, L.H., 1995. Tectonics of the Longmen Shan and Adjacent Regions, Central China. *International Geology Review* 37, 661-735.

Bureau of Geology and Mineral Resources of Sichuan Province (BGMR Sichuan), 1991, *Regional Geology of Sichuan Province*: Beijing, Geological Publishing House, 610 p.

Bureau of Geology and Mineral Resources of Yunnan Province (BGMR Yunnan), 1990, *Regional Geology of Yunnan Province*: Beijing, Geological Publishing House, 178 p.

Clark, M.K., House, M.A., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X., Tang, W., 2005. Late Cenozoic uplift of southeastern Tibet. *Geology* 33, 525-528.

Clark, M.K., Royden, L.H., 2000. Topographic ooze: Building the eastern margin of Tibet by lower crustal flow. *Geology* 28, 703-706.

Clark, M.K., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X., Tang, W., 2006. Use of a regional, relict landscape to measure vertical deformation of the eastern Tibetan Plateau. *Journal of Geophysical Research-Earth Surface* 111.

Cook, K.L., Royden, L.H., Burchfiel, B.C., Lee, Y.-H., Tan, X., 2013. Constraints on Cenozoic tectonics in the southwestern Longmen Shan from low-temperature thermochronology. *Lithosphere* 5, 393-406.

514 Dirks, P.H.G.M., Wilson, C.J.L., Chen, S., Luo, Z.L., Liu, S., 1994. Tectonic evolution
 515 of the NE margin of the Tibetan Plateau; evidence from the central Longmen
 516 Mountains, Sichuan Province, China. *Journal of Southeast Asian Earth Sciences* 9,
 517 181-192.

518 Duvall, A.R., Clark, M.K., Avdeev, B., Farley, K.A., Chen, Z., 2012. Widespread late
 519 Cenozoic increase in erosion rates across the interior of eastern Tibet constrained
 520 by detrital low-temperature thermochronometry. *Tectonics* 31, TC3014.

521 Egholm, D.L., Nielsen, S.B., Pedersen, V.K., Lesemann, J.E., 2009. Glacial effects
 522 limiting mountain height. *Nature* 460, 884-887.

523 Farley, K.A., 2002. (U-Th)/He Dating: Techniques, Calibrations, and Applications.
 524 *Reviews in Mineralogy and Geochemistry* 47, 819-844.

525 Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M.,
 526 Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J.,
 527 Werner, M., Oskin, M., Burbank, D., Alsdorf, D., 2007. The shuttle radar
 528 topography mission. *Reviews of Geophysics* 45, RG2004.

529 Fu, P., Harbor, J.M., Stroeve, A.P., Hättestrand, C., Heyman, J., Zhou, L., 2013a.
 530 Glacial geomorphology and paleoglaciation patterns in Shaluli Shan, the
 531 southeastern Tibetan Plateau - Evidence for polythermal ice cap glaciation.
 532 *Geomorphology* 182, 66-78.

533 Fu, P., Stroeve, A.P., Harbor, J.M., Hättestrand, C., Heyman, J., Caffee, M.W., Zhou,
 534 L., 2013b. Paleoglaciation of Shaluli Shan, southeastern Tibetan Plateau.
 535 *Quaternary Science Reviews* 64, 121-135.

536 Gallagher, K., 2012. Transdimensional inverse thermal history modeling for
 537 quantitative thermochronology. *Journal of Geophysical Research: Solid Earth* 117,
 538 n/a-n/a.

539 Godard, V., Pik, R., Lave, J., Cattin, R., Tibari, B., de Sigoyer, J., Pubellier, M., Zhu, J.,
 540 2009. Late Cenozoic evolution of the central Longmen Shan, eastern Tibet:
 541 Insight from (U-Th)/He thermochronometry. *Tectonics* 28.
 542 Guenthner, W.R., Reiners, P.W., Tian, Y., 2014. Interpreting date–eU correlations in
 543 zircon (U-Th)/He datasets: A case study from the Longmen Shan, China. *Earth*
 544 *Planet Sc Lett* 403, 328-339.
 545 Hales, T.C., Roering, J.J., 2009. A frost “buzzsaw” mechanism for erosion of the
 546 eastern Southern Alps, New Zealand. *Geomorphology* 107, 241-253.
 547 Hetzel, R., Dunkl, I., Haider, V., Strobl, M., von Eynatten, H., Ding, L., Frei, D., 2011.
 548 Peneplain formation in southern Tibet predates the India-Asia collision and
 549 plateau uplift. *Geology* 39, 983-986.
 550 Heyman, J., 2014. Paleoglaciation of the Tibetan Plateau and surrounding mountains
 551 based on exposure ages and ELA depression estimates. *Quaternary Science*
 552 *Reviews* 91, 30-41.
 553 Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high
 554 resolution interpolated climate surfaces for global land areas. *International Journal*
 555 *of Climatology* 25, 1965-1978.
 556 Hoke, G.D., Liu-Zeng, J., Hren, M.T., Wissink, G.K., Garzione, C.N., 2014. Stable
 557 isotopes reveal high southeast Tibetan Plateau margin since the Paleogene. *Earth*
 558 *Planet Sc Lett* 394, 270-278.
 559 Kirby, E., Reiners, P.W., Krol, M.A., Whipple, K.X., Hodges, K.V., Farley, K.A.,
 560 Wenqing, T., Zhiliang, C., 2002. Late Cenozoic evolution of the eastern margin of
 561 the Tibetan Plateau: Inferences from $^{40}\text{Ar}/^{39}\text{Ar}$ and (U-Th)/He
 562 thermochronology. *Tectonics* 21.
 563 Li, H., Zhang, Y., 2013. Zircon U–Pb geochronology of the Konggar granitoid and

564 migmatite: Constraints on the Oligo-Miocene tectono-thermal evolution of the
565 Xianshuihe fault zone, East Tibet. *Tectonophysics* 606, 127-139.

566 Liu-Zeng, J., Tapponnier, P., Gaudemer, Y., Ding, L., 2008. Quantifying landscape
567 differences across the Tibetan plateau: Implications for topographic relief
568 evolution. *Journal of Geophysical Research-Earth Surface* 113.

569 Oskin, M., Burbank, D.W., 2005. Alpine landscape evolution dominated by cirque
570 retreat. *Geology* 33, 933-936.

571 Ouimet, W., Whipple, K., Royden, L., Reiners, P., Hodges, K., Pringle, M., 2010.
572 Regional incision of the eastern margin of the Tibetan Plateau. *Lithosphere* 2,
573 50-63.

574 Ouimet, W.B., Whipple, K.X., Granger, D.E., 2009. Beyond threshold hillslopes:
575 Channel adjustment to base-level fall in tectonically active mountain ranges.
576 *Geology* 37, 579-582.

577 Reid, A.J., Wilson, C.J.L., Phillips, D., Liu, S., 2005. Mesozoic cooling across the
578 Yidun Arc, central-eastern Tibetan Plateau: A reconnaissance $^{40}\text{Ar}/^{39}\text{Ar}$ study.
579 *Tectonophysics* 398, 45-66.

580 Reiners, P.W., 2005. Zircon (U-Th)/He Thermochronometry. *Reviews in Mineralogy*
581 and *Geochemistry* 58, 151-179.

582 Roger, F., Jolivet, M., Malavieille, J., 2010. The tectonic evolution of the
583 Songpan-Garzê (North Tibet) and adjacent areas from Proterozoic to Present: A
584 synthesis. *Journal of Asian Earth Sciences* 39, 254-269.

585 Roger, F., Malavieille, J., Leloup, P.H., Calassou, S., Xu, Z., 2004. Timing of granite
586 emplacement and cooling in the Songpan–Garzê Fold Belt (eastern Tibetan
587 Plateau) with tectonic implications. *Journal of Asian Earth Sciences* 22, 465-481.

588 Rohrmann, A., Kapp, P., Carrapa, B., Reiners, P.W., Guynn, J., Ding, L., Heizler, M.,

589 2012. Thermochronologic evidence for plateau formation in central Tibet by 45
 590 Ma. *Geology* 40, 187-190.

591 Shi, Y., 2002. Characteristics of late Quaternary monsoonal glaciation on the Tibetan
 592 Plateau and in East Asia. *Quaternary International* 97–98, 79-91.

593 Tan, X.-B., Lee, Y.-H., Chen, W.-Y., Cook, K.L., Xu, X.-W., 2014. Exhumation history
 594 and faulting activity of the southern segment of the Longmen Shan, eastern Tibet.
 595 *Journal of Asian Earth Sciences* 81, 91-104.

596 Tian, Y., Kohn, B.P., Gleadow, A.J.W., Hu, S., 2014a. A thermochronological
 597 perspective on the morphotectonic evolution of the southeastern Tibetan Plateau.
 598 *Journal of Geophysical Research: Solid Earth* 119, 2013JB010429.

599 Tian, Y., Kohn, B.P., Hu, S., Gleadow, A.J.W., 2014b. Postorogenic rigid behavior of
 600 the eastern Songpan-Ganze terrane: Insights from low-temperature
 601 thermochronology and implications for intracontinental deformation in central
 602 Asia. *Geochemistry, Geophysics, Geosystems* 15, 453-474.

603 Tian, Y., Kohn, B.P., Hu, S., Gleadow, A.J.W., 2015. Synchronous fluvial response to
 604 surface uplift in the eastern Tibetan Plateau: Implications for crustal dynamics.
 605 *Geophysical Research Letters* 42, 2014GL062383.

606 van der Beek, P., Van Melle, J., Guillot, S., Pecher, A., Reiners, P.W., Nicolescu, S.,
 607 Latif, M., 2009. Eocene Tibetan plateau remnants preserved in the northwest
 608 Himalaya. *Nature Geoscience* 2, 364-368.

609 Vandenberghe, J., French, H.M., Gorbunov, A., Marchenko, S., Velichko, A.A., Jin, H.,
 610 Cui, Z., Zhang, T., Wan, X., 2014. The Last Permafrost Maximum (LPM) map of
 611 the Northern Hemisphere: permafrost extent and mean annual air temperatures,
 612 25–17 ka BP. *Boreas* 43, 652-666.

613 Wallis, S., Tsujimori, T., Aoya, M., Kawakami, T., Terada, K., Suzuki, K., Hyodo, H.,

2003. Cenozoic and Mesozoic metamorphism in the Longmenshan orogen:
 Implications for geodynamic models of eastern Tibet. *Geology* 31, 745-748.

Wang, E., Kirby, E., Furlong, K.P., van Soest, M., Xu, G., Shi, X., Kamp, P.J.J.,
 Hodges, K.V., 2012. Two-phase growth of high topography in eastern Tibet
 during the Cenozoic. *Nature Geosci* 5, 640-645.

Xu, G., Kamp, P.J.J., 2000. Tectonics and denudation adjacent to the Xianshuihe Fault,
 eastern Tibetan Plateau: Constraints from fission track thermochronology. *Journal*
of Geophysical Research: Solid Earth 105, 19231-19251.

Yang, R., Willett, S.D., Goren, L., 2015. In situ low-relief landscape formation as a
 result of river network disruption. *Nature* 520, 526-529.

Yin, A., 2010. Cenozoic tectonic evolution of Asia: A preliminary synthesis.
Tectonophysics 488, 293-325.

Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan-Tibetan orogen.
Annual Review of Earth and Planetary Sciences 28, 211-280.

Zhang, Y.-Z., Replumaz, A., Wang, G.-C., Leloup, P.H., Gautheron, C., Bernet, M., van
 der Beek, P., Paquette, J.L., Wang, A., Zhang, K.-X., Chevalier, M.-L., Li, H.-B.,
 2015. Timing and rate of exhumation along the Litang fault system, implication
 for fault reorganization in Southeast Tibet. *Tectonics* 34, 2014TC003671.

Figure captions

Fig. 1 Landscape and glacial maximum glacier distribution in eastern Tibet. a) large
 scale topographic features of the Tibetan Plateau. Red and blue lines highlight the

outlines of hypothesized early Cenozoic extent of the Tibetan Plateau (modified
 after Rohrmann et al., 2012), with uncertain extent in eastern Tibet. Green coded
 polygons indicate mapped low-relief plateau surface (Clark et al., 2005; Ouimet et
 al., 2010). Blue circle is the Bangoin Paleocene-Eocene peneplain (Hetzl et al.,
 2011), which was interpreted to be generated near sea level prior to uplift to ~5.0
 km. Orange circle represents an Eocene surface remnants, Deosai Plateau in
 northwestern Himalaya (van der Beek et al., 2009). Purple polygons are mapped
 Late Pleistocene glacier extents (Fu et al., 2013a, b) b) Swath profile (200 km ×
 2,000 km) across the eastern and southeastern Tibet, showing consistency
 between mean elevation, low-relief surface elevation, and glacial ELAs.
 Maximum elevations step downward across the Yalong Thrust Belt (Liu-Zeng et
 al., 2008).

Fig. 2 Tectonic setting (a) and thermochronology study localities (b) of eastern Tibet.

Note the continuity of the pre-Mesozoic outcrops from the Longmen Shan
 Tectonic Belt to the Yalong Thrust Belt across the Xianshuihe Fault (a).
 Preponderance of pre-15 Ma rapid exhumation was observed southwest of the
 Xianshuihe fault (XSHF), and more uniform timing of exhumation to the
 northeast (b). Abbreviations for study sites: YLTB, Yalong Thrust Belt; DC,
 Daocheng transect (Tian et al., 2014a); JL, Jiulong Shan (this study); LQ, Liqui
 transect (Ouimet et al., 2010); KG, Konggar massif (Li and Zhang, 2013). LT,
 Litang transect (Zhang et al., 2015); LTB, Longmen Shan Thrust Belt (Cook et al.,
 2013; Godard et al., 2009; Guenther et al., 2014; Tan et al., 2014; Wang et al.,
 2012); DD, Dadu transect (Clark et al., 2005; Ouimet et al., 2010); LH,
 Lianghekou transect, HS, Heishui transect (Tian et al., 2015); MS, Minshan

(Kirby et al., 2002).

Fig. 3 Detailed glacier distribution and transects for U-Th/He thermochronometry, featuring the Jaggai (JG), Liqiu (LQ) section (Ouimet et al., 2010), and Jiulong (JL) sites (our present study). Green polygons, are interpreted as relict peneplain surfaces (Clark et al., 2005; Ouimet et al., 2010). Purple outlines show Late Pleistocene glacial extents mapped for this study. Cenozoic exhumation rates were determined by AHe ages from Jaggai assuming a geothermal gradient of $20 - 30\text{ }^{\circ}\text{C km}^{-1}$ and AHe age-elevation fitting for Jiulong and Liqiu sections (Fig. 5), respectively. Exhumation rate of the downstream Liqiu and Jiulong transect regions is ten times higher than the cooling rate of the low-relief plateau region near Jaggai.

Fig. 4 Topographic profiles, averaged ELAs and exhumation pattern (AHe ages) along a north-south swath through eastern Tibet. See Fig. 3 for swath location. Samples from low-relief plateau surface give AHe cooling ages $\sim 58 - 76\text{ Ma}$. Southward increase of exhumation amount and rate indicated by interpolated AHe isochrons (dashed lines). LQ: Liqiu age-elevation transect; JL Jiulong age-elevation transect. Mapped low-relief plateau surface (Clark et al., 2006) is absent south of Liqiu transect.

Fig. 5 AHe and ZHe (U-Th)/He thermochronometry results and age-elevation relationships from Liqiu-Jiulong region. Exhumation rates for Liqiu (LQ), and Jiulong (JL) vertical transects were obtained by least-square fitting all the ages weighted by measurement errors of individual grains. Anomalously old sample

MEO-13 was excluded from Jiulong transect. For samples MEO-01/02/04 (squares, diamonds and stars in red) from the low-relief Jaggai (JG) region, only AHe ages for individual grains were shown for comparison. Note the nearly coincident elevations of early Cenozoic and late Cretaceous ages from the low-relief plateau region at Jaggai.

Fig. 6 Cooling history modeling results of the Jiulong (a-c) and Liquu (d-f) relief transects by transdimensional monte-carlo simulation software, QTQt v5.4.3 (Gallagher, 2012). a and d: cooling history for all samples in transect; b and e: best-fit and probability distribution of cooling history for top sample of transects; c and f show same for lower sample of transects. Both AHe and ZHe cooling ages from Jiulong and Liquu transects reveal relatively rapid ($\sim 10^\circ/\text{Myr}$) cooling. Note that the Jiulong transect also features two stages of increased cooling rate during early Oligocene and late Miocene to present, with slower exhumation rate during the early Miocene.

Fig. 7 Examples of mapped glacial landforms in eastern Tibet, showing cirques, cirque-floor lakes, and lateral and terminal moraines identified from interpretation of SRTM topography and high-resolution imagery in Google Earth. a: example from low-relief plateau surface near Jaggai; b: example from higher-relief region near Jiulong.

Fig. 8 ZHe dates – eU correlations for the Jiulong (green dots; our present study) and Liquu (brown dots; Ouimet et al., 2010) transects. This inverse correlation may arise from the effects of radiation damage on He diffusion, and effective closure

temperature of the Liqui samples may be lowered due to radiation damage from the high U content.

Fig. 9 a: Oblique view of a portion of eastern Tibet corresponding to the swath analyzed in Fig. 4. Yellow contour lines in a are located at 4,400 m and correspond approximately to the Late Pleistocene ELA. b: slope distribution of area shown in a. c: conceptual model of landscape evolution for eastern Tibet. . Where the landscape has undergone slow ($<50 \text{ m Ma}^{-1}$) exhumation, glacial erosion limits ridgeline elevations and helps to maintain a low-relief plateau surface. More intensively glaciated landscapes are associated with higher ($>500 \text{ m Ma}^{-1}$) exhumation rates. Here, low-relief glacial cirques floors and wide, flat U-shaped valleys are common, but expansive low-relief plateau surfaces are not developed. As exhumation rates decline, glacial erosion of ridgelines, frost-driven periglacial weathering (Hales and Roering, 2009), and transport-limited stream systems (Liu-Zeng et al., 2008) facilitate smoothing of the plateau landscape.

Table 1 Sample descriptions

Sample location	Sample ID	Rock type	Age	Long. (°E)	Lat. (°N)	Elev. (m)	Apatite replicates	Zircon replicates	Mean age Apatite (Ma)	Mean age Zircon (Ma)	Reference
Jaggai	MEO12-01	Granite	Mz	101.376	30.032	4283	5	3	59.6 ± 3.8	139.8 ± 28.2	this study
	MEO12-02	Granite	Mz	101.396	30.016	4274	5	3	72.8 ± 11.1	129.2 ± 49.6	this study
	MEO12-04	Granite	Mz	101.569	29.888	3480	5	3	37.3 ± 2.6	103.8 ± 5.8	this study
	MC01-49	Granite	Mz	101.532	30.124	4000	6	–	57.6 ± 2.7	–	Clark et al., 2005
Jiulong	MEO12-10	Granite	Mz	101.424	29.224	3666	5	3	7.6 ± 0.7	30.2 ± 1.5	this study
	MEO12-11	Granite	Mz	101.420	29.226	3863	5	3	7.3 ± 1.7	33.2 ± 1.7	this study
	MEO12-12	Granite	Mz	101.417	29.227	4013	5	3	7.2 ± 0.7	29.4 ± 2.8	this study
	MEO12-13	Granite	Mz	101.415	29.227	4153	5	3	14.3 ± 2.9	58.2 ± 19.2	this study
	MEO12-14	Granite	Mz	101.412	29.228	4308	5	–	6.5 ± 1.1	–	this study
	MEO12-15	Granite	Mz	101.412	29.218	4445	5	3	7.9 ± 0.2	33.3 ± 8.5	this study
	MEO12-16	Granite	Mz	101.408	29.217	4602	5	3	9.2 ± 0.5	31.8 ± 1.9	this study
	MEO12-17	Granite	Mz	101.408	29.214	4800	5	3	9.6 ± 0.7	32.9 ± 2.8	this study
	MC-01-25	Granodiorite	Mz	101.751	28.543	1700	3	–	4.6 ± 0.8	–	Clark et al., 2005
	MC-01-27	Granite	Mz	101.734	28.552	1950	3	–	5.0 ± 1.2	–	Clark et al., 2005
	MC-01-29	Granite	Mz	101.603	28.835	2100	5	–	8.3 ± 1.4	–	Clark et al., 2005
	MC-01-30	Granite	Mz	101.573	28.874	2550	4	–	10.1 ± 4.5	–	Clark et al., 2005
Liqiu	wbo-04-41C	Granite	Mz	101.244	29.460	4000	4	2	5.6 ± 0.8	13.7 ± 0.5	Ouimet et al., 2010
	wbo-04-41A	Granite	Mz	101.240	29.448	3700	3	1	4.7 ± 0.2	11.7 ± 0.7	Ouimet et al., 2010
	wbo-03-16A	Granite	Mz	101.235	29.432	3100	2	–	3.6 ± 0.5	–	Ouimet et al., 2010
	wbo-04-41E	Granite	Mz	101.228	29.420	2800	3	4	1.7 ± 0.5	8.6 ± 0.8	Ouimet et al., 2010

Zhang et al. Figure 1

Zhang et al. Figure 2

Zhang et al. Figure 3

Zhang et al., Figure 4

Zhang et al., Figure 5

Zhang et al., Figure 6

Zhang et al., Figure 7

Zhang et al. Figure 8

Zhang et al., Figure 9