Cenozoic paleoaltimetry of the SE margin of the Tibetan Plateau: Constraints on the tectonic evolution of the region

Shanying Li ^{a,*}, Brian S. Currie ^a, David B. Rowley ^b, Miquela Ingalls ^b

a) Department of Geology and Environmental Earth Science, Miami University, Oxford, OH 45056, USA

b) Department of the Geophysical Sciences, The University of Chicago, Chicago, IL 60637, USA

* Corresponding author: lis9@MiamiOH.edu

Abstract

An improved understanding of the elevation history of the Tibetan Plateau is crucial in discriminating among the various tectonic models for the evolution of the India-Asia continental collision. We reconstruct the paleoelevation history for three Cenozoic sedimentary basins from SE Tibet and Yunnan, China, to provide more constraints on the tectonic processes for raising the SE margin of the Tibetan Plateau. The results presented here, together with those of previous studies, indicate that (1) the plateau margin of NW Yunnan was near its elevation (~2.6 km) by the latest middle Eocene (~40 Ma); (2) the plateau margin of SE Yunnan reached its current elevation (~1.6 km) by the middle Miocene (~13 Ma). Interpretation of the tectonic processes responsible for this inferred surface uplift of the region is made in the context of well-documented surface geology. We conclude that high landscape (~2.6 km elevation) in NW Yunnan may represent the remnants of the Eocene Tibetan plateau that originally formed in the northeastern Qiangtang Block by crustal thickening associated with the India-Asia continental collision. The near-modern elevation of SE Yunnan since ~13 Ma probably reflects the initiation of lower crustal flow in this area at least at that time. Collectively, these paleoaltimetric data disagree with previously proposed middle Miocene to Pliocene crustal flow acting as a sole tectonic process for raising the SE margin of the plateau, but support a protracted surface uplift, that most likely involved crustal thickening during the Eocene, southeastward extrusion of a portion of Eocene

Tibetan plateau during the Oligocene to early Miocene, and lower crustal flow beneath this region since at least the early Miocene.

Key works: paleoelevation, lacustrine carbonate, oxygen isotope, crustal flow, Tibetan Plateau, Yunnan

1. Introduction

The long-wavelength, low-gradient SE margin of the Tibetan Plateau has been widely viewed as one of the best areas on Earth illustrating topography produced as a consequence of orogenically forced middle to lower crustal flow (Royden et al., 1997; Clark et al., 2000; Clark et al., 2005a; Royden et al., 2008). Rapid cooling and exhumation inferred from thermochronology suggest that flow-induced crustal thickening and surface uplift commenced in the middle-late Miocene along the plateau margin of western Sichuan and migrated to the southeast into southern Yunnan by the Pliocene (Kirby et al., 2002; Schoenbohm et al. 2004; Clark et al., 2005b; Schoenbohm et al., 2006; Godard et al., 2009; Ouimet et al., 2010).

However, the overall contribution of middle Miocene to Pliocene lower crustal flow to the elevation of the SE margin of the plateau has been challenged by a recent paleoaltimetry study that interprets high elevations in NW Yunnan since the latest middle Eocene (Hoke et al., 2014). In addition, studies on the evolution of regional drainage systems indicate that headwater capture and drainage reversal frequently occurred on the plateau margin of western Sichuan and eastern Yunnan during the Eocene to Miocene, but similar events didn't occur in SE Tibet and western Yunnan (Hoang et al., 2009; Yan et al., 2012). This suggests that surface uplift in SE Tibet and western Yunnan may have started during or prior to Oligocene time (Clift et al., 2006), well before the middle Miocene-Pliocene uplift of the region suggested by thermochronologic and geomorphic data from western Sichuan and southern Yunnan (Kirby et al., 2002; Clark et al., 2004; Schoenbohm et al., 2004; Clark et al., 2005b; Schoenbohm et al., 2006; Godard et al., 2009; Ouimet et al., 2010; E. Wang et al. 2012).

We present lacustrine carbonate-derived oxygen isotope data from three Cenozoic sedimentary basins in SE Tibet and Yunnan, China. Our data provide additional paleoelevation estimates for the SE margin of the Tibetan Plateau that help constrain the timing of surface uplift that are compared with the potential tectonic mechanisms of uplift of the region.

2. Geologic setting

The SE Tibetan Plateau margin is situated in southeastern Tibet, Yunnan, western Sichuan, and Guizhou in southwestern China, and northeastern Myanmar (Fig. 1). This region is bounded by the eastern Himalayan syntaxis to the southwest, the Sichuan Basin to the northeast, and extends southeastward >1000 km along the Indochina Peninsula. Morphologically, the region displays a series of spectacular north-south valleys, ridges (The Three Rivers–Hengduan Mountains), and other ranges with peaks exceeding 4000 m elevation. To the east, the topography transitions into a broad, gentle-relief plateau (Yunnan-Guizhou Plateau), with average elevations of 2000-2500 m.

The tectonic evolution of the SE Tibetan Plateau margin is complex. The region comprises several crustal fragments, including the Lhasa Block, Qiangtang Block, Songpan Ganze belt, South China Block, Lanping-Simao Block, and Indochina Block (Burchfiel and Chen, 2012). Formation and convergence of these major crustal fragments began in the early Paleozoic and culminated with strike-slip deformation associated with Indo-Asian collision during the Cenozoic (Yin and Harrison, 2000; Burchfiel and Chen, 2012). Major Cenozoic structural features in the region are the Gaoligong Shan fault, Chong Shan fault, Ailao Shan-Red River fault, Xianshuihe-Xiaojiang fault, and Sagaing fault (Burchfiel and Chen, 2012). The activity of the right-lateral Gaoligong Shan fault and left-lateral Chong Shan fault spans the time of ~34-27 Ma (Wang et al., 2006; Akciz et al., 2008), while, to the south, activity on the right-lateral Sagaing fault continued during ~30-15 Ma (Leloup et al., 2001). The Ailao Shan-Red River fault underwent a mid-Tertiary (~35-17 Ma) sinistral shear displacement before it was reactivated as a right-lateral system during

the Pliocene (Leloup et al., 1993). The Xianshuihe-Xiaojiang fault has been documented to be active since ~13 Ma (Roger et al., 1995; Wang et al., 2009; Li et al., 2015).

Pre-Cenozoic sedimentary rocks in the region are composed mainly of Mesozoic shallow- or non-marine rocks that were strongly deformed across most of the region, particularly in the Songpan-Ganze belt (Burchfiel and Chen, 2012). Paleogene sedimentary rocks are largely confined to the Lanping-Simaog Basin and Chuxiong Basin (YBGMR, 1990) and are composed of lacustrine, fluvial, and alluvial deposits (YBGMR, 1990). Neogene sedimentary rocks in this same area are much more limited and consist primarily of fluvial and lacustrine strata deposited in transtensional and isolated sag ponds associated with the regional strike-slip fault systems (Wu and Wang, 1988; YBGMR, 1990).

3. Basin stratigraphic age

Lacustrine carbonates analyzed for this study were collected from three Cenozoic sedimentary basins spanning 800 km from the SE Tibetan Plateau to SE Yunnan. These basins include the Markam Basin in SE Tibet, and the Jianchuan and Xiaolongtan basins in NW and SE Yunnan (Fig. 1). Ages of the stratigraphic intervals of our samples are assigned based on reported biostratigraphic ages, radiometric dates, and paleomagnetic studies (see supplementary material for complete references and techniques used for age assignment). The early Miocene Lawula Group (~23-16 Ma) in the Markam Basin contains tuffaceous sandstone, siltstone, mudstone, and sandy limestone with some interbedded coal deposits (TBGMR, 1982). Samples for this study in the Jianchuan Basin were collected from the early Miocene Shuanghe Formation (~23-16 Ma) that consists of interbedded sandstone, marl, and coal deposits (YBGMR, 1990). The studied mid-late Miocene Xiaolongtan Formation (12.7-10 Ma) in the Xiaolongtan Basin are predominately lacustrine marl, carbonaceous mudstone, and coal (Li et al., 2015).

4. Materials and analytical methods

A total of 48 Cenozoic lacustrine carbonates were collected and analyzed to determine their oxygen and carbon isotopic compositions. Lacustrine deposits for calculating paleoelevations included marl, sandy limestone, siderite, and aragonitic gastropod shell. In order to identify potential diagenetic alteration, detailed petrological analyses were conducted on collected samples using routine petrological techniques (see supplementary material for the analyses and results).

Samples for oxygen and carbon isotopic analyses were obtained using a microdrill (1mm-diameter bit) on thin-section billets. The isotopic analyses were conducted at Harvard University and the University of Chicago. At Harvard, ~2 mg of each carbonate was loaded into a stainless steel vial and dried in an oven at 50°C for 48 hours. Carbonates were dissolved in a common phosphoric acid bath at 90°C. Isotopic data were collected on a VG Optima dual inlet mass spectrometer. Precision (1σ) averages were 0.07‰ for oxygen and 0.05‰ for carbon. At Chicago, the liberation of CO₂ from the samples was performed on a Thermo GasBench II by adding common phosphoric acid to samples at 70°C. Stable isotope ratio measurements were carried out with a Thermo Delta V Plus isotope ratio mass spectrometer. The reproducibility for both oxygen and carbon was better than 0.2‰. The results were reported relative to the VPDB standard for both oxygen and carbon.

5. Results

5.1. Stable isotope compositions of carbonates

Stable isotopic analyses of sampled carbonates from the Markam Basin yielded $\delta^{18}\text{O}_c$ values ranging from -15.4‰ to -9.4‰ VPDB and $\delta^{13}\text{C}_c$ values of -0.8‰ to 4.2‰ VPDB (Fig. 2; supplementary data Table S1). Jianchuan Basin sample $\delta^{18}\text{O}_c$ values are between -14.8‰ to -9.5‰ and have $\delta^{13}\text{C}_c$ values ranging from -5.3‰ to 5.4‰. Xiaolongtan Basin carbonates yielded $\delta^{18}\text{O}_c$ values of between -14.4‰ and -4.5‰ and $\delta^{13}\text{C}_c$ values of -9.4‰ to 13.3‰. While there is no discernable stratigraphic trend of changing $\delta^{18}\text{O}_c$ values for Markam and Jianchuan samples, a significant up-section increase in $\delta^{18}\text{O}_c$ values is observed in samples from the Xiaolongtan Basin. Here, samples from the coal-dominated lower Xiaolongtan

Formation have a mean value of -12.0‰; samples have a mean value of -5.5‰ in the marl-dominated upper formation. The high covariance between $\delta^{18}\text{O}_c$ and $\delta^{13}\text{C}_c$ (correlation coefficient $R=0.97$, Fig. 2) in the upper Xiaolongtan Formation implies that this increase is likely related to evaporative isotopic enrichment (Talbot, 1990). In addition, extreme ^{13}C enrichments ($\delta^{13}\text{C}$ values as great as 13.3 ‰) in the lower Xiaolongtan Formation suggest these carbonates were strongly influenced by bacterial methanogenic degradation of organic matter (Talbot and Kelts, 1986).

5.2. Calculated meteoric water $\delta^{18}\text{O}$ compositions

Determination of paleometeoric water $\delta^{18}\text{O}$ from lacustrine deposits is the most crucial aspect of calculating the paleoelevations of the studied basins. Authigenic calcium carbonates and aragonitic mollusc shells, such as those collected from our basins, are well-accepted proxies for the $\delta^{18}\text{O}$ of lake water and place constraints on the meteoric water from which they were derived (Garzzone et al., 2000a; Cyr et al., 2005; Rowley and Garzzone, 2007; Saylor et al., 2009). Early diagenetic siderite nodules (FeCO_3) have been recognized as a faithful recorder of groundwater $\delta^{18}\text{O}$ compositions (Baker et al., 1996; Ludvigson et al., 1998).

In order to determine the isotopic composition of the water from which ancient carbonates precipitated, it is necessary to estimate paleotemperature due to the temperature dependence of isotopic fractionation between carbonate and water. Mean annual air temperatures (MAAT) inferred from fossil leaf-margin studies from Markam, Jianchuan, and Xiaolongtan strata are $15.1 \pm 3.9^\circ\text{C}$, $18.2 \pm 3.6^\circ\text{C}$, and $22 \pm 2.1^\circ\text{C}$, respectively (Table 1) (Xia et al., 2009; Yao et al., 2011; Sun et al., 2011). We use $\text{MAAT} + 5^\circ\text{C}$ as a conservative estimate for the carbonate formation temperature in the basins. Recent carbonate clumped-isotope thermometry suggests that carbonate precipitation temperature in lakes is close to MAAT or less than $\text{MAAT} + 3^\circ\text{C}$ when the lake MAAT is close to or greater than 20°C (Huntington et al., 2010; Hren and Sheldon, 2012).

Using the above temperatures and the fractionation factors for calcite-water (Kim and O'Neil, 1997), aragonite-water (Kim et al., 2007), and siderite-water (Zhang et al.,

2001), sampled carbonates yielded $\delta^{18}\text{O}$ values of the lake waters ($\delta^{18}\text{O}_w$) ranging from -16.5‰ to -10.5‰ VSMOW for the Markam Basin, -12.9‰ to -7.5‰ for the Jianchuan Basin, and -11.6‰ to -1.7‰ for the Xiaolongtan Basin (supplementary data Table S1).

Given the nature of the modern lake systems in the study area, it is likely that samples with most negative $\delta^{18}\text{O}_w$ values more closely reflect paleometeoric water compositions (e.g., Dettman et al., 2003), and the use of these values provide best estimates of basin paleoelevation. To test this assumption, we evaluated published $\delta^{18}\text{O}_c$ values of Quaternary authigenic carbonate from two modern lakes in Yunnan. Wan et al. (2003) and Hodell et al. (1999) reported $\delta^{18}\text{O}_c$ value ranges of carbonates from Lake Xingyun (~70 km south of Kunming) and Lake Erhai (near Dali) are -13.6‰ to -5.7‰ PDB and -12.1‰ to -4.8‰, respectively. MAAT in the two localities is 18.9 °C and 15.6 °C (climate-data.org), respectively. Using MAAT + 5°C as carbonate formation temperature, calculation yielded mean values of the most negative $\delta^{18}\text{O}_w$ of -9.3‰ and -10.4‰ SMOW, respectively, for the least evaporatively enriched lake waters. The value -9.3‰ for Lake Xingyun is ~1‰ higher than the weighted mean value -10.35‰ at Kunming (IAEA/WMO, 2015). The -10.4‰ for Lake Erhai is close to the range of -10.5‰ to -11.8‰ reported from surface waters in nearby Dali by Hoke et al. (2014). In both of these cases, the small mismatch likely reflects the conservative temperature estimate that was used to convert $\delta^{18}\text{O}_c$ to $\delta^{18}\text{O}_w$.

On the basis of discussion above, our best estimate of $\delta^{18}\text{O}$ values of Miocene meteoric water ($\delta^{18}\text{O}_{mw}$) in the studied basins are based on the means of the most negative $\delta^{18}\text{O}_w$ values and they are $-16.5 \pm 0.8\text{‰}$ VSMOW for the Markam Basin, $-12.4 \pm 0.7\text{‰}$ for the Jianchuan Basin, and $-11.2 \pm 0.4\text{‰}$ for the Xiaolongtan Basin (supplementary data Table S1).

5.3. The paleoaltimetry model

In a rising parcel of air, the stable isotopic composition of precipitation changes systematically with altitude due to progressive distillation of water vapor during condensation. This "altitude effect" can be modeled as an open-system Rayleigh

distillation with a temperature-dependent isotopic fractionation factor (Rowley et al., 2001). If the isotopic composition of meteoric water at a particular location is known, the altitude of that location can be estimated using theoretical and empirically derived functions for changes in the isotopic composition of precipitation with respect to altitude (Garzione et al., 2000b; Poage and Chamberlain, 2001; Rowley et al., 2001).

In this study, paleoelevations for the late Cenozoic basins of SE Tibet and Yunnan are calculated from the difference between the oxygen isotopic composition of high- and low-elevation precipitation $\Delta(\delta^{18}\text{O}_{\text{mw}})$ using the model detailed in Rowley et al. (2001) and Rowley (2007), and modified by Polissar et al. (2009). In order to test the applicability of the model to the SE Tibetan Plateau region we compiled published $\delta^{18}\text{O}_{\text{mw}}$ data from the region including local and IAEA-GNIP station precipitation records (Zhang et al., 2007; IAEA/WMO, 2015), stream, lake, and spring waters (Yu et al., 1984; Bershaw et al., 2012; Hoke et al., 2014; Sun et al., 2014), and water compositions determined from Quaternary speleothem carbonates (Cai et al., 2006) (Fig. 3; supplementary data Table S2).

Isotopic compositions of these waters display a general decrease in $\delta^{18}\text{O}_{\text{mw}}$ values with increasing sample locality elevation (Table S2), with a moderate degree of variability from surface water samples at elevations >3.5 km. This variability likely reflects the potential of single surface water samples to be more highly influenced by short-term variability in precipitation oxygen isotopic compositions, likely influenced by seasonal/annual meteorological conditions, moisture input from the plateau, and moisture recycling (Blisniuk and Stern, 2005; Vuille et al., 2005; Hren et al., 2009; Bershaw et al., 2012; Xu et al., 2014). The $\delta^{18}\text{O}_{\text{mw}}$ values from longer-term, amount-weighted precipitation data include data from station precipitation records and calculated data from lake waters and speleothem carbonates (red-shaded symbols in Figs. 4A, 4B), regarded as most robust data for altimetry purposes (Rowley and Garzione, 2007). These data, similar to the more negative surface waters sampled from the region, provide a measure of confidence in the use of these values to discern the regional relationships between modern $\delta^{18}\text{O}_{\text{mw}}$ and elevation.

Precipitation across the SE margin of the plateau is derived primarily from a southwestern summer monsoon vapor source (An et al., 2011). The weighted mean $\delta^{18}\text{O}_{\text{mw}}$ values in coastal locations in this area (Yangon and Dhaka) are between -4.34‰ and -4.78‰ (IAEA/WMO, 2015). -4.6‰ is used as the low elevation precipitation composition to calculate $\Delta(\delta^{18}\text{O}_{\text{mw}})$ and model elevations. Calculated model elevations relative to sample locality elevations and $\Delta(\delta^{18}\text{O}_{\text{mw}})$ values are listed in supplementary data Table S2 and plotted in Fig. 4A. Model elevations from $\Delta(\delta^{18}\text{O}_{\text{mw}})$ values in the region strongly correlate with sampling site or mean sample catchment elevations (correlation coefficient $R=0.83$), suggesting the model captures the first-order relations between elevation increases and associated ^{18}O depletion in precipitation. This relationship supports previous paleoaltimetry studies within the Tibetan Plateau and confirms the utility of the model in the SE margin of the plateau (Hoke et al., 2014). The model, however, systematically overestimates sample elevation by up to 1.1 km, especially at sampling elevation of <3 km (Fig. 4A). This overestimation suggests that, besides the altitude effect, other effects may also exert an influence on precipitation $\delta^{18}\text{O}$ in the region.

The SE Tibetan Plateau margin has high elevations (>4.5 km) in the northwest that decrease gradually to <1 km in the southeast, with >65% area at elevations <3 km (Clark and Royden, 2000). In addition, meteoric water sample localities utilized in this study are located as much as 1200 km from the summer monsoon vapor source in the Indian Ocean. Given these relationships, we speculate that regional ^{18}O depletion in precipitation, particularly in areas across southeastern Yunnan, may reflect the combined effects of increasing altitude and continentality. The "continental effect" refers to a progressive isotopic depletion in precipitation with increasing distance from the coast and is related to progressive rain-out and inland surface water recycling into air vapor through evaporation (Dansgaard, 1964; Rozanski et al., 1993).

Because of the presence of a significant altitude effect and sparse IAEA-GNIP stations on SE margin of the plateau, the contribution of the continental effect on meteoric water isotopic compositions across the region is difficult to ascertain. However, a recent quantitative study of the global continental effect by Winnick et al.

(2014) provides one possible way to estimate magnitude of this effect in the region. Global variations of continentality effect are largely controlled by degrees of moisture recycling and eddy-driven vapor transport, which can be described by Damköhler number and Peclet number (Winnick et al., 2014). Comparisons of these values between the SE margin of the Tibetan Plateau and Europe suggest that magnitude of continental effect in the SE margin of the plateau is similar to that in Europe (-2.0‰/1000 km) (Rozanski et al., 1993). It is thus reasonable to assume a continental effect of -2.0‰/1000 km for the SE margin of the plateau.

An assessment of the potential effects of continentality on calculated model elevations is shown in Fig. 4B and listed in supplementary data Table S3. The magnitude of the continental effect on each sample $\delta^{18}\text{O}_{\text{mw}}$ value is calculated by multiplying the gradient -2.0‰/1000 km by the distance from the Indian Ocean coast to the precipitation site along the moisture trajectories shown in Fig. 4. The resulting continental effect is then subtracted from the calculated $\Delta(\delta^{18}\text{O}_{\text{mw}})$ for each sample locality, with the adjusted model then returning a predicted elevation. Compared to the initial model elevations, this calibration provides a significant improvement relative to the 1:1 correlation between two variables. This implies that, besides the increasing altitude, continentality is very likely another important factor in controlling isotopic depletion in precipitation from sites in the region, especially those situated at relatively low elevations (< 3 km).

5.4. Paleoaltimetry of the SE margin of the Plateau

In this study, paleoelevations for the studied Cenozoic basins from the SE margin of the Tibetan Plateau are calculated from the difference between the isotopic composition of high- and low-elevation meteoric water ($\Delta(\delta^{18}\text{O}_{\text{mw}})$). Low-elevation paleometeoric water $\delta^{18}\text{O}_{\text{mw}}$ was estimated from the $\delta^{18}\text{O}$ of paleosol carbonates in the Miocene Siwalik Group (17-7.8 Ma) from the western Himalayan foreland basin (-9.5 ± 1.4‰ VPDB; Quade and Cerling, 1995). Given that recent clumped-isotope investigations of modern soil carbonates indicate a strong warm-season bias in soil-carbonate precipitation (Quade et al., 2013; Hough et al., 2014), we used the

warm month mean temperature of 28.1 ± 3.4 °C derived from Miocene fossil floral of northern India (Khan et al. 2014) as the precipitation temperature of the paleosol carbonates from the Siwalik Group. Using these data, we calculated a low-elevation $\delta^{18}\text{O}_{\text{mw}}$ value of $-6.6\text{‰} \pm 1.4\text{‰}$ VSMOW for the early to late Miocene paleoprecipitation.

In the model, Miocene $\Delta(\delta^{18}\text{O}_{\text{mw}})$ calculated from pedogenic carbonates from the foreland and lacustrine carbonates from our basins is $-9.9 \pm 3.5\text{‰}$ VSMOW for the Markam Basin, $-5.9 \pm 3.1\text{‰}$ for the Jianchuan Basin, and $-4.6 \pm 2.8\text{‰}$ for the Xiaolongtan Basin (Table 2). Initial non-continentiality adjusted model elevations for the drainages feeding the lacustrine systems in each basin are $4.0 +1.1/-1.6$ km for the Markam Basin, $2.8 +0.9/-1.2$ km for the Jianchuan Basin, and $2.3 +0.7/-1.0$ km for the Xiaolongtan Basin (Table 2; Figs. 5A, 5B). The 2σ model uncertainties reported here are the combination of uncertainties from the range of temperatures used in calculating the meteoric water compositions and isotope measurement (Rowley et al., 2001; Rowley and Currie, 2006).

The discussion above indicates that the calculated Miocene $\Delta(\delta^{18}\text{O}_{\text{mw}})$ values reflect the combined effects of increasing altitude and continentality between the studied basins and the Himalayan foreland basin. To calculate this continental effect, Miocene distances between the studied basins and the Himalayan foreland need to be known. Basin analyses indicate that the Siwalik Group within the sub-Himalayan sequence used for calculating $\delta^{18}\text{O}_{\text{mw}}$ in the Himalayan foreland were deposited in the flexural foredeep of the Miocene Himalayan foreland basin (DeCelles et al., 1998). No studies clearly demonstrate that the relative distance of the Siwalik foredeep depozone has moved significantly relative to the Indus-Tsangpo suture (DeCelles et al., 1998; Yin, 2006), despite >1000 km of convergence between India and Asia since ~20 Ma (Ingalls et al., in review; van Hinsbergen et al., 2011). Thus, the minimum distances between the studied basins and the foredeep of the Himalayan foreland in the Miocene can be estimated by measuring their modern counterparts along the moisture transport pathways in present-day's basin and mountain configuration. In addition, horizontal displacements along the primary strike-slip dominated shear

zones of the region (e.g., the Ailao Shan-Red River and Gaoligong Shan faults) since the middle Miocene are estimated to be <50 km (Replumaz et al., 2001). Also, because the displacement has likely been near parallel to strike of the orogen in this region, the strike-slip fault translation should not have significantly affected the distance between our basin and low elevations to the south of the eastern Himalaya syntaxis and to the west of the Indo-Burmese accretionary wedge. Taking these distances, we employed the continental isotopic gradient of -2.0‰/1000 km to calculate the continental effect (Table 2).

After accounting for the estimated continentality effect, Miocene $\Delta(\delta^{18}\text{O}_{\text{mw}})$ are $-9.3 \pm 3.5\text{‰}$ VSMOW for the Markam Basin, $-5.3 \pm 3.1\text{‰}$ for the Jianchuan Basin, and $-3.0 \pm 2.8\text{‰}$ for the Xiaolongtan Basin (Table 2). Recalculated model elevations using these values are $3.8 +1.1/-1.6$ km for the Markam Basin, $2.6 +0.8/-1.1$ km for the Jianchuan Basin, and $1.6 +0.5/-0.7$ km for the Xiaolongtan Basin (Table 2; Figs. 5A, 5B). After removal of the continental effect, the model yielded only slightly lower predicted elevations for the Markam and Jianchuan basins, but a moderate decrease (~ 0.7 km) for the Xiaolongtan Basin, likely reflecting the longer transport path of monsoonal moisture for SE Yunnan. Our predicted elevations are identical within error to present basin-floor/sample elevations from all three basins (Fig. 5A), and they are also statistically indistinguishable from modern mean elevation of each basin location (see swath profile in Fig. 5B).

6. Discussion

6.1. Uplift history of the SE margin of the Plateau

Our results from the Markam and Jianchuan basins estimate that SE Tibet and NW Yunnan had elevations of $\sim 3.8 +1.1/-1.6$ km and $\sim 2.6 +0.8/-1.1$ km during the early Miocene (~ 23 -16 Ma). Previous paleoelevation reconstruction using stable isotope composition of pedogenic carbonates from the Liming Basin indicates that NW Yunnan has been at its present elevation (~ 2.6 km) since the latest middle Eocene (~ 40 Ma) (Hoke et al., 2014). Our data are thus in good agreement with this previous interpretation. For SE Yunnan, our data from the Xiaolongtan Basin indicate that this

area has been at elevations of $\sim 1.6 \pm 0.5/-0.7$ km since the middle-late Miocene (12.7-10 Ma). This estimate is in agreement with inferred Miocene paleoelevation of 1.0-2.4 km for the basin and surrounding areas determined from paleobotanical data (Shi et al., 1988). Also, our estimation is within reported error to the 1.0 ± 0.8 km elevation for the late Miocene Lühe Basin reported by Hoke et al. (2014). Our data from the Xiaolongtan Basin, however, are inconsistent with previous geomorphic studies by Schoenbohm et al. (2004), who suggested that initial river incision and ~ 1.4 km of surface uplift along the Red River in southern Yunnan (~ 150 km west of Xiaolongtan Basin) occurred in the Pliocene (see discussion in section 6.2.2).

When viewed collectively, the paleoaltimetric interpretations presented in this study and by Hoke et al. (2014) indicate that near present-day elevations have prevailed in NW Yunnan since the latest middle Eocene (~ 40 Ma), and SE Yunnan since the middle Miocene (~ 13 Ma). These interpretations provide a comparison with those derived from low-temperature thermochronometry and geomorphological data that suggest that major surface uplift of the eastern margin of Tibet and Sichuan began in the middle-late Miocene (13-9 Ma) (Kirby et al., 2002; Clark et al., 2004; Clark et al., 2005b; Enkelmann et al., 2006; Godard et al., 2009; Ouimet et al., 2010; Wilson and Fowler, 2011) and southern Yunnan in the Pliocene (Schoenbohm et al., 2004; Schoenbohm et al., 2006). Below we propose that near-modern elevation of NW Yunnan since at least ~ 40 Ma probably resulted from crustal shortening associated with the initiation of the India-Asia collision, or from lower crustal flow in the Lhasa and Qiangtang blocks during the Paleocene-Eocene. Uplift of SE Yunnan is probably the consequence of lower crustal flow beneath the plateau margin since at least the early Miocene.

6.2. Tectonic evolution of the region

6.2.1. Eocene crustal thickening in NW Yunnan

Three large shear zones (the Gaoligong Shan, Chong Shan, and Ailao Shan shear zones) cross NW Yunnan and define the deformed western and eastern boundaries of the Lanping-Simao and Indochina blocks. This spatial association of NW Yunnan and

major shear zones raised the possibility that the elevated NW Yunnan in the Eocene could be the result of extensive shearing along these major shear zones during middle Cenozoic time (Wang and Burchfiel, 1997). A proposed kinematic model of extrusion of the Indochina Block suggests that a transpressional regime has dominated in NW Yunnan during the extrusion, which may have resulted in regional surface uplift and extensive exhumation focused on the shear zones (Harrison et al., 1996; Leloup et al., 2001). However, cooling ages from these shear zones indicate that shearing along the Gaoligong Shan-Chong Shan and Ailao Shan shear zones occurred ~34-32 Ma (Wang et al., 2006; Akciz et al., 2008) and ~35 Ma (Leloup et al., 1995; Leloup et al., 2001), respectively. These ages suggest that NW Yunnan was at high elevation ~40 Ma, prior to the Indochina extrusion (Hoke et al., 2014). Moreover, sediment provenance analyses (detrital zircon geochronology) and lithological records suggest that Oligocene-Miocene strata were largely derived locally, by exhumation of the Ailao Shan shear zone (Schoenbohm et al., 2005) and Eocene rocks were mainly sourced from the recycling of Triassic marine sediments from the Songpan Garze belt (Yan et al., 2012). These observations together suggest that deposition of Eocene strata and their near-modern elevation in NW Yunnan at ~40 Ma were not related to extrusion of the Indochina Block.

Although the Eocene basins in NW Yunnan were not genetically connected to extrusion of the Indochina Block, these basins apparently were rearranged by this event (Wang and Burchfiel, 1997). Paleomagnetic studies have demonstrated that NW Yunnan has undergone ~90-45° clockwise rotation (relative to the South China Block) from Oligocene to present (Sato et al., 2001, 2007). This suggests that presently N-S trending, Eocene basins in NW Yunnan (Hoke et al., 2014) may have formed with an E-W to SE-NW orientation, and presumably parallel with adjacent topography. We speculate that high landscape (~2.6 km) in present NW Yunnan may represent the remnants of the northeastern portion of the Eocene Tibetan plateau, and surface uplift of this portion of the plateau in the Eocene may be related to crustal thickening associated with the beginning of the India-Asia collision at ~52 Ma (Huang et al., 2015). It has been suggested that significant syncollisional shortening occurred widely

in the northern Qiangtang Block (Spurlin et al., 2005), where the Yunnan Eocene basins originally formed (Sato et al., 2001, 2007). Also, a present-like deformation scope may have been established in Tibet by the late Eocene, ~10 Ma after the collision (Yin et al., 2008; Clark et al., 2010). These paleoaltimetric results from Tibet and NW Yunnan (Rowley and Currie, 2006; Ding et al., 2014; Hoke et al., 2014; Ingalls et al., in review), together with these observed plateau-wide crustal deformation (Spurlin et al., 2005; Yin et al., 2008; Clark et al., 2010), strongly suggest that a large portion of the Tibetan plateau, at least comprising the Lhasa and Qiangtang blocks (Tapponnier et al., 2001; Hoke et al., 2014), has been significantly elevated since the Eocene. Unlike the present-day high altitude (4.5-5 km) of the entire Lhasa and Qiangtang blocks, the Eocene Tibetan plateau seems to show a slightly different picture with high altitude (4.0-4.5 km) in both the Lhasa Block and the southern Qiangtang Block (Rowley and Currie, 2006; Ding et al., 2014), but medium altitude (~2.6 km) in the northeastern Qiangtang Block (Hoke et al., 2014). This suggests ~1.5 km of surface uplift in the present-day northeastern Qiangtang Block since the Oligocene.

An alternative tectonic process for the surface uplift of NW Yunnan in the Eocene involves lower crustal flow that resulted in progressive, regional growth to the surrounding lowland (Royden et al., 1997). Assuming crustal flow was singularly responsible for the elevation of the region, constant near-modern elevations of NW Yunnan since the latest middle Eocene (~40 Ma) suggests that this process may have been active in this area during the Eocene (Hoke et al., 2014). According to the Beaumont et al. (2004) thermal-mechanical model, thickened crust may have produced ductile flows that propagated into adjacent thinner crust after a ~10-20 Myr thermal weakening of the lower crust. This implies that the Tibetan hinterland may have exhibited a thickened crust by ~60-50 Ma. Recent paleoaltimetry results from the Linzizong Group from southern Tibet imply that the central Lhasa Block achieved high elevations (~4.5 km), indicative of a thickened crust, at least by ~53 Ma (Ding et al., 2014; Ingalls et al. in review). It is therefore possible the presence of a weak, viscous lower crust in the Lhasa Block during the Paleocene and Eocene, as well as

outward flow of this lower crust away from the Lhasa Block into the Qiangtang block, initiated the uplift of the northeastern Qiangtang Block in the middle Eocene (Cook and Royden, 2008; Hoke et al., 2014).

6.2.2 . Miocene lower crustal flow in SE Yunnan

The area encompassing SE Yunnan is characterized by a low-relief upland landscape (elevations 1500-2500 m), extending from east of the Red River in southern Yunnan to western Guizhou (Fig. 1). Strike-slip and extensional faulting, focused on the Xianshuihe-Xiaojiang and Red River fault systems, has been active since the middle Miocene (Wang et al., 1998). There is no evidence for significant crustal shortening in SE Yunnan since the middle Miocene (Wang et al., 1998). Given the structural and morphological observations outlined above, we propose that surface uplift of SE Yunnan may be the result of lower crustal flow in this area since at least ~13 Ma. This agrees with the proposed prevalent crustal flow model for the formation of the SE margin of the plateau (Clark and Royden, 2000; Royden et al., 2008). However, our inferred timing of crustal flow ($> \sim 13$ Ma) in SE Yunnan is not compatible with that derived from the geomorphological data that suggest a Pliocene onset of crustal flow in southern Yunnan (Schoenbohm et al., 2004; Schoenbohm et al., 2006). We suggest that the observed river incision by Schoenbohm et al. (2004) may have been induced by progressive base level fall, which is facilitated by fault-related drainage capture associated with reactivation of the Red River fault system during Pliocene time (Leloup et al., 1995; Replumaz et al., 2001), combined with intensification of erosion associated with Quaternary climate change (Schoenbohm et al., 2004). Similar suggestions for explaining the discrepancies among geomorphological, exhumation, and paleoaltimetric records have been made for other areas in the SE margin of the Tibetan Plateau and Sichuan Basin (Richardson et al., 2008; Hoke et al., 2014).

Many low-temperature thermochronometry studies in western Sichuan have focused on exhumation histories to discern the initiation of crustal flow in this area. These studies have demonstrated that rapid cooling and erosion in western Sichuan

began 30 Ma to 25 Ma (E., Wang et al., 2012), 28 Ma to 12 Ma (Wilson and Fowler, 2011), 22 Ma to 15 Ma (Xu and Kamp, 2000; Tian et al., 2014), 17 Ma (S. Wang et al., 2012), and more frequently 13 Ma to 5 Ma (Kirby et al., 2002; Clark et al., 2004; Clark et al., 2005b; Enkelmann et al., 2006; Godard et al., 2009; Ouimet et al., 2010; Wilson and Fowler, 2011; E., Wang et al., 2012). It has been suggested that rapid erosion since 13-5 Ma may indicate the onset of regional-scale base level fall (Hoke et al., 2014). This base level fall may be triggered by the activity of the Xianshuihe fault since ~13 Ma (Roger et al., 1995; Wang et al., 2009) and the reactivation of the Longmen Shan fault since ~12-8 Ma (Kirby et al., 2002; Godard et al., 2009), both associated with clockwise rotation of the region around the eastern Himalayan syntaxis since ~15-13 Ma (Wang et al., 2014). Our data from SE Yunnan clearly indicate that crustal flow in western Sichuan, as being upstream reaches for the flow in SE Yunnan as suggested by geophysical surveys (Bao et al., 2015), may have occurred at least several million years earlier than ~13 Ma, strengthening the idea that observed rapid exhumation in western Sichuan since ~13-5 Ma likely reflect base-level fall associated with active faulting in the area since that time (Hoke et al., 2014). We speculate that the documented early rapid exhumation at 30-25 Ma may signal the beginning of crustal thickening associated with lower crustal flow in western Sichuan. This Oligocene crustal flow in western Sichuan may correspond to Eocene crustal flow in NW Yunnan, although the exact timing and kinematics of the crustal flow in the SE margin of the plateau remains poorly understood.

7. Conclusions

Surface uplift estimates derived from stable isotope paleoaltimetry results in this study and Hoke et al (2014) help constrain the tectonic evolution of the SE margin of the Tibetan Plateau. High elevation (~2.6 km) in the plateau margin of NW Yunnan may have persisted from the latest middle Eocene (~40 Ma), and the plateau margin of SE Yunnan likely attained its near-modern elevation no later than the middle Miocene (~13 Ma). We propose that high paleoelevations in NW Yunnan may represent the remnants of the Eocene Tibetan plateau that originally formed in the

northeastern Qiangtang Block by crustal shortening associated with the on-going India-Asia collision, or from lower crustal flow in the Lhasa and Qiangtang blocks during the Paleocene-Eocene. This topographically rise of NW Yunnan occurred earlier than the shearing along the Gaoligong Shan-Chong Shan and Ailao Shan shear zones, suggesting highland in NW Yunnan since the Eocene is not related to extrusion of the Indochina Block. Furthermore, near-modern elevation of SE Yunnan since ~13 Ma may reflect the initiation of the lower crustal flow in this area at least at that time. These paleoaltimetric data indicate that the SE margin of the plateau underwent a protracted surface uplift, which probably involved crustal thickening during the Eocene, southeastward extrusion of a portion of Eocene Tibetan plateau during the Oligocene to early Miocene, and lower crustal flow beneath the region since the Oligocene and Miocene.

Acknowledgments

We are grateful to Gerry Olack and Albert Colman at the University of Chicago and Daniel Schrag at Harvard University for stable isotope analyses reported in this paper. We thank John Rakovan and Matthew Duley at Miami University for their assistance in the XRD and SEM laboratory. Two anonymous reviewers provided careful and constructive reviews that greatly improved the quality of the manuscript. This work was funded by the National Science Foundation (EAR-0609756 to Currie and EAR-0609782 and EAR-1111274 to Rowley).

References

Akciz, S., Burchfiel, B.C., Crowley, J.L., Yin, J., Chen, L., 2008. Geometry, kinematics, and regional significance of the Chong Shan shear zone, Eastern Himalayan Syntaxis, Yunnan, China. *Geosphere* 4, 292–314.

- 539 An, Z., Clemens, S.C., Shen, J., Qiang, X., Jin, Z., Sun, Y., Prell, W.L., Luo, J., Wang,
540 S., Xu, H., Cai, Y., Zhou, W., Liu, X., Liu, W., Shi, Z., Yan, L., Xiao, X., Chang,
541 H., Wu, F., Ai, L., Lu, F., 2011. Glacial-interglacial Indian summer monsoon
542 dynamics. *Science* 333, 719–723.
- 543 Arne, D., Worley, B., Wilson, C., Chen, S., Foster, D., Lou, Z., Liu, S., Dirks,
544 P.H.G.M., 1997. Differential exhumation in response to episodic thrusting along
545 the eastern margin of the Tibet Plateau. *Tectonophysics* 280, 239–256.
- 546 Baker, J.C., Kassan, J., Hamilton, P.J., 1996. Early diagenetic siderite as an indicator
547 of depositional environment in the Triassic Rewan Group, southern Sydney basin,
548 eastern Australia. *Sedimentology* 43, 77–88.
- 549 Bao, X., Sun, X., Xu, M., Eaton, D.W., Song, X., Wang, L., Ding, Z., Mi, N., Li, H.,
550 Yu, D., 2015. Two crustal low-velocity channels beneath SE Tibet revealed by
551 joint inversion of Rayleigh wave dispersion and receiver functions. *Earth Planet.*
552 *Sci. Lett.* 415, 16–24.
- 553 Beaumont, C., Jamieson, R.A., Nguyen, M.H., Medvedev, S., 2004. Crustal channel
554 flows: 1. Numerical models with applications to the tectonics of the
555 Himalayan-Tibet orogen. *J. Geophys. Res.* B06406, doi:10.1029/2003JB002809.
- 556 Bershaw, J., Penny, S.M., Garzione, C.N., 2012. Stable isotopes of modern water
557 across the Himalaya and eastern Tibetan Plateau: implications for estimates of
558 paleoelevation and paleoclimate. *J. Geophys. Res.* 117, D02110,
559 doi:10.1029/2011JD016132.
- 560 Blisniuk, P.M., Stern, L.A., 2005. Stable isotope paleoaltimetry: a critical review. *Am.*
561 *J. Sci.* 305, 1033–1074.
- 562 Burchfiel, B.C., Chen, Z., 2012. Tectonics of the southeastern Tibetan Plateau and its
563 adjacent foreland. *Geol. Soc. Am. Mem.* 210, pp.1–165.
- 564 Cai, Y., An, Z., Cheng, H., Edwards, R.L., Kelly, M.J., Liu, W., Wang, X., Shen, C.,
565 2006. High-resolution absolute-dated Indian Monsoon record between 53 and 36
566 ka from Xiaobailong Cave, southwestern China. *Geology* 34, 621–624.
- 567 Clark, M.K., Royden, L.H., 2000. Topographic ooze: building the eastern margin of
568 Tibet by lower crustal flow. *Geology* 28, 703–706.
- 569 Clark, M.K., Schoenbohm, L.M., Royden, L.H., Whipple, K.X., Burchfiel, B.C.,
570 Zhang, X., Tang, W., Wang, E., Chen, L., 2004. Surface uplift, tectonics, and
571 erosion of eastern Tibet from large-scale drainage patterns. *Tectonics* 23, TC1006,
572 doi:10.1029/2002TC001402.
- 573 Clark, M.K., Bush, J.W.M., Royden, L.H., 2005a. Dynamic topography produced by
574 lower crustal flow against rheologic strength heterogeneities bordering the
575 Tibetan Plateau. *Geophys. J. Int.* 162, 575–590.
- 576 Clark, M.K., House, M.A., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X.,
577 Tang, W., 2005b. Late Cenozoic uplift of southern Tibet. *Geology* 33, 525–528.
- 578 Clark, M.K., Farley, K.A., Zheng, D., Wang, Z., Duvall, A.R., 2010. Early Cenozoic
579 faulting of the northern Tibetan Plateau margin from (U–Th)/He ages. *Earth*
580 *Planet. Sci. Lett.* 296, 78–88.

- 581 Clift, P.D., Blusztajn, J., Nguyen, A.D., 2006. Large scale drainage capture and
582 surface uplift in eastern Tibet–SW China before 24 Ma inferred from sediments of
583 the Hanoi Basin, Vietnam. *Geophys. Res. Lett.* 33, L19403,
584 doi:10.1029/2006GL027772.
- 585 Cook, K.L., Royden, L.H., 2008. The role of crustal strength variations in shaping
586 orogenic plateaus, with application to Tibet. *J. Geophys. Res.* 113, B08407, doi:
587 10.1029/2007JB005457.
- 588 Cook, K.L., Royden, L.H., Burchfiel, B.C., Lee, Y., Tan, X., 2013. Constraints on
589 Cenozoic tectonics in the southwestern Longmen Shan from low-temperature
590 thermochronology. *Lithosphere* 5, 393–406.
- 591 Cyr, A.J., Currie, B.S., Rowley, D.B., 2005. Geochemical evaluation of Fenghuoshan
592 Group lacustrine carbonates, north-central Tibet: implications for the
593 paleoaltimetry of the Eocene Tibetan Plateau. *J. Geol.* 113, 517–533.
- 594 Dansgaard, W., 1964. Stable isotopes in precipitation. *Tellus* 16, 436–468.
- 595 DeCelles, P.G., Gehrels, G.E., Quade, J., Ojha, T.P., Kapp, P.A., Upreti, B.N., 1998.
596 Neogene foreland basin deposits, erosional unroofing, and the kinematic history
597 of the Himalayan fold-thrust belt, western Nepal. *Geol. Soc. Am. Bull.* 110, 2–
598 21.
- 599 Dettman, D.L., Fang, X., Garzione, C.N., Li, J., 2003. Uplift-driven climate change at
600 12 Ma: a long $\delta^{18}\text{O}$ record from the NE margin of the Tibetan plateau. *Earth*
601 *Planet. Sci. Lett.* 214, 267–277.
- 602 Ding, L., Xu, Q., Yue, Y., Wang, H., Cai, F., Li, S., 2014. The Andean-type Gangdese
603 Mountains: paleoelevation record from the Paleocene-Eocene Linzhou Basin.
604 *Earth Planet. Sci. Lett.* 392, 250–264.
- 605 Enkelmann, E., Ratschbacher, L., Jonckheere, R., Nestler, R., Fleischer, M., Gloaguen,
606 R., Hacker, B.R., Zhang, Y., Ma, Y., 2006. Cenozoic exhumation and deformation
607 of northeastern Tibet and the Qinling: is Tibetan lower crustal flow diverging
608 around the Sichuan Basin? *Geol. Soc. Am. Bull.* 118, 651–671.
- 609 Garzione, C.N., Dettman, D.L., Quade, J., DeCelles, P.G., Butler, R.F., 2000a. High
610 times on the Tibetan Plateau: paleoelevation of the Thakkhola Graben, Nepal.
611 *Geology* 28, 339–342.
- 612 Garzione, C.N., Quade, J., DeCelles, P.G., English, N.B., 2000b. Predicting
613 paleoelevation of Tibet and the Himalaya from $\delta^{18}\text{O}$ vs altitude gradients in
614 meteoric water across the Nepal Himalaya. *Earth Planet. Sci. Lett.* 183, 215–229.
- 615 Godard, V., Pik, R., Lavé, J., Cattin, R., Tibari, B., de Sigoyer, J., Pubellier, M., 2009.
616 Late Cenozoic evolution of the central Longmen Shan, eastern Tibet: insight from
617 (U-Th)/He thermochronometry. *Tectonics* 28, TC5009,
618 doi:10.1029/2008TC002407.
- 619 Harrison, T.M., Leloup, P.H., Ryerson, F.J., Tapponnier, P., Lacassin, R., Chen, W.,
620 1996. Diachronous initiation of transtension along the Ailao Shan-Red River
621 shear zone, Yunnan and Vietnam. In: Yin, A., Harrison, T.M. (eds.), *The Tectonic*
622 *Evolution of Asia*, pp. 208–226.

- 623 Hren, M.T., Bookhagen, B., Blisniuk, P.M., Booth, A.L., Chamberlain, C.P., 2009.
624 $\delta^{18}\text{O}$ and δD of streamwaters across the Himalaya and Tibetan Plateau:
625 implications for moisture sources and paleoelevation reconstructions. *Earth Planet.*
626 *Sci. Lett.* 288, 20–32.
- 627 Hren, M.T., Sheldon, N.D., 2012. Temporal variations in lake water temperature:
628 paleoenvironmental implications of lake carbonate $\delta^{18}\text{O}$ and temperature records.
629 *Earth Planet. Sci. Lett.* 337, 77–84.
- 630 Hoang, L.V., Wu, F., Clift, P.D., Wysocka, A., Swierczewska, A., 2009. Evaluating the
631 evolution of the Red River system based on in-situ U–Pb dating and Hf isotope
632 analysis of zircons. *Geochem. Geophys. Geosyst.* 10, Q11008,
633 doi:10.1029/2009GC002819.
- 634 Hodell, D.A., Brenner, M., Kanfoush, S.L., Curtis, J.H., Stoner, J.S., Song, X., Wu, Y.,
635 Whitmore, T.J., 1999. Paleoclimate of southwestern China for the past 50,000 yr
636 inferred from lake sediment records. *Quat. Res.* 52, 369–380.
- 637 Hoke, G.D., Liu-Zeng, J., Hren, M.T., Wissink, G.K., Garzione, C.N., 2014. Stable
638 isotopes reveal high southeast Tibetan Plateau margin since the Paleogene. *Earth*
639 *Planet. Sci. Lett.* 394, 270–278.
- 640 Hough, B.G., Fan, M., Passey, B.H., 2014. Calibration of the clumped isotope
641 geothermometer in soil carbonate in Wyoming and Nebraska, USA: implications
642 for paleoelevation and paleoclimate reconstruction. *Earth Planet. Sci. Lett.* 391,
643 110–120.
- 644 Huang, W., Dupont-Nivet, G., Lippert, P.C., van Hinsbergen, D.J.J., Dekkers, M.J.,
645 Waldrip, R., Ganerød, M., Li, X., Guo, Z., Kapp, P., 2015. What was the
646 Paleogene latitude of the Lhasa terrane? A reassessment of the geochronology and
647 paleomagnetism of Linzizong volcanic rocks (Linzhou basin, Tibet). *Tectonics* 34,
648 594–622.
- 649 Huntington, K.W., Wernicke, B.P., Eiler, J.M., 2010. Influence of climate change and
650 uplift on Colorado Plateau paleotemperatures from carbonate clumped isotope
651 thermometry. *Tectonics* 29, TC3005, doi:10.1029/2009TC002449.
- 652 IAEA/WMO, 2015. Global Network of Isotopes in Precipitation, the GNIP database.
653 Accessible at: <http://www.iaea.org/water>.
- 654 Khan, M.A., Spicer, R.A., Bera, S., Ghosh, R., Yang, J., Spicer, T.E.V., Guo, S., Su, T.,
655 Jacques, F., Gote, P.J., 2014. Miocene to Pleistocene floras and climate of the
656 Eastern Himalayan Siwaliks, and new palaeoelevation estimates for the
657 Namling-Oiyug Basin, Tibet. *Glob. Planet. Chang.* 113, 1–10.
- 658 Kim, S.T., O’Neil, J.R., 1997. Equilibrium and nonequilibrium oxygen isotope effects
659 in synthetic carbonates. *Geochim. Cosmochim. Acta* 61, 3461–3475.
- 660 Kim, S.T., O’Neil, J.R., Hillaire-Marcel, C., Mucci, A., 2007. Oxygen isotope
661 fractionation between synthetic aragonite and water: influence of temperature and
662 Mg^{2+} concentration. *Geochim. Cosmochim. Acta* 71, 4704–4715.
- 663 Kirby, E., Reiners, P.W., Krol, M.A., Whipple, K.X., Hodges, K.V., Farley, K.A., Tang,
664 W., Chen, Z., 2002. Late Cenozoic evolution of the eastern margin of the Tibetan

- 665 Plateau: inferences from $^{40}\text{Ar}/^{39}\text{Ar}$ and (U-Th)/He thermochronology. *Tectonics*
666 21, doi:10.1029/2000TC001246.
- 667 Leloup, P.H., Kienast, J.R., 1993. High Temperature metamorphism in a major
668 Tertiary ductile continental strike-slip shear zone: the Ailao Shan-Red River (P. R.
669 C.). *Earth Planet. Sci. Lett.* 118, 213–234.
- 670 Leloup, P.H., Lacassin, R., Tapponnier, P., Scharer, U., Zhong, D., Liu, X., Zhang, L.,
671 Ji, S., Trinh, P.T., 1995. The Ailao Shan-Red River shear zone (Yunnan, China),
672 Tertiary transform boundary of Indochina. *Tectonophysics* 251, 3–84.
- 673 Leloup, P.H., Arnaud, N., Lacassin, R., Kienast, J.R., Harrison, T.M., PhanTrong, T.T.,
674 Replumaz, A., Tapponnier, P., 2001. New constraints on the structure,
675 thermochronology, and timing of the Ailao Shan-Red River shear zone, SE Asia. *J.*
676 *Geophys. Res.* 106, 6683–6732.
- 677 Li, S., Deng, C., Dong, W., Sun, L., Liu, S., Qin, H., Yin, J., Ji, X., Zhu, R., 2015.
678 Magnetostratigraphy of the Xiaolongtan Formation bearing *Lufengpithecus*
679 *keiyuanensis* in Yunnan, southwestern China: constraint on the initiation time of
680 the southern segment of the Xianshuihe–Xiaojiang fault. *Tectonophysics*, doi:
681 10.1016/j.tecto.2015.06.002.
- 682 Ludvigson, G.A., Gonzalez, L.A., Metzger, R.A., Witzke, B.J., Brenner, R.L., Murillo,
683 A.P., White, T.S., 1998. Meteoric sphaerosiderites lines and their use for
684 paleohydrology and paleoclimatology. *Geology* 26, 1039–1042.
- 685 Ouimet, W., Whipple, K., Royden, L., Reiners, P., Hodges, K., Pringle, M., 2010.
686 Regional incision of the eastern margin of the Tibetan Plateau. *Lithosphere* 2,
687 50–63.
- 688 Poage, M.A., Chamberlain, C.P., 2001. Empirical relationships between elevation and
689 the stable isotope composition of precipitation: considerations for studies of
690 paleoelevation change. *Am. J. Sci.* 301, 1–15.
- 691 Polissar, P.J., Freeman, K.H., Rowley, D.B., Mcinerney, F.A., Currie, B.S., 2009.
692 Paleoaltimetry of the Tibetan Plateau from D/H ratios of lipid biomarkers. *Earth*
693 *Planet. Sci. Lett.* 287, 64–76.
- 694 Quade, J., Cerling, T.E., 1995. Expansion of C4 grasses in the late Miocene of
695 northern Pakistan: evidence from stable isotopes in paleosols. *Palaeogeogr.*
696 *Palaeoclimatol. Palaeoecol.* 115, 91–116.
- 697 Quade, J., Eiler, J., Daëron, M., Achyuthan, H., 2013. The clumped isotope
698 geothermometer in soil and paleosol carbonate. *Geochim. Cosmochim. Acta* 105,
699 92–107.
- 700 Replumaz, A., Lacassin, R., Tapponnier, P., Leloup, P.H., 2001. Large river offsets and
701 Plio-Quaternary dextral slip rate on the Red River fault (Yunnan, China). *J.*
702 *Geophys. Res.* 106, 819–836.
- 703 Richardson, N.J., Densmore, A.L., Seward, D., Fowler, A.P., Wipf, M., Li, Y., Ellis,
704 M.A., Zhang, Y., 2008. Extraordinary denudation in the Sichuan Basin: insights
705 from low-temperature thermochronology adjacent to the eastern margin of the
706 Tibetan Plateau. *J. Geophys. Res.* 113, B04409, doi: 10.1029/2006JB004739.

- 707 Roger, F., Calassou, S., Lancelot, J., Malavieille, J., Mattauer, M., Xu, Z., Hao, Z.,
708 Hou, L., 1995. Miocene emplacement and deformation of the Konga Shan granite
709 (Xianshuihe Fault zone, west Sichuan, China): geodynamical implications. *Earth*
710 *Planet. Sci. Lett.* 130, 201–216.
- 711 Rowley, D.B., Pierrehumbert, R.T., Currie, B.S., 2001. A new approach to stable
712 isotope-based paleoaltimetry: implications for paleoaltimetry and
713 paleohypsometry of the high Himalaya since the late Miocene. *Earth Planet. Sci.*
714 *Lett.* 188, 253–268.
- 715 Rowley, D.B., Currie, B.S., 2006. Palaeoaltimetry of the late Eocene to Miocene
716 Lunpola basin, central Tibet. *Nature* 439, 677–681.
- 717 Rowley, D.B., 2007. Stable isotope-based paleoaltimetry: theory and validation. In:
718 Kohn, M.J. (ed.), *Paleoaltimetry: geochemical and thermodynamic approaches.*
719 *Mineralogical Society of America, Chantilly*, pp.23–52.
- 720 Rowley, D.B., Garzione, C.N., 2007. Stable isotope-based paleoaltimetry. *Annu. Rev.*
721 *Earth Planet. Sci.* 35, 463–508.
- 722 Royden, L.H., Burchfiel, B.C., King, R.W., Wang, E., Chen, Z., Shen, F., Liu, Y., 1997.
723 Surface deformation and lower crustal flow in eastern Tibet. *Science* 276,
724 788–790.
- 725 Royden, L.H., Burchfiel, B.C., van der Hilst, R.D., 2008. The geological evolution of
726 the Tibetan Plateau. *Science* 321, 1054–1058.
- 727 Rozanski, K., Araguas-Araguas, L., Gonfiantini, R., 1993. Isotopic patterns in
728 modern global precipitation. In: Swart, P.K., Lohmann, K.C., McKenzie, J., Savin,
729 S. (eds.), *Climate Change in Continental Isotopic Records.* In: *Geoph. Monogr.*
730 *Series* 78, pp.1–36.
- 731 Sato, K., Liu, Y., Zhu, Z., Yang, Z., Otofujii, Y., 2001. Tertiary paleomagnetic data
732 from northwestern Yunnan, China: further evidence for large clockwise rotation of
733 the Indochina block and its tectonic implications. *Earth Planet. Sci. Lett.* 185,
734 185–198.
- 735 Sato, K., Liu, Y., Wang, Y., Yokoyama, M., Yoshioka, S., Yang, Z., Otofujii, Y., 2007.
736 Paleomagnetic study of Cretaceous rocks from Pu'er, western Yunnan, China:
737 evidence of internal deformation of the Indochina block. *Earth Planet. Sci. Lett.*
738 258, 1–15.
- 739 Saylor, J.E., Quade, J., Dettman, D.L., DeCelles, P.G., Kapp, P.A., Ding, L., 2009.
740 The Late Miocene through present paleoelevation history of southwestern Tibet.
741 *Am. J. Sci.* 309, 1–42.
- 742 Schoenbohm, L.M., Whipple, K., Burchfiel, B.C., 2004. River incision into a relict
743 landscape along the Ailao Shan shear zone and Red River fault in Yunnan
744 Province, China. *Geol. Soc. Am. Bull.* 116, 895–909.
- 745 Schoenbohm, L.M., Burchfiel, B.C., Chen, L., Yin, J., 2005. Exhumation of the Ailao
746 Shan shear zone recorded by Cenozoic sedimentary rocks, Yunnan Province,
747 China. *Tectonics* 24, TC6015, doi:10.1029/2005TC001803.
- 748 Schoenbohm, L.M., Burchfiel, B.C., Chen, L., 2006. Propagation of surface uplift,

- 749 lower crustal flow, and Cenozoic tectonics of the southeast margin of the Tibetan
750 Plateau. *Geology* 34, 813–816.
- 751 Shi, C., Yan, W., Lei, F., 1988. Tertiary coal-forming plants and their paleoecology in
752 Xiaolongtan Basin. *J. Ecol.* 7, 37–52.
- 753 Spurlin, M.S., Yin, A., Horton, B.K., Zhou, J., Wang, J., 2005. Structural evolution of
754 the Yushu-Nangqian region and its relationship to syncollisional igneous activity,
755 east-central Tibet. *Geol. Soc. Am. Bull.* 117, 1293–1317.
- 756 Sun, B., Wu, J., Liu, Y., Ding, S., Li, X., Xie, S., Yan, D., Lin, Z., 2011.
757 Reconstructing Neogene vegetation and climates to infer tectonic uplift in western
758 Yunnan, China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 304, 328–336.
- 759 Sun, H., Liu, Z., Yan, H., 2014. Oxygen isotope fractionation in travertine-depositing
760 pools at Baishuitai, Yunnan, SW China: effects of deposition rates. *Geochim.*
761 *Cosmochim. Acta* 133, 340–350.
- 762 Talbot, M.R., Kelts, K., 1986. Primary and diagenetic carbonates in the anoxic
763 sediments of lake Bosumtwi, Ghana. *Geology* 14, 912–916.
- 764 Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and
765 oxygen isotopic ratios in primary lacustrine carbonates. *Chem. Geol.* 80,
766 261–279.
- 767 Tapponnier, P., Xu, Z., Palmer, T.N., Shukla, J., Tomas, R.A., Yanai, M., Yasunari, T.,
768 2001. Oblique stepwise rise and growth of the Tibetan Plateau. *Science* 294,
769 1671–1677.
- 770 TBGMR (Tibet Bureau of Geology and Mineral Resources), 1982. Regional geology
771 of Xizang (Tibet) Autonomous Region, Beijing, pp.1–245.
- 772 Tian, Y., Kohn, B.P., Gleadow, A.J.W., Hu, S., 2014. A thermochronological
773 perspective on the morphotectonic evolution of the southeastern Tibetan Plateau. *J.*
774 *Geophys. Res.* 119, 676–698.
- 775 van Hinsbergen, D.J.J., Kapp, P., Dupont-Nivet, G., DeCelles, P.G., Lippert, P.C.,
776 Torsvik, T.H., 2011. Restoration of Cenozoic deformation of Asia, and the size of
777 Greater India. *Tectonics* 30, TC5003, doi:10.1029/2011TC002908.
- 778 Vuille, M., Werner, M., Bradley, R.S., Keimig, F., 2005. Stable isotopes in
779 precipitation in the Asian monsoon region. *J. Geophys. Res.* 110, D23108,
780 doi:10.1029/2005JD006022.
- 781 Wan, G., Bai, Z., Qing, H., Mather, J.D., Huang, R., Wang, H., Tang, D., Xiao, B.,
782 2003. Geochemical records in recent sediments of Lake Erhai: implications for
783 environmental changes in a low latitude-high altitude lake in southwest China. *J.*
784 *Asian Earth Sci.* 21, 489–502.
- 785 Wang, E., Burchfiel, B.C., 1997. Interpretation of Cenozoic tectonics in the
786 right-lateral accommodation zone between the Ailao Shan shear zone and the
787 eastern Himalayan syntaxis. *Int. Geol. Rev.* 39, 191–219.
- 788 Wang, E., Burchfiel, B.C., Royden, L.H., Chen, L., Chen, J., Li, W., Chen, Z., 1998.
789 Late Cenozoic Xianshuihe-Xiaojiang, Red River, and Dali fault systems of
790 southwestern Sichuan and central Yunnan, China. *Spec. Pap., Geol. Soc. Am.* 327,

- 791 pp.1–108.
- 792 Wang, E., Kirby, E., Furlong, K.P., van Soest, M., Xu, G., Shi, X., Kamp, P.J.J.,
793 Hodges, K.V., 2012. Two-phase growth of high topography in eastern Tibet
794 during the Cenozoic. *Nat. Geosci.* 5, 640–645.
- 795 Wang, E., Meng, K., Su, Z., Meng, Q., Chu, J.J., Chen, Z., Wang, G., Shi, X., Liang,
796 X., 2014. Block rotation: tectonic response of the Sichuan basin to the
797 southeastward growth of the Tibetan Plateau along the Xianshuihe-Xiaojiang fault.
798 *Tectonics* 33, 686–717.
- 799 Wang, P., Clemens, S., Beaufort, L., Braconnot, P., Ganssen, G., Jian, Z., Kershaw, P.,
800 Sarnthein, M., 2005. Evolution and variability of the Asian monsoon system: state
801 of the art and outstanding issues. *Quat. Sci. Rev.* 24, 595–629.
- 802 Wang, S., Fang, X., Zheng, D., Wang E., 2009. Initiation of slip along the Xianshuihe
803 fault zone, eastern Tibet, constrained by K/Ar and fission-track ages. *Int. Geol.*
804 *Rev.* 51, 1121–1131.
- 805 Wang, S., Jiang, G., Xu, T., Tian, Y., Zheng, D., Fang, X., 2012. The Jinhe-Qinghe
806 fault—An inactive branch of the Xianshuihe–Xiaojiang fault zone, eastern Tibet.
807 *Tectonophysics* 544–545, 93–102.
- 808 Wang, Y., Fan, W., Zhang, Y., Peng, T., Chen, X., Xu, Y., 2006. Kinematics and
809 $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the Gaoligong and Chongshan shear systems, western
810 Yunnan, China: implications for early Oligocene tectonic extrusion of SE Asia.
811 *Tectonophysics* 418, 235–254.
- 812 Wilson, C.J.L., Fowler, A.P., 2011. Denudational response to surface uplift in east
813 Tibet: evidence from apatite fission-track thermochronology. *Geol. Soc. Am. Bull.*
814 123, 1966–1987.
- 815 Winnick, M.J., Chamberlain, C.P., Caves, J.K., Welker, J.M., 2014. Quantifying the
816 isotopic ‘continental effect’. *Earth Planet. Sci. Lett.* 406, 123–133.
- 817 Wu, F., Wang, P., 1988. Tectonics of western Yunnan Province, China. *Geology* 16,
818 153–157.
- 819 Xia, K., Su, T., Liu, Y., Xing, Y., Jacques, F.M.B., Zhou, Z., 2009. Quantitative
820 climate reconstructions of the late Miocene Xiaolongtan megaflora from Yunnan,
821 southwest China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 276, 80–86.
- 822 Xu, G., Kamp, P.J.J., 2000. Tectonics and denudation adjacent to the Xianshuihe Fault,
823 eastern Tibetan Plateau; constraints from fission track thermochronology. *J.*
824 *Geophys. Res.* 105, 19231–19251.
- 825 Xu, Q., Hoke, G.D., Liu-Zeng, J., Ding, L., Wang, W., Yang, Y., 2014. Stable isotopes
826 of surface water across the Longmenshan margin of the eastern Tibetan Plateau.
827 *Geochem. Geophys. Geosyst.* 15, 3416–3429.
- 828 Yan, Y., Carter, A., Huang, C., Chan, L., Hu, X., Lan, Q., 2012. Constraints on
829 Cenozoic regional drainage evolution of SW China from the provenance of the
830 Jianchuan Basin. *Geochem. Geophys. Geosyst.* 13, Q03001,
831 doi:10.1029/2011GC003803.
- 832 Yao, Y., Bruch, A.A., Mosbrugger, V., Li, C., 2011. Quantitative reconstruction of

- 833 Miocene climate patterns and evolution in Southern China based on plant fossils.
834 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 304, 291–307.
- 835 Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan-Tibetan orogen.
836 *Annu. Rev. Earth Planet. Sci.* 28, 211–280.
- 837 Yin, A., 2006. Cenozoic tectonic evolution of the Himalayan orogen as constrained by
838 along-strike variation of structural geometry, exhumation history, and foreland
839 sedimentation. *Earth-Sci. Rev.* 76, 1–131.
- 840 Yin, A., Dang, Y., Wang, L., Jiang, W., Chen, X., Gehrels, G.E., McRivette, M.W.,
841 2008. Cenozoic tectonic evolution of the Qaidam basin and its surrounding
842 regions (Part 1): the southern Qilian Shan-Nan Shan thrust belt and northern
843 Qaidam basin. *Geol. Soc. Am. Bull.* 120, 813–846.
- 844 Yu, J., Zhang, H., Yu, F., Liu, D., 1984. Oxygen and hydrogen isotopic compositions
845 of meteoric waters in the eastern part of Xizang. *Geochemistry* 3, 93–101.
- 846 YBGMR (Yunnan Bureau of Geology and Mineral Resources), 1990. Regional
847 geology of Yunnan Province. Beijing, pp.236–253.
- 848 Zhang, C., Horita, J., Cole, D.R., Zhou, J., Lovley, D.R., Phelps, T.J., 2001.
849 Temperature-dependent oxygen and carbon isotope fractionation of biogenic
850 siderite. *Geochim. Cosmochim. Acta* 65, 2257–2271.
- 851 Zhang, X., Liu, J., Sun, W., Huang, Y., Zhang, J., 2007. Relations between oxygen
852 stable isotopic ratios in precipitation and relevant meteorological factors in
853 southwest China. *Sci. China Ser. D* 50, 571–581.

872 **Figures**

Fig. 1. Topographic map of the SE margin of the Tibetan Plateau shows location of the studied Cenozoic basins and location of Chinese provinces (Yunnan, Sichuan, and Tibet), major rivers, lakes, and fault zones that are referred in text. The map also shows location of previous studies on paleoaltimetry, low-temperature thermochronometry, and fluvial geomorphology and their major conclusions. Major lithospheric components and bounding fault zones are modified from Burchfiel and Chen (2012). The inserted regional topographic map shows location of the SE margin of plateau (black box). References: 0—this study, 1—Hoke et al. (2014), 2—Clark et al. (2005b), 3—Ouimet et al. (2010), 4—Clark et al. (2004), 5—Schoenbohm et al. (2004), 6—Kirby et al. (2002), 7—E. Wang et al. (2012), 8—Godard et al. (2009), 9—Enkelmann et al. (2006), 10—Wilson and Fowler (2011), 11—Cook et al. (2013), 12—Tian et al. (2014), 13—S. Wang et al. (2012), 14—Arne et al. (1997). Abbreviations: ALSF—Ailao Shan shear zone, CSF—Chong Shan shear zone, GLGF—Gaoligong Shan shear zone, LMSF—Longmen Shan fault, RRF—Red River fault, SF—Sagaing fault, XSXJF—Xianshuihe-Xiaojiang fault, YLF—Yalong thrust.

Fig. 2. Carbonates $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from the Markam, Jianchuan, and Xiaolongtan basins. Petrological analyses indicate that the carbonates from the Markam and Jianchuan basins and the upper Xiaolongtan Formation from the Xiaolongtan basin were primarily precipitated from lake waters. There is a medium covariance (correlation coefficient $R=0.67$) for Jianchuan carbonates, and a strong covariance ($R=0.97$) for the upper Xiaolongtan Formation.

928

929

930 Fig. 3. Topographic map of the SE margin of the Tibetan Plateau and Indochina
931 Peninsula with summer moisture transport pathway (black arrows) (Wang et al., 2005).
932 Map shows location of IAEA-GNIP stations and location of previous studies on
933 precipitation at Simao, Mengzi, and Tengchong, stream/lake/spring waters, and
934 meteoric water values derived from speleothem carbonates. Rectangle shows location
935 of the swath profile in Fig. 5B.

936

937

938

939

940

941

942

943

944

945

946

947

948

949

950

951

952

953

954 Fig. 4. Comparisons of model elevation and mean basin elevation for recent isotopic
 955 compositions of meteoric waters from southern Asia. (A) Initial predicted elevation
 956 versus mean drainage basin elevation or sample elevation for all data in
 957 supplementary Table S2. Note that some of stream waters from Hoke et al. (2014)
 958 collected during 2012 occurred during a drought year and thus evaporation may have
 959 influenced model elevation of some samples sites at >3 km. (B) Plot of model
 960 elevation versus mean drainage basin elevation for same data in Fig. 4A after
 961 accounting for the possible continental effect.

Fig. 5. (A) Plot of predicted basin elevation vs. mean basin elevation. Blue-shaded circles are initial model elevations without deducting the continental effect. Red-shaded circles are model results after removing the continental effect. (B) Plot of the same results on a topographic swath profile on the SE margin of the Tibetan Plateau that extracted from the 3-arc Shuttle Radar Topography Mission digital elevation model. The profile was generated using a 150 km wide and 1150 km long swath (see Fig. 3 for its position) where the maximum, mean with 1 σ (standard deviation), and minimum elevations were determined in 5 km-wide segments along the profile.

Tables

Table 1. Paleotemperature estimates for the Miocene lakes in Tibet and Yunnan

Locality	Age (Ma)	MAAT ^a (°C)	Method ^b	Reference
Markam basin	~23-16	15.1±3.9	CA	Yao et al., 2011
Jianchuan basin	~23-16	18.2±3.6	LMA	Sun et al., 2011
Xiaolongtan basin	12.7-10	22.3±2.1	LMA	Xia et al., 2009

^a MAAT- mean annual air temperature.^b CA-coexistence approach, LMA-leaf margin analysis.

1020
1021

Table 2. Predicted Miocene sedimentary basin paleoelevations

Initial model elevations							
Locality	Present basin elevation (m)	$\delta^{18}\text{O}_{\text{mw}}$ (‰, <i>vsmow</i>)	$\Delta(\delta^{18}\text{O}_{\text{mw}})$ (‰, <i>vsmow</i>)	Model elevation (m)	2 σ model uncert. (+m)	2 σ model uncert. (-m)	
Markam basin	~4000	-16.47±1.56	-9.91±3.49	3987	1140	-1619	
Jianchuan basin	~2300	-12.44±1.46	-5.88±3.07	2816	861	-1222	
Xiaolongtan basin	~1100	-11.15±0.83	-4.59±2.76	2335	728	-1035	
After accounting for continental (cont.) effect (preferred predicted basin elevations)							
Locality	Age	Cont.distance (km)	Cont. effect (‰, <i>vsmow</i>)	$\Delta(\delta^{18}\text{O}_{\text{mw}})$ (‰, <i>vsmow</i>)	Predicted elevation (m)	2 σ model uncert. (+m)	2 σ model uncert. (-m)
Markam basin	~23-16	~300	-0.6	-9.31±3.49	3837	1108	-1574
Jianchuan basin	~23-16	~300	-0.6	-5.28±3.07	2601	802	-1140
Xiaolongtan basin	12.7-10	~800	-1.6	-2.99±2.76	1645	525	-747

1022