# High times on the Tibetan Plateau: Paleoelevation of the Thakkhola graben, Nepal

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**ABSTRACT**

**East-west extension in the Tibetan Plateau is generally assumed to have resulted from gravitational collapse following thickening and uplift. On the basis of this assumption, several studies have dated east-west extensional structures to determine when the plateau attained its current high elevation. However, independent estimates of elevation are needed to determine whether extension occurred before, during, or after the plateau achieved its current elevation. Because the isotopic composition of meteoric water decreases with increasing elevation, significant change in local elevation throughout the Thakkhola graben depositional history should be recorded by change in $\delta^{18}$O values of fluvial and lacustrine carbonates. The $\delta^{18}$O values of –16‰ to –23‰ of Thakkhola graben carbonates reflect meteoric water values similar to modern values and suggest that the southern Tibetan Plateau attained its current elevation prior to east-west extension. Initiation of Thakkhola graben extension is constrained between 10 and 11 Ma, based on magnetostratigraphy of the older Tetang Formation. The $\delta^{13}$C values of soil carbonates suggest an age younger than 8 Ma for the base of the Thakkhola Formation.**

**Keywords:** Tibetan Plateau, paleoelevation, oxygen isotopes.

## INTRODUCTION

Timing of surface uplift of the Tibetan Plateau has received much attention because of proposed links between high topography and change in regional and global climate, southern Asian paleoecology, and ocean chemistry (Quade et al., 1989; Edmond, 1992; Prell and Kutzbach, 1992; Raymo and Ruddiman, 1992; Molnar et al., 1993; Derry and France-Lanord, 1996). However, the actual vintage of high elevation of the Tibetan Plateau is undocumented. A Pliocene-Quaternary age of uplift has been inferred on the basis of fossil plants from Tibet, the nearest modern relatives of which grow at low elevations (Xu, 1981; Li, 1995). A suggested late Miocene age of uplift (Pan and Kidd, 1992; Coleman and Hodges, 1995; Harrison et al., 1995) assumes that east-west extensional faults and basins of late Miocene age in the southern part of the Tibetan Plateau developed in response to gravitational collapse of a thickened, high plateau (Molnar and Tapponnier, 1978; Armijo et al., 1986; Harrison et al., 1992; Molnar et al., 1993). In this view, basins are assumed to be symptomatic of high elevation, and their ages then give the timing of the uplift. However, McCaffrey and Nabelek (1998) and Seeber and Pêcher (1998) challenged the link between high elevation and east-west extension, pointing out that kinematic models predict extension parallel to the arcuate Himalayan belt and do not require high elevation to explain such extension.

Previous attempts to understand the elevation history in the southern Tibetan Plateau lacked information from basin deposits. We present oxygen isotopic data from carbonate rocks in the Thakkhola graben as a proxy of relative change in paleoelevation of the southern Tibetan Plateau. Age constraints are provided by new magnetostratigraphic and carbon isotopic data.

The Thakkhola graben is located in north-central Nepal between the South Tibetan detachment system and the Indus suture zone (Fig. 1A). The South Tibetan detachment system is a low-angle, north-dipping, normal fault system, located just north of the highest part of the Himalaya. The Indus suture zone is the boundary between Indian and Asian crust. Mesozoic Tethyan series rocks are exposed in the eastern footwall of Thakkhola graben and Paleozoic Tethyan series rocks are in the western footwall (Colchen et al., 1986) (Fig. 1B). The basin contains two depositional sequences, separated by an angular unconformity: the Tetang Formation, to 230 m thick; and the overlying Thakkhola Formation, to 720 m thick (Fort et al., 1982; Garzione et al., 1999) (Fig. 1B). The Tetang Formation crops out in the

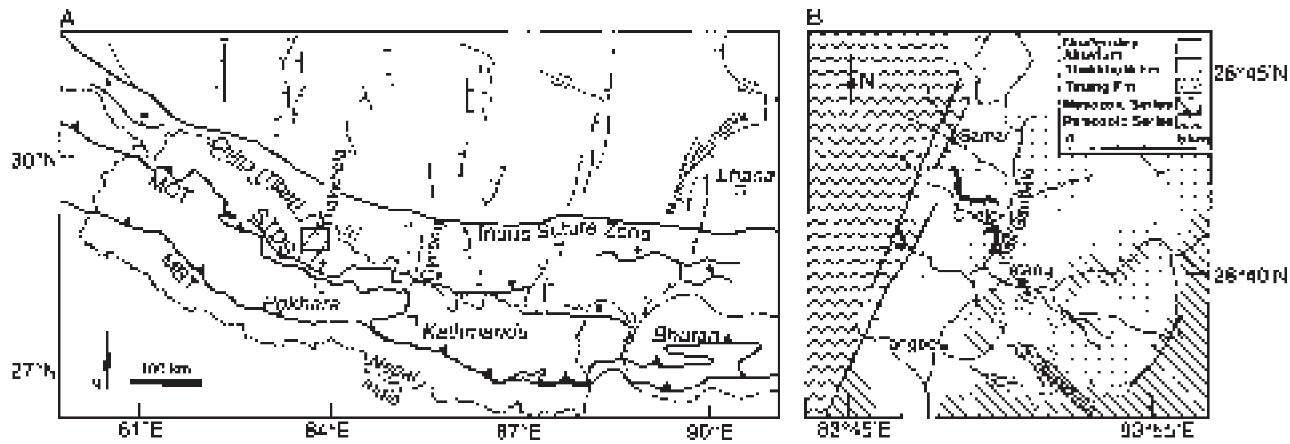


**Figure 1. A: General tectonic map of southern Tibetan Plateau and Nepal Himalaya, modified from Coleman and Hodges (1995). Hachures are north-south–striking normal faults. Lines with ball and stick ornaments are South Tibetan detachment system (STDS). Barbed lines are Main Central thrust (MCT) and Main Boundary thrust (MBT). Thakkhola, Gyirong, and Nyainqentanghla grabens are shown. Box shows location of study area detailed in B. B: Geologic map of Thakkhola graben showing sampling transects for Tetang (star) and Thakkhola Formations (thick line). Modified from Fort et al. (1982) and Colchen et al. (1986).**

**Data Repository item 200038 contains additional material related to this article.**

southeastern portion of the basin and consists of fluvial deposits that grade into lacustrine deposits toward the top of the section. Tetang strata were rotated into the western basin-bounding fault prior to deposition of the Thakkhola Formation, causing the angular unconformity between the two formations. The Thakkhola Formation, exposed throughout the basin, consists of alluvial fan deposits along the western basin-bounding fault, and fluvial and minor lacustrine deposits in the central and eastern parts of the basin.

## AGE CONSTRAINTS

### Carbon Isotope Results

The carbon isotopic composition of paleosol carbonates is determined by the type of vegetation growing during soil formation and by soil respiration rates. Most south Asian plants photosynthesize along two different metabolic pathways, $C_3$ and $C_4$. $C_3$ plants, dominantly trees, shrubs, and cool-growing-season grasses, produce $\delta^{13}C$ values for soil-respired $CO_2$ of about –22‰ to –32‰, whereas $C_4$ plants, dominantly warm-growing-season grasses, respire $CO_2$ with $\delta^{13}C$ values between –10‰ and –15‰. In soils with moderate to high respiration rates, there is an ~15‰ enrichment of $\delta^{13}C$ of soil carbonates with respect to soil-respired $CO_2$. The average observed range of soil carbonate formed in equilibrium with $C_3$-respired $CO_2$ is $\delta^{13}C$ = –13‰ to –9‰, whereas soil carbonates formed in the presence of $C_4$ plants have $\delta^{13}C$ = +1‰ to +3‰ (Cerling and Quade, 1993).

Paleosols are rare and contain no soil carbonate in the Tetang Formation, whereas paleosols are abundant and well developed in the Thakkhola Formation, where they typically consist of red to gray, clay-rich B horizons that have been bioturbated and leached of carbonate. Organic A horizons are absent. Below leached zones, most paleosols contain pedogenic carbonate. We sampled paleosol carbonate more than 30 cm below the top of the paleosol profile and in most cases below 50 cm to minimize the influence of atmospheric $CO_2$.

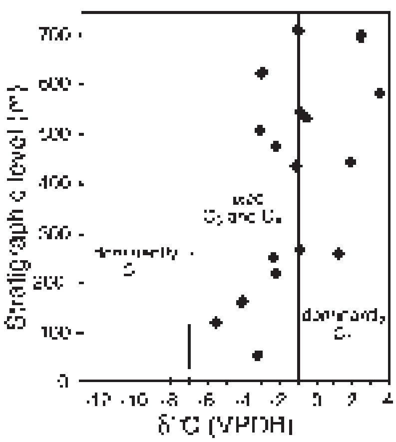

**Figure 2. $\delta^{13}C$ (Vienna Peedee belemnite, VPDB) of soil carbonates versus stratigraphic level in Thakkhola Formation. Ranges of $\delta^{13}C$ values for soil carbonates formed in equilibrium with dominantly $C_3$, mixed $C_3$ and $C_4$, and dominantly $C_4$ soil-respired $CO_2$ are shown.**

The carbon isotopic record of soil carbonate helps to constrain the age of Thakkhola Formation sedimentation. The $\delta^{13}C$ (Vienna Peedee belemnite [VPDB]) values of Thakkhola Formation paleosol carbonate are between –5.6‰ and +3.5‰, in the ranges observed in mixed $C_3$-$C_4$ and dominantly $C_4$ environments (Fig. 2). In dry settings, high $\delta^{13}C$ values could be produced by low respiration rates and/or the presence of $C_4$ plants. However, well-developed leached horizons and locally abundant organic material argue against low respiration rates and significant contribution of atmospheric $CO_2$ during soil formation. We obtained $\delta^{13}C$ values of –12.3‰ to –12.8‰ from 4 of 10 different species of modern grass collected between 3000 m and 4000 m, thus verifying the presence of $C_4$ grass in the basin today. We therefore interpret the high $\delta^{13}C$ values from paleosol carbonates to reflect the presence of both $C_3$ and $C_4$ vegetation on the valley floor during Thakkhola Formation deposition. Because $C_4$ vegetation is not observed in the South Asian soil record until ca. 7 Ma (Quade et al., 1989, 1995), the presence of $C_4$ vegetation by 50 m in the section suggests a maximum age of 8 Ma for the base of the Thakkhola Formation. Organic separates from mudstones containing visible plant material at 117 m, 186 m, and 190 m in the Tetang Formation yielded $\delta^{13}C$ values between –21.9‰ and –26.5‰, indicating the presence of only $C_3$ vegetation. Lack of $C_4$ vegetation in the Tetang Formation is consistent with deposition prior to 7 Ma, before expansion of $C_4$ grasses in South Asia.

### Magnetostratigraphy

We sampled 200 m of Tetang Formation at Tetang village for magnetostratigraphic analysis.[1] We took 3–6 core samples at 55 stratigraphic levels using standard techniques (Butler, 1992). Unblocking temperatures for characteristic remanent magnetization (ChRM) were below 600 °C, suggesting that magnetite is the dominant carrier of this component of magnetization. Samples yielding line fits with maximum angular deviation (MAD) >15° were rejected from further analysis. Sites with N ≥ 3 samples and site-mean clustering of ChRM directions significant from random at 95% confidence level are designated class A sites; sites with N ≥ 3 samples but more dispersed ChRM directions are designated class B sites; and sites with N ≤ 2 ChRM directions are designated class C sites. The resulting magnetic polarity stratigraphy (Fig. 3) is based on 23 class A sites, 8 class B sites, and 17 class C sites. Seven sites yielded no samples with MAD ≤ 15°.

[1]GSA Data Repository item 200038, Magnetostratigraphic data and techniques, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

A minority of samples had natural remanent magnetization (NRM) that decreased by an order of magnitude upon thermal demagnetization to 200 °C; most samples had erratic thermal demagnetization behavior from which ChRM could not be identified. We believe this component of low unblocking temperature is carried by goethite, which is a likely alteration product of Tethyan series marine sedimentary rocks bounding the Thakkhola graben. A previous magnetostratigraphic study (Yoshida et al., 1984) employed alternating-field (AF) demagnetization, which could not remove a high coercivity component of NRM carried by goethite.

The shift from $C_3$ vegetation in the Tetang Formation to mixed $C_3$-$C_4$ vegetation in the Thakkhola Formation suggests a minimum age of 7 Ma for the Tetang Formation. Basal strata of the neighboring Gyirong graben (Fig. 1A) contain a *Hipparion* fauna, providing a maximum age of about 10.7 Ma (Barry et al., 1982; Cande and Kent, 1995) for initiation of sediment accumulation in Gyirong graben. Assuming similar ages for the formation of the Thakkhola and Gyirong grabens, the magnetic polarity zonation of the Tetang Formation most reasonably correlates with the geomagnetic polarity time scale from chron 5n.2 to chron 4Ar.2. The corresponding absolute age of the top of the sampled section is 9.6 Ma (Fig. 3). Although the sampled section contains no absolute age horizon, dense sampling and almost entirely normal polarity sites in the lower half of the section make other correlations difficult without assuming large fluctuations in sediment accumulation rates. This correlation yields an average accumulation rate of ~20 cm/1000 yr, which is reasonable for a fluvial depositional environment (Sadler, 1981). The gradation from fine-grained fluvial to lacustrine deposition suggests that accumulation rates were fairly stable and may have decreased gradually, supporting an age of about 11–10 Ma for the base of the section, during chron 5n.2.

## OXYGEN ISOTOPIC RESULTS AND IMPLICATIONS

Paleosol carbonates, lacustrine micrites, and fossil mollusks were analyzed for oxygen isotopic compositions. Thakkhola Formation paleosol carbonates, micrites, and shells (*Planorbis* and *Pisidium*) have $\delta^{18}O_{c(carbonate)}$ values of –15.9‰ to –22.4‰, except one paleosol carbonate at 257 m with $\delta^{18}O_c$ = –12.4‰ (Fig. 4A). Micritic carbonates of the underlying Tetang Formation have $\delta^{18}O_c$ values of –17.2‰ to –23.4‰, similar to Thakkhola Formation carbonates (Fig. 4B).

Many factors influence $\delta^{18}O_c$, such as the $\delta^{18}O$ value of local meteoric water ($\delta^{18}O_{mw}$), evaporation, diagenetic effects, and temperature of calcite and/or aragonite precipitation. After evaluating these factors in the following discussion, we suggest that $\delta^{18}O_{mw}$ is the main determinant of $\delta^{18}O_c$ in our samples and that the main determinant of $\delta^{18}O_{mw}$ in this region is elevation.

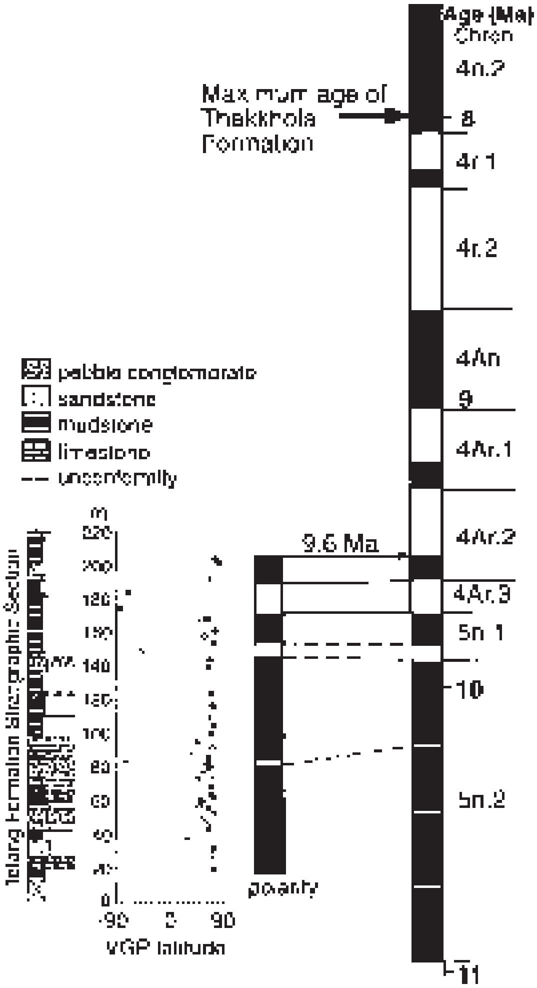


**Figure 3. Correlation of Tetang Formation magnetic polarity stratigraphy to geomagnetic polarity time scale of Cande and Kent (1995). Site-mean virtual geomagnetic pole (VGP) latitude is plotted versus stratigraphic level in Tetang Formation. Positive VGP latitude indicates normal polarity show as black intervals; negative VGP latitude indicates reversed polarity show as white intervals. Filled circles are class A sites, open circles are class B sites, small open circles are class C sites.**

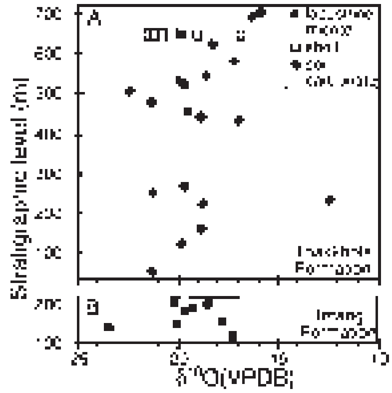


**Figure 4. $\delta^{18}O_c$ (Vienna Peedee belemnite, VPDB) versus stratigraphic level for (A) Thakkhola Formation and (B) Tetang Formation. For individual mollusks that were microsampled for seasonal variations, highest and lowest $\delta^{18}O$ values are shown.**

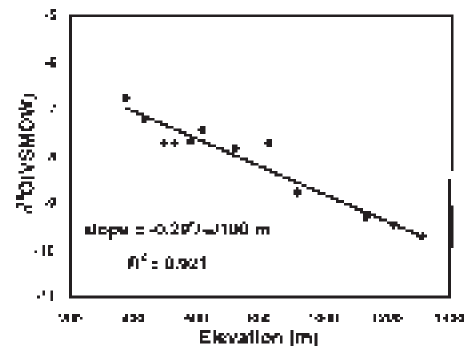


**Figure 5. $\delta^{18}O$ (Vienna standard mean ocean water, VSMOW) versus elevation for small tributaries to Seti River in far western Nepal, sampled during dry season in late March and early April. In dry season, small drainages are fed by ground water and represent average annual rainfall for elevation of their drainage basin (Yonge et al., 1989).**

The overlap between Thakkhola Formation micrites and paleosol carbonates suggests that lake waters underwent minimal evaporation. Multiple shells and growth bands of individual shells collected from 647 m in the Thakkhola Formation compare well with lacustrine micrite from this bed (Fig. 4), implying that shells and micrites precipitated during the same time of year.

Diagenetic alteration of primary $\delta^{18}O_c$ values appears to be small in most, but not all, of our samples. Paleosol carbonates are micritic, lack secondary sparry calcite, and retain primary pedogenic features, such as root tunnels. Petrographic inspection and Feigel solution tests show that mollusks in the Thakkhola Formation have retained original aragonitic structure. However, Tetang Formation mollusks have been calcitized and are therefore not included in the following discussion. In thin section, lacustrine micrite shows minor secondary growth of calcite in pore spaces. Analysis of primary micrite and secondary calcite from 183 m in the Tetang Formation yielded similar $\delta^{18}O$ values of –18.9‰ and –19.1‰ respectively, demonstrating that secondary growth of calcite in micrites is most likely an early diagenetic processes that did not significantly affect $\delta^{18}O$ values of primary carbonate.

Oxygen isotopic fractionation between calcite and water ($\alpha_{c\text{-}w}$) depends on the temperature of calcite precipitation:

$$1000 \ln \alpha_{c\text{-}w} = 2.78(10^6\, T^{-2}) - 2.89, \qquad (1)$$

where $\alpha_{c\text{-}w} = (^{18}O/^{16}O)_c/(^{18}O/^{16}O)_w$ and $T$ is temperature (Friedman and O'Neil, 1977). The current mean annual temperature at Lo Manthang, in the northern Thakkhola graben, is 6 °C (3750 m above sea level) (Climatological Records of Nepal, 1977). Global cooling since Miocene time allows us to infer that this region may have been warmer in the past. Mean $\delta^{18}O$ (VPDB) values of Tetang micrites and Thakkhola micrites and paleosol carbonates is –19.4‰ and –18.8‰, respectively. If there was a similar 6 °C average annual temperature during Tetang and Thakkhola deposition, carbonates would have precipitated from meteoric waters with mean $\delta^{18}O$ (VSMOW, Vienna standard mean ocean water) of –21.7‰ and –21.1‰, respectively. Assuming that the temperature during Tetang Formation deposition was as much as 10 °C warmer than today's temperatures (an extreme circumstance), calculated $\delta^{18}O_{mw}$ values would only increase by ~2.3‰. Changes in mean annual temperature therefore introduce some uncertainty into the calculation of $\delta^{18}O_{mw}$, but this uncertainty is ~2‰ or less.

In general, there is a strong inverse relationship between $\delta^{18}O_{mw}$ and elevation (Yonge et al., 1989; Clark and Fritz, 1997). Globally, $\delta^{18}O_{mw}$ varies between ~–0.15‰ and –0.5‰/100 m (Clark and Fritz, 1997). Very negative and invariant $\delta^{18}O_c$ values in both the Tetang and Thakkhola Formations are evidence for unchanging, high elevation of the basin through time. Similar, negative $\delta^{18}O_c$ values of –11‰ to –22‰ for lacustrine deposits have been documented from Gyirong graben sequences (Wang et al., 1996). Although data on average annual $\delta^{18}O$ of rainfall in this region are not available, we can estimate this using the $\delta^{18}O$/altitude relationship from small tributaries to the Seti River in western Nepal of –0.29‰/100 m (Fig. 5). Modern rainfall $\delta^{18}O$ of New Delhi (elevation = 212 m, $\delta^{18}O$ = –5.81‰ weighted mean; Rozanski et al., 1993) is the starting value for moisture moving over the Himalaya. This value appears to be a reasonable initial value subsequent to ca. 7 Ma, based on similar meteoric water values represented in paleosol carbonate $\delta^{18}O$ from Siwalik foreland basin deposits since that time (Quade et al., 1995). Using the far western Nepal $\delta^{18}O$/altitude gradient, the elevation of precipitation with a $\delta^{18}O$ value of –21‰ is ~5450 m. This is consistent with the modern mix of water sources between 4000 m, where the highest Thakkhola graben fill is exposed, and the highest peaks at ~6700 m that flank the basin. The elevation calculated for the most negative waters (~–25‰) is 6830 m, a relatively good match for water sourced in permanently snow-covered peaks surrounding the basin. The elevation derived from the Thakkhola graben $\delta^{18}O_c$ data are slightly higher than those observed in the region today. If temperatures were warmer in the late Miocene, the calculated $\delta^{18}O$ value for water would be more positive, resulting in lower elevation estimates that more closely match modern elevation.

From the Siwalik soil carbonate record, source moisture before ca. 7 Ma could have been ~3‰ more negative (average $\delta^{18}O$ [VSMOW] = –9‰) (Quade et al., 1995). Prior to 7 Ma, the monsoon may have also been less intense (Prell and Kutzbach, 1992), causing less $^{18}O$ rain-out and lower $\delta^{18}O$-altitude gradients in the Himalaya. These effects counter each other and may explain why the Tetang Formation has $\delta^{18}O_c$ values similar to those of the Thakkhola Formation. Although the $\delta^{18}O$-altitude relationship and the $\delta^{18}O$ values of source moisture may have varied somewhat prior to 7 Ma, it is striking how well modern $\delta^{18}O$ values and elevations fit estimates for the late Miocene. Extremely negative Tetang $\delta^{18}O_c$ values suggest that the region was already elevated at that time.

## CONCLUSIONS

This study has implications for the debate on timing of Tibetan Plateau uplift. Magnetostratigraphy of the Tetang Formation suggests that deposition began between ca. 11 and 10 Ma. Trends in $\delta^{13}C$ values in soil carbonates suggest an age younger than 8 Ma for the base of the Thakkhola Formation. From $\delta^{18}O$ values of Thakkhola graben carbonates, we have inferred that local elevation must have been high, similar to modern elevation, since the onset of deposition in the graben. Our data provide the oldest independent estimates for high elevation on the southern Tibetan Plateau and are contrary to interpretations that significant uplift occurred during the Pliocene and Quaternary. Paleobotanical data from Thakkhola, Gyirong, and other basins in the southern plateau, indicating warmer than modern climatic conditions, may simply reflect global cooling trends since the Miocene. In addition, these data challenge the commonly held notion that east-west extension began at 8 Ma, corresponding to the timing of uplift of the plateau and intensification of the Asian monsoon (Harrison et al., 1992; Molnar et al., 1993). Although these results argue for attainment of high elevation prior to east-west extension, a direct relationship between high elevation and extension cannot be determined without paleoelevation data extending further back in time.


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