Late Miocene topographic inversion in southwest Tibet based on integrated paleoelevation reconstructions and structural history

Michael A. Murphy a,*, Joel E. Saylor b, Lin Ding c

a University of Houston, 312 Science & Research Bldg. 1, Houston, TX 77204-5007, United States
b University of Arizona, Tucson, Arizona 85721, United States
c Institute of Tibetan Plateau Research and Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China

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ABSTRACT

Investigations of the deformation history of the Himalayan orogen support interpretations of rapid and striking changes in the landscape of the Tibetan Himalaya and High Himalaya. We examine this issue by integrating oxygen isotope-based paleoelevation reconstructions of the Zada basin in southwestern Tibet with information on the structural evolution of the High and Tibetan Himalaya between 79°E and 84°30′E. Δδ18Osw values were calculated from δ18O values from pristine fluvial Miocene gastropod shells. Analyses comparing the most negative δ18Osw and reconstructed δ18Osw values to Δδ18Osw versus elevation relationships based on both thermodynamic models and an empirical data set suggest a decrease in the mean watershed elevation of 1 to 1.5 km since the Late Miocene. Geologic mapping and structural data from crustal scale fault systems in the Zada region and regions to its east indicate a phase of arc-normal shortening and vertical thickening since the Middle Miocene, followed by ongoing arc-parallel extension and vertical thinning. These results suggest that regions in this part of the orogen transitioned from undergoing arc-normal shortening to arc-parallel extension in the Late Miocene, and that arc-parallel extensional structures root deeply within the Himalayan thrust wedge. When combined with data on the distribution, age, and provenance of sediments, our geologic mapping, structural data, and paleoelevation results suggest that this transition from shortening to extension was accompanied by a topographic inversion from mountains to basins in ~4 m.y. These observations can be explained by a foreland propagating fault system that accommodates outward radial expansion of the Himalayan orogen.

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1. Introduction

Convergent orogens worldwide share some common characteristics in their evolution: all result in horizontal crustal shortening, leading to thickened crust and surface uplift. Following crustal thickening, crests of the mountain ranges often undergo crustal extension, while crustal extension continues on the flanks of the mountain range (e.g., Molnar and Lyon-Caen, 1988) (Fig. 1). It has been unclear whether the transition to extension marks attainment of maximum elevations or if crustal thickening through shortening outpaces crustal thinning through extension (e.g., Molnar and Lyon-Caen, 1988). Although this transition is recognized in nearly all convergent orogens (e.g., Dewey, 1988), our understanding of its temporal and spatial relationship with respect to ongoing processes within orogens is poor.

The transition from shortening to extension is important to understand because it is a record of how forces evolve within and outside an orogen. Tectonic models explaining the change from shortening to extension in the Himalayan orogen have invoked collapse of a growing thrust wedge (Davis et al., 1983), changing thrust wedge boundary conditions (Yin, 1993), oroclinal bending (Klootwijk et al., 1985; Ratschbacher et al., 1994), oblique convergence (McCaffrey and Nabelek, 1998), outward radial expansion of the Himalayan thrust front (Seeber and Armbruster, 1984; Molnar and Lyon-Caen, 1988; Seebacher and Pecher, 1998; Murphy and Copeland, 2005), and mass accumulation and dissipation processes (Hodges et al., 2001).

Southwestern Tibet and northwest Nepal in the western Himalaya preserve geologic features that archive the transition from shortening to extension in the Himalayan fold-thrust belt (Fig. 2). Extension is expressed in part in the largest topographic depression (250 km × 90 km) in the Himalayan range. This depression includes the Zada and Pulang basins. The Zada basin fill is broadly constrained to be Late Miocene to Pleistocene in age (Saylor et al., 2009; Wang et al., 2008) and is composed, in part, of sediments derived from north of the basin. The basin currently lies in the hinterland of the Himalayan fold-thrust belt and developed on a regionally extensive thrust system known to be active in the Middle Miocene. This suggests that this part of the orogen transitioned from a topographic high to a topographic low in only a few million years.

Below, we present a study which integrates oxygen isotope-based paleoelevation reconstructions of the Zada basin in southwestern Tibet with information on the structural evolution of the High and
Tibetan Himalaya between 79°E and 84°30′E. A detailed documentation and synthesis of the oxygen and carbon isotope analyses and magnetostratigraphy is presented elsewhere (Saylor et al., 2009). The purpose of this contribution is to present our data and interpretations pertaining to the Miocene to present structural evolution and paleogeography of rocks exposed in southwestern Tibet and northwest Nepal and their broader tectonic implications.

2. Distribution and kinematics of shortening structures

Early to Middle Miocene horizontal shortening is manifested along south-directed thrust-sense shear zones (Main Central thrust zone — MCT) and north-directed thrust faults (Great Counter thrust — GCT) (Figs. 1 and 2). The mapped position of the GCT in the Mt. Kailas area is based on mapping by Yin et al. (1999). Its position to the northwest and east of Mt. Kailas as well as the fault-slip data shown on Fig. 2 is based on fieldwork conducted during this study. The age of rock units are based on those cited by Cheng and Xu (1987). The GCT is a regional north-directed thrust system that has been identified across the entire length of the Himalaya from northwest India to Eastern Tibet (this study, Heim and Ganser, 1939; Ganser, 1964; Harrison et al., 1992; Ratschbacher et al., 1994; Yin et al., 1999). In general, the fault system juxtaposes the Tethyan sedimentary sequence (TSS) in its hanging wall against a 2.5–km-thick Late Oligocene-Middle Miocene nonmarine clastic sedimentary sequence, referred to as the Kailas (or Gangrinboche) Conglomerate— in Tibet and the Indus Molasse in India (Fig. 2, Ganser, 1964; Harrison et al., 1993; Aitchison et al., 2002).

The eastern margin of the Zada basin was mapped at a scale of 1:100,000. Our mapping focused on the geologic relationships exposed along and adjacent to the trace of the GCT. The trace of the GCT extends north-northwest across the mapped area. It juxtaposes phyllites and slates of probable Ordovician age (TSS) in its hanging wall against boulder-cobble conglomerate in its footwall. The GCT along the eastern margin of the Zada basin is a 3–3 m-thick zone of brecciated rock and throughgoing fault surfaces lined with a dark brown to red clay gouge. Striations in the clay gouge yield a mean slip direction of N55E along the northeastern margin of the basin (letter G on Fig. 2) and N39E along the east-central margin of the basin (letter H on Fig. 2). The hanging wall of the GCT as well as its surface trace is onlapped by the youngest strata of the Zada basin in the northeast corner of the basin.

The GCT is mappable through the Mt. Kailas area (Yin et al., 1999) and eastward to the Lopukangri area (84°30′E) (letter K on Fig. 2). Rocks immediately east of Lopukangri (7024 m) were mapped at a scale of 1:100,000. The GCT extends WNW-ESE across the mapped area and consists of 5 subparallel thrust faults distributed within a 4 km-wide zone. Striations on the fault surfaces yield a mean slip direction of N05E (letter K on Fig. 2). This system of faults juxtaposes Paleozoic through Mesozoic phyllites, slates, sandstones, and limestones of probable Paleozoic through Mesozoic age (TSS) in its hanging wall against boulder-cobble conglomerate in its footwall.

The slip direction of the GCT estimated in the Zada and Lopukangri regions demonstrate that it is approximately arc-normal (Fig. 2). Structural reconstructions of deformation in the Mt. Kailas area indicate 64 km of north-south shortening across the GCT (Murphy and Yin, 2003). Similarities between the rocks juxtaposed along the GCT suggest that this shortening estimate may be applicable to the Zada and Lopukangri areas. On the basis of modeled K-feldspar 40Ar/39Ar data from clasts in the Kailas conglomerate in the Mt. Kailas area, Yin et al. (1999) suggested that the thrust was active between 19–13 Ma. These ages overlap those determined by Quideleau et al. (Quideleau et al., 1997) for the slip on the GCT (locally termed the Renbu Zendot thrust) in eastern Tibet. Movement on the GCT created as much as 10 km of crustal thickening (Yin et al., 1999) and associated topography in the hanging wall.

Where observed in the Zada basin, near Mt. Kailas and in the Lopukangri region the GCT juxtaposes low-grade sedimentary and meta-sedimentary rocks of the Tethyan sedimentary sequence (TSS) in the hanging wall against a cobble-boulder conglomerate in the footwall. This conglomerate lies unconformably on top of porphyritic granite (Fig. 2). It consists of two mappable units based on clast composition. Clasts in the youngest conglomerate unit are dominated by sedimentary and volcanic rocks of unknown age, while the older unit almost exclusively consists of clasts of porphyritic granite. We interpret this conglomerate sequence as the Kailas conglomerate and correlated it to its type location exposed in the Mt. Kailas area based on the similarity in their structural position and composition. As in the Zada and Mt. Kailas regions, the conglomerate in the footwall of the
GCT near Lopukangri lies unconformably on top of porphyritic granite and consists of two mappable units distinguished, as above, based on clast composition which can be correlated to those recognized in the Mt. Kailas and Zada areas.

The trace of the MCT zone extends across the southern flanks of the Western and Central Himalaya between 2200 and 3800 m elevation and dips moderately to the north. The average slip direction on faults within the MCT zone in the Central Himalaya is approximately arc-normal (S10W±4°) (Fig. 2). The timing of slip on the MCT in the Central Himalaya is estimated by 40Ar/39Ar thermochronology and provenance data in foreland basin deposits as Early Miocene (~21–22 Ma) (DeCelles et al., 2001). Other major thrusts to the south of the MCT broke in a generally southward younging sequence, beginning in middle Miocene time with the Ramgarh thrust and following sequentially with the development of a large duplex in Lesser Himalayan Sequence rocks, the Main Boundary thrust, and the Main Frontal thrust (DeCelles et al., 2001). The average slip direction on imbricate thrusts in the Lesser Himalaya, immediately south of the MCT in northwestern Nepal is S19W±3° (Fig. 2).

3. Distribution and kinematics of extensional structures

Late Miocene to Recent arc-parallel extensional deformation is expressed in the Western and Central Himalaya by three regional structures; the Karakoram fault, Leo Parghil horst (Qusum normal fault), and Gurla Mandhata-Humla fault system (Fig. 2). Between 79°E and 81°30′E deformation along the Karakoram fault occurs within a narrow zone (2–20 km wide) consisting of right-lateral faults, normal faults, and right-lateral ductile shear zones that strike N40W north of 31°30′N and N55W south of 31°30′N (Fig. 2) (Armijo et al., 1986; Ratschbacher et al., 1994; Murphy et al., 2000). Fault-slip data show that the direction of displacement along the fault rotates to more easterly orientations from north to south between 79°E and 82.5°E (Fig. 2). This trend broadly parallels the trace of the Himalayan thrust.

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4. Basins associated with extensional structures

The Zada basin (7,500 km²) is the largest Late Miocene to Pleistocene basin in the Himalaya (Cheng and Xu, 1987) (Fig. 1). Research in the Zada basin has produced an array of conclusions regarding basin formation and evolution (Cheng and Xu, 1987; Chamberlain and Poage, 2000; Garzione et al., 2000a,b; Currie et al., 2005; Cyr et al., 2005; Rowley and Currie, 2006; Rowley and Garzione, 2007). In the ideal case, the δ18O value of surface water (δ18Osw) reflects the average δ18O value in the catchment. Departures from the ideal case tend to increase the δ18Osw values via preferential evaporation of H218O, which results in a lowering of calculated paleoelevation. Carbonates ultimately derive their oxygen from surface water and so carbonate δ18O values (δ18Ocarb) provide a record of paleo-surface water δ18O values (δ18Osw), dependent on the temperature of carbonate formation. After correcting for other climatic factors, paleoelevation can be reconstructed. Local departures from the modern global average δ18O versus elevation lapse rate can potentially be redressed by direct measurement and modeling of local lapse rates as has been done for southern Tibet (Garzione et al., 2000b; Rowley et al., 2001).

Modern calibration is based on 28 water samples collected at 20 locations ranging from the Sutlej River mainstream to small seep springs throughout Zada Basin over multiple years. Virtually no local rain fell during the sampling campaigns, meaning we were sampling higher elevation run-off. We calculated the elevation at which precipitation fell by obtaining hypsometric mean and maximum watershed elevations for each sample. δ18Osw values range from −17.9 to −11.9‰, and δDsw values from −137 to −86‰ (VSMOW). Modern water from the Zada Basin plots on the global meteoric water line meaning that it is free of extensive evaporation.

Late Miocene–Pliocene water data is based on fossil gastropods collected from a variety of depositional settings in two measured sections spanning the lower ~550 m (8–2.5 Ma) of the Zada Formation. We are confident that gastropod samples are unaffected by diagenesis and retain their original δ18O values for the following four reasons: (1) all samples which returned usable X-ray diffraction results (11 of 12) were aragonite, and none showed evidence of recrystallization; (2) the samples are visually pristine; and (3) samples which we microdrilled showed seasonal variation which is unexpected if the samples were reset to a regional δ18Osw value during diagenesis. (4) The results from this representative sampling can be applied across the basin because the sediments were never buried.

5. Oxygen isotope paleoaltimetry

In the following section we summarize the results of an oxygen isotope paleoelevation study the full details of which are presented by Saylor et al. (2009). The principle underlying oxygen isotope paleoereconstructions is that the oxygen isotopic composition of meteoric water (expressed as δ18Osw in units ‰) decreases by ~2.8‰/km (Siegenthaler and Oeschger, 1980; Chamberlain and Poage, 2000; Garzione et al., 2000a,b; Garzione et al., 2000a,b; Garzione et al., 2000a,b; Currie et al., 2005; Cyr et al., 2005; Blisniuk and Stern, 2005; Rowley and Currie, 2006; Rowley and Currie, 2006; Rowley and Garzione, 2007). In the central part of the basin, a ~800-m-thick succession of upper Miocene to Pleistocene deposits records an upward transition from fluvial to lacustrine sedimentation and finally alluvial fan deposits. The formation rests unconformably on the TSS which is deformed by shortening structures. Zada basin strata were deposited on an erosional surface with significant relief; where observed, basin fill is subhorizontal and undeformed. In the northeast corner of the basin, the basinfill onlaps the hanging wall and trace of the GCT (Fig. 2).

Paleocurrent direction indicators show that porphyritic granite clasts in the uppermost Zada formation whose composition matches granites in the footwall of the GCT are indeed derived from the footwall of the GCT (Poage and Chamberlain, 2001). Along the northwestern margin of the basin, the basin fill abuts the Qusum normal fault. Paleocurrent indicators show that mylonitic clasts in the uppermost Zada basin fill are derived from rocks of similar composition in the footwall of the Qusum normal fault (Saylor et al., in review). We interpret the presence of a late Miocene basin in the hanging wall of the GCT to signify an inversion of the topography between the latest movement on the GCT and deposition within the Zada basin (Fig. 2) (Yin et al., 1999; Aitchison et al., 2002).

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deviate from a ±0.5‰ uncertainty due to variation in the most negative values of δ\(^{18}\)O\(_{\text{pw}}\) in Mio-Pliocene low-elevation paleosol carbonates between western Nepal and Pakistan (Quade et al., 1995), and ±1.5‰ uncertainty due to seasonal changes in the temperature of aragonite precipitation.

We applied the Rayleigh fractionation models with \(T_1 = 295\) K and \(T_i = 300\) K (both with initial relative humidity of 0.8) and the empirically based model to our data in order to compare the elevations predicted by \(\Delta\delta^{18}\text{O}_{\text{psw}}\) and \(\Delta\delta^{18}\text{O}_{\text{pw}}\) values. In light of the observed 3‰ increase in \(\delta^{18}\text{O}\) values from Himalayan and Tibetan glaciers in the 20th century (Thompson et al., 1997, 2000; Kang et al., 2001), we added 3‰ to our \(\Delta\delta^{18}\text{O}_{\text{psw}}\) value. Even with this correction the models still yield a difference in predicted elevations between the \(\Delta\delta^{18}\text{O}_{\text{psw}}\) and \(\Delta\delta^{18}\text{O}_{\text{pw}}\) values that is greater than the uncertainty associated with those data points (Fig. 4). The addition of 3‰ to the \(\Delta\delta^{18}\text{O}_{\text{psw}}\) value may not be warranted, as interpretation of the glacial record remains unclear and the inferred increase in \(\delta^{18}\text{O}_{\text{psw}}\) values may be due to a short-term, transitory change. However, without the correction for the changes in \(\delta^{18}\text{O}\) values observed in Tibetan glaciers, our estimates of paleoelevation would increase by ~0.5–0.7 km.

Possible alternative explanations for extremely negative \(\delta^{18}\text{O}\) values from Zada basin include; gastropods precipitated their shells in warm water (41 °C), the lapse rate has changed between the Miocene and present or the low-elevation temperature was 4.5 °C cooler in the Miocene. However, all of these require extreme and unobserved scenarios.

6. Discussion

6.1. Paleogeography

The spatial and temporal relationship between the, Zada basin, and shortening and extensional structures suggests a rapid and striking change in the landscape between the Tibetan plateau and Himalaya. The age of the GCT and estimates of crustal thickening indicated by \(^{40}\)Ar/\(^{39}\)Ar modeling (Yin et al., 1999) indicate that the hanging wall of the GCT, which currently underlies the Zada basin fill was elevated and may have supplied detritus northward into the Kailas basin from the Oligocene–Miocene (e.g., Yin et al., 1999; Atchison et al., 2002). Thus, based on the aerial extent of the GCT and Kailas conglomerate, the region immediately south of the GCT between 79°E and 84°30'E was arguably topographically higher than the region to the north (Figs. 2 and 6). Based on timing estimates on the GCT, we interpret this first-order characteristic of the landscape to have existed from the Early to Middle Miocene.

Development of the Zada basin and the Pulun basin during the Late Miocene to Pleistocene occurred within the region occupied by the hanging wall of the GCT, a region of previously elevated relative topography. The aerial extent of the Zada basin fill and the Pulun basin fill in the Mt. Kailas area (Fig. 2) implies that a semi-discontinuous 300 km long topographic depression formed on the south side of the GCT trace between the last movement on the GCT and initiation of sedimentation in the Zada basin (i.e.: between the Middle and Late Miocene. Coeval with the development of the Zada and Pulun basins was initiation of local slip along the Karakoram fault, GMH, Leo Parghil shear zone, and Qusum normal fault. This implies a genetic link between arc-parallel extension and basin development in the Tibetan Himalaya and High Himalaya. These geologic observations indicate that the region occupied by the Zada basin evolved from being a topographic high to topographic low during the transition from arc-normal shortening to arc-parallel extension in this part of the orogen. Our paleoelevation results suggest that, in addition to the decrease in elevation between the Middle to Late Miocene, continued elevation loss between the Late Miocene to present may have been as much as 1.5 km. In support of a topographic inversion in the Zada region is the presence of wind gaps in the mountain ranges to the east and west of the basin (Fig. 2).
interpret the inception of entrenchment of rivers on the eastern and western margins of the Zada region to have occurred during the Early to Middle Miocene phase of arc-normal shortening. We envision that rivers on the eastern margin flowed to the northeast and those on the western margin flowed to the southwest. We interpret the wind gaps to have formed during the transition from shortening to extension as the Zada basin developed (Fig. 6).

6.2. Explanations for arc-parallel extension

The discussion above highlights several foundational observations that must be incorporated into models explaining arc-parallel extension. These are (1) the transition and the timing of the transition from arc-normal shortening to arc-parallel extension, (2) the topographic inversion, (3) the large topographic depression which the Zada basin occupies and its uniqueness in the Himalayan range and (4) the magnitude and depth of exhumation accommodated by extensional structures. Corollary observations to these include crustal thinning implied by a loss of elevation of 1–1.5 km and the distribution of extensional structures associated with the Zada topographic depression. Table 1 compares the predictions of the tectonic models mentioned in the introduction to the observations listed above. This comparison shows that two of the models that best explain arc-parallel extension of the Himalayan orogen are outward expansion of the arc-shaped Himalayan thrust front (Seeber and Armbruster, 1984; Klooitwijk et al., 1985; Molnar and Lyon-Caen, 1988; Ratschbacher et al., 1994; Seeber and Pecher, 1998; Murphy and Copeland, 2005), and oblique convergence along an arc-shaped boundary (McCaffrey and Nabelek, 1998).

McCaffrey and Nabelek (1998) show that coeval arc-normal shortening and arc-parallel extension can result from basal shear caused by the Indian plate sliding obliquely beneath the Himalayas and Tibetan plateau. The model predicts, due to greater obliquity between the convergence direction and the orogen front, the rate of arc-parallel extension is greater in the western Himalaya compared to that in the central Himalaya. This may provide an explanation for the presence of large Late Miocene basins in the Tibetan Himalaya of the western Himalaya and their apparent absence in the central Himalaya. Oblique convergence links the timing of the transition from arc-normal shortening to arc-parallel extension systematically to events within the orogenic wedge by linking it to a change in the force imposed by basal shear stress. This change could be explained by initiation of a forward propagating thrust system which increases the area of the orogenic wedge in contact with the basal detachment, thereby increasing the force imposed by the obliquely subducting plate to the point where it overcomes the internal strength of the rocks to resist translation and they are translated towards the syntaxes. This predicts that prior to breaking the forward propagating

Table 1

<table>
<thead>
<tr>
<th>Observations from southwest Tibet</th>
<th>Collapse of growing thrust wedge</th>
<th>Changing thrust boundary conditions</th>
<th>Oroclinal bending</th>
<th>Oblique convergence</th>
<th>Radial expansion</th>
<th>Mass accumulation/disipation processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc-normal shortening</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Arc-parallel extension</td>
<td>Not explicit but possible</td>
<td>Not explicit but possible</td>
<td>Yes (limited to zone of arc-normal shortening)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (if lateral variations in potential energy are present)</td>
</tr>
<tr>
<td>Transition from arc-normal shortening to arc-parallel extension</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Timing of transition</td>
<td>Adjusting from super-critical state</td>
<td>Increase in pore-pressure or initiation of a forward propagating thrust system.</td>
<td>Not predicted. Arc-normal shortening and arc-parallel extension are synchronous.</td>
<td>Not explicit but possible. Caused by change in force imposed by basal shear. Linked to change in direction or rate of convergence.</td>
<td>Passage of shortening zone</td>
<td>No (possibly synchronous, possibly due to an abrupt increase in potential energy within the orogen)</td>
</tr>
<tr>
<td>Topographic inversion</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Uniqueness and location of Zada</td>
<td>Not predicted</td>
<td>Not predicted</td>
<td>Not Predicted</td>
<td>Not explicit but possible</td>
<td>Not explicit but possible</td>
<td>Not explicit but possible</td>
</tr>
<tr>
<td>Crustal thinning</td>
<td>Yes (orogen-wide) not localized</td>
<td>Yes (orogen-wide) not localized</td>
<td>Yes (orogen-wide) not localized</td>
<td>Yes (locally)</td>
<td>Yes (orogen-wide) due to minimization of excess potential energy</td>
<td>Yes (if lateral variations in potential energy are present)</td>
</tr>
<tr>
<td>Arc-parallel extensional structures</td>
<td>Yes (possible)</td>
<td>Yes (possible)</td>
<td>Yes. But limited to zone of active arc-normal shortening.</td>
<td>Yes</td>
<td>Yes</td>
<td>Not explicit</td>
</tr>
<tr>
<td>Strike slip structures</td>
<td>Not predicted</td>
<td>Not predicted but possible</td>
<td>Not predicted</td>
<td>Possible</td>
<td>Yes</td>
<td>Limited by southward extruding MCT zone</td>
</tr>
<tr>
<td>Depth of exhumation</td>
<td>Not predicted</td>
<td>Not predicted but possible</td>
<td>Not predicted</td>
<td>Possible</td>
<td>Yes</td>
<td>Limited by southward extruding MCT zone</td>
</tr>
</tbody>
</table>

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thrust system only the zones of greatest obliquity (i.e. the zones closest to the syntaxes) should have experienced translation. Although not formally discussed, the oblique convergence model of McCaffrey and Nabelek (McCaffrey and Nabelek, 1998) also predicts that the strike-slip faults on which the blocks are translated towards the syntaxes will propagate towards the center of the orogen in discrete steps related to forward propagation of the thrust front (Murphy et al., 2000).

Models calling upon outward radial growth of the Himalaya also offer an explanation for how an orogen may transition from shortening to extension (e.g., Murphy and Copeland, 2005). The geologic observations presented above demonstrate that arc-parallel extension shortly followed arc-normal shortening within the High and Tibet Himalaya; is contemporaneous with crustal shortening in the Lesser and Subhimalaya; and that the slip direction on extensional faults parallels the trace of the Himalayan arc. The fault slip data on the GCT and MCT between 79°E and 84°30′E are a manifestation of an Early to Middle Miocene phase of deformation dominated by arc-normal shortening (Fig. 2). Assuming that these structures root into a regional south-directed thrust as indicated by seismological, geodetic, and structural data (Pandey et al., 1999; DeCelles et al., 2001; Jade et al., 2004), this motion requires the Himalayan arc to lengthen assuming no deformation of the downgoing Indian plate. In the simplest scenario, whereby the Himalayan arc grows radially outward along a single thrust, the magnitude of extension is highest at the thrust front since the radius of curvature of the arc is greatest at this position, and decrease towards the hinterland. However, in the Himalaya whereby multiple thrust faults have initiated successively from north to south (i.e. hinterland to foreland), the magnitude of arc-parallel extension should increase toward the hinterland, as the rearmost hanging wall has been translated furthest towards the foreland. As the magnitude of arc-parallel extension is directly proportional to that of arc-normal translation, the rearmost hanging walls will undergo greater extension than the hanging walls of younger thrusts at the thrust front (Fig. 5). The magnitude of extension can be expressed as

\[ e = \frac{r_2 - r_1}{\alpha e} / 180 \]  

where \( r_2 \) and \( r_1 \) are the post expansion and pre-expansion radii of curvature, and \( \alpha \) is the central angle which describes the sector length considered. The pattern of extension calculated for a thrust belt in which thrusts initiate successively towards the foreland is consistent with the widespread exposure of mylonitic rocks in the core of the Gurla Mandhata metamorphic core complex which signify a large magnitude of extension within the high Himalaya (Murphy et al., 2002; Murphy and Copeland, 2005). Structural reconstructions across the Himalayan fold-thrust belt suggest 228 km of horizontal shortening have occurred in the region between the Main Central Thrust and the Main Frontal Thrust in northwest India (Srivastava and Mitra, 1994) and in western Nepal (DeCelles et al., 1998). Assuming a simple scenario whereby this shortening is fed into a single top-to-south detachment implies that the rocks in the high Himalaya have been translated toward the foreland for a distance of 228 km. The kinematic model presented here predicts 150 km of arc-parallel extension within the high Himalaya (hanging wall of the MCT) between 77°3′ E and 90°E which represents a 45° sector of the Himalayan arc. Moreover, this model provides an explanation for how the arcuate geometry of the Himalayan orogen may have maintained steady-state equilibrium since the Late Miocene.

Arc-parallel extension as described above requires extension of the entire thrust wedge. This is consistent with field observations as well as isotopic data that show that the GmH assists in exhumation of Greater and Lesser Himalayan rocks, cuts the South Tibetan detachment system as well as the MCT zone, and extends into the Lesser Himalaya (Ratschbacher et al., 1994; Murphy, 2007).

The mechanism for extension favored in this study is only applicable to the Himalayan arc due to the SLF in the north where structural trends define an arcuate pattern and slip directions trend outward radially. Although extension is prevalent throughout the Tibetan plateau to the north (Lhasa and Qiangtang blocks) much of the region is characterized by Mesozoic and early Cenozoic north-south shortening and therefore unlikely to be a component of the Neogene Himalayan thrust wedge. Nonetheless, if extension within the Tibetan plateau were driven by outward radial growth of the Himalayan arc, then the geometry of extensional structures is predicted to be arc-normal resulting in northeast-trending rifts in western Tibet and northwest-trending rifts in eastern Tibet (Seaber and Armbruster, 1984). Kapp and Gwynn (2004) showed that the first-order geometry of Tibetan rifts is exactly opposite to this prediction, with northwest-trending rifts in western Tibet and northeast-trending rifts in eastern Tibet. The kinematics of Tibetan rifts, although poorly known, do not show slip parallel to the trace of the Himalayan arc. In western Tibet, the Lunggar rift displays a shear sense towards the east-northeast (Pullen et al., 2008), while the shear sense of the Nyainqentanglha extensional system in eastern Tibet is top-to-southeast (Harrison et al., 1992). Thus, extension of the Tibetan plateau north of the India-Asia suture zone is likely a result of some other mechanism, such as eastward extrusion of central Tibet relative to southern Tibet (Taylor et al., 2003) or gravitational collapse of thickened lithosphere (Molnar et al., 1993). Therefore, the age, lifespan, and kinematics of normal faulting within the Tibetan lithosphere may not correlate to that within the Himalaya.

Estimates of the along–arc extension rate as derived by geodetic methods range from 4.5 ± 3.5 mm/yr (Jouanne et al., 1999) to 14 ± 2 mm/yr (Chen et al., 2004). The higher rate estimated by Chen et al. (2004) is consistent with the rate of east-west extension between Leh and Lhasa calculated by Jade et al. (2004). The onset of extension in the Himalayas is estimated to be 8 Ma (Harrison et al., 1995), 11 Ma (Murphy et al., 2002), and 14 Ma (Coleman and Hodges, 1995). Taking the slip rate estimated by Chen et al. (2004) with these timing estimates yields a magnitude of arc-parallel extension of 112 km, 154 km and 196 km, respectively. This range overlaps the estimate calculated in the kinematic model presented here as well as the model presented by McCaffrey and Nabelek (1998). The extension rate estimated by Jouanne et al. (1999) yields magnitudes of extension that are significantly lower than that estimated from the geologic data and therefore may not be representative of the long-term rate.

6.3. Integrated paleogeography and tectonic model

The outward radial expansion model described above explains the structural relationships and basin development observed in southwest Tibet (Fig. 6). Arc-normal shortening during the Early Miocene to Middle Miocene resulted in vertical thickening, surface uplift, and denudation of rocks between the MCT zone and Indus–Yu lists crustal zones (Yin et al., 1999; Atchison et al., 2002). Onset of arc-parallel extension in the Late Miocene resulted in vertical thinning and subsidence of the region previously thickened. It is envisioned that Zada basin fill accumulated in such a locality. During this transition we suggest that wind gaps, discussed earlier, formed on the eastern and western margins of the Zada basin. We interpret the transition from shortening to extension to be a consequence of foreland propagation of arc-normal shortening structures. As the zone of arc-normal shortening propagated towards the foreland, the region thickened is brought into a zone of arc-parallel extension. This creates a transition zone between the foreland dominated by crustal shortening and the hinterland dominated by arc-parallel extension.

Whether or not this model is applicable to the entire Himalayan arc remains an open question. Structures equivalent to the GCT span the length of the Himalayan arc (Heim and Ganser, 1939; Ganser, 1964; Harrison et al., 1992; Ratschbacher et al., 1994; Quideulle et al., 1997; Yin...
et al., 1999; Wang et al., 2000; Aitchison et al., 2002), indicating that the TSS in the hanging wall of the GCT may have been regionally elevated, as it is today, since the Early Miocene. An intriguing recent observation in the eastern Himalaya by Li and Yin (2008) is the presence of a ~100-km wide zone of left-slip faults that strike parallel to the trace of the Himalayan arc. The slip rate on this fault system is estimated to be 4–8 mm/yr which is broadly comparable to slip rate estimates along the Karakoram fault system suggesting a common mechanism for the development of arc-parallel strike-slip faults. Nonetheless, our current understanding of the geology of the Himalaya indicates that the Zada basin is unique as no known equivalent has been recognized in the central Himalaya. This indicates that arc-normal crustal thickening and uplift spanned the length of the Himalayan arc but arc-parallel extension and elevation loss is focused in the western portion of the arc. While the model presented above does not provide an explanation for the apparent absence a possible explanation may involve varying rates of convergence between the western and central Himalaya. If the rate of convergence in the western Himalaya is less than the rate of arc-parallel extension then the crust may be thinning faster than crustal thickening via underthrusting/underplating leading to a net decrease in elevation. By contrast to the east, if the rate of convergence is faster or equal to the rate of extension then crustal thinning in response to arc-parallel extension is equal to crustal thickening such that no major holes/basins are produced and elevation is in a semi-steady state.

7. Conclusions

Our integrated study of oxygen isotope-based paleoelevation reconstructions of the Zada basin in southwestern Tibet with information on the distribution, age, and kinematics of faulting between 79°E and 84°30′E yields the following results:

1. The most negative δ18Osw and reconstructed δ18Opsw values were compared to Δδ18Osw versus elevation relationships based on both thermodynamic models and an empirical data set and suggest a decrease in the mean watershed elevation of 1 to 1.5 km since the Late Miocene.

2. A phase of arc-normal shortening and vertical thickening, followed by arc-parallel extension and vertical thinning that is ongoing.

3. The spatial relationship between shortening and extension implies first order changes in the landscape that is supported by our oxygen isotope-based paleoelevation reconstructions.

4. Regions in this part of the orogen transitioned from undergoing arc-normal shortening to arc-parallel extension in the Late Miocene.

5. These observations can be explained by foreland propagating fault systems that work together to accommodate outward radial expansion and maintain the arcuate shape of the Himalayan orogen.

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