The Gangdese retroarc thrust belt revealed

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ABSTRACT

The Cretaceous–early Tertiary Gangdese arc in southern Tibet is generally attributed to the northward subduction of Neotethyan oceanic lithosphere prior to Indo-Asian collision. However, the history and tectonic significance of deformation and sedimentation in Tibet during this time interval have remained enigmatic. We show that contractional structures and clastic rocks near the city of Lhasa can be attributed to the development of a northward-propagating retroarc thrust belt that was active between 105 and 53 Ma. A kinematic model shows that the thrust belt could have accommodated >230 km (>55%) of N-S shortening. An episode of large magnitude (>160 km) and rapid (>8 mm/yr) shortening predated the onset of a magmatic flare-up ca. 69 Ma, which is linked to removal of overthickened mantle lithosphere. This tectonic history implies that southern Tibet underwent substantial crustal thickening and elevation gain prior to the Indo-Asian collision.

Keywords: Tibet, plateau, retroarc thrust belt, Lhasa terrane, Gangdese.

INTRODUCTION

During the Late Cretaceous to Eocene, the convergence rate between the Indian and Asian plates exceeded 10 cm/yr (e.g., Patriat and Achache, 1984; Klootwijk et al., 1992; Lee and Lawver, 1995). This convergence was coeval with northward subduction of Neotethyan oceanic lithosphere beneath southern Asia and the development of the Gangdese continental magmatic arc in southern Tibet (e.g., Schärer et al., 1984). An angular unconformity in the Lhasa terrane between strongly shortened Cretaceous and older strata and overlying, weakly deformed uppermost Cretaceous to lower Tertiary volcanic-bearing strata of the Linzizong Formation (Fig. 1) has led to speculation that there is a contractional (Cordilleran-style) orogen related to the Gangdese arc (e.g., Burg et al., 1983; England and Searle, 1986; Ratschbacher et al., 1992). However, the hypothetical thrust belt has not been documented and only parts of the expected foreland basin system have been recently recognized (Leier et al., 2007).

We present initial results of ongoing work in the Lhasa region (Figs. 1 and 2). We document a retroarc thrust belt and foreland basin associated with the Cretaceous–early Tertiary Cordilleran-style southern margin of Asia. Our results and interpretations provide an integrated picture of the Gangdese continental margin tectonic system and shed light on the nature of the Tibetan lithosphere prior to the Indo-Asian collision.

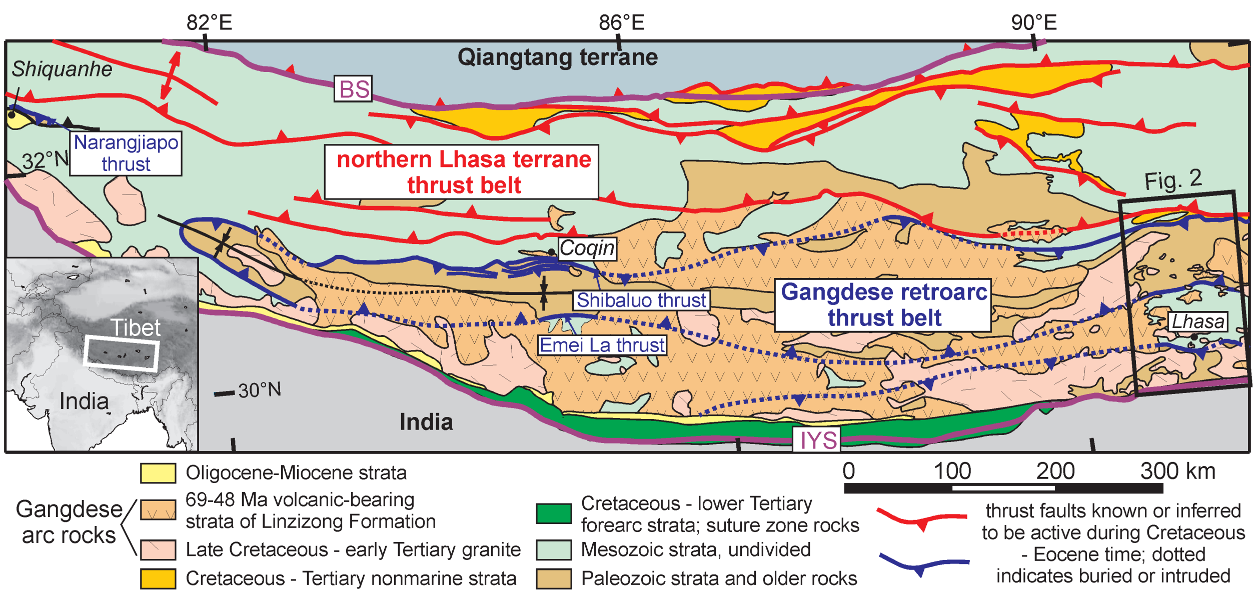

Figure 1. Tectonic map of southern Tibet modified from Kapp et al. (2003). Distribution of Paleozoic strata based on Liu (1988). BS—Bangong suture; IYS—Indus-Yarlung suture.

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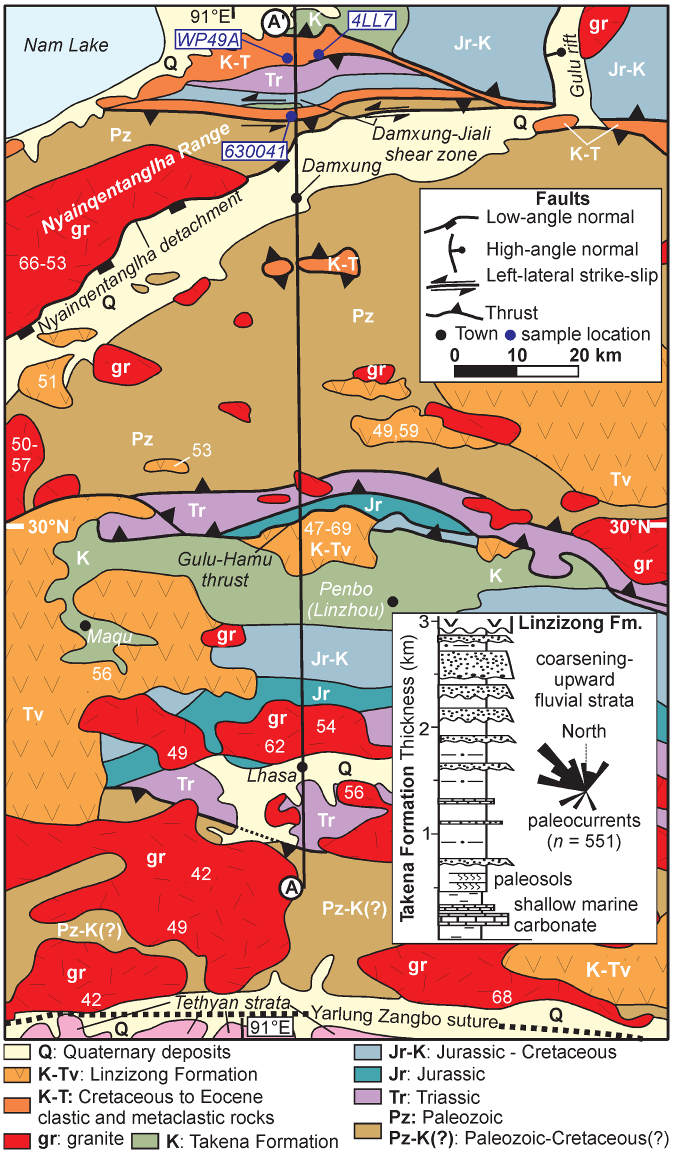

Figure 2. Simplified geologic map of the Lhasa region modified from Kidd et al. (1988) to account for our new mapping and age data. White numbers: crystallization ages of igneous rocks in m.y. (Schärer et al., 1984; Xu et al., 1985; Coulon et al., 1986; Copeland et al., 1987, 1995; Pan, 1993; Mo et al., 2003; Kapp et al., 2005a; He et al., 2007). Schematic stratigraphic column for the Takena Formation is based on measured sections presented in Leier et al. (2007).

THE TAKENA FORMATION: RETROARC FORELAND BASIN DEPOSITS

The Takena Formation consists of an ~250-m-thick lower unit of Aptian-Albian marine carbonate parasequences that is conformably overlain by an ~100-m-thick zone of stacked paleosol horizons and >2 km of upward coarsening fluvial redbeds (Fig. 2; Leier et al., 2007). Paleocurrent indicators demonstrate dominantly northwestward paleoflow (Fig. 2). The presence of metasedimentary clasts and abundant plagioclase and volcanic grains in sandstones imply derivation from the Gangdese arc and metasedimentary country rocks to the south (Fig. 2). The upward-coarsening trend within the Takena Formation, combined with a subsidence history of initial slow accumulation followed by progressively increasing rates, is indicative of a foreland basin setting (Jordan, 1995; DeCelles and Giles, 1996). The lowermost ca. 105 Ma limestones and overlying paleosol-rich strata are interpreted to represent flexural backbulge-forebulge deposits (e.g., Dorobeck, 1995; DeCelles and Giles, 1996) that accumulated during the initial stages of retroarc foreland basin development. The age of the youngest Takena redbeds is ca. 90 Ma.

NORTH-DIRECTED THRUST FAULTS NEAR LHASA AND PENBO

An E-W–striking fault interpreted to have exhumed arc and metasedimentary rocks coeval with Takena deposition is located ~12 km south of Lhasa (Fig. 2). It is subvertical and juxtaposes Paleozoic to Cretaceous (?) metasedimentary rocks to the south against lower-grade Triassic strata in the north (Kidd et al., 1988). The fault predates Indo-Asian collision; it is intruded by Paleocene-Eocene granites and unconformably overlain by ca. 56 Ma Linzizong volcanic rocks (Xu et al., 1985; Fig. 2). Although previously interpreted to be a N-dipping thrust, we raise the possibility that it is a N-directed thrust fault (with higher-grade rocks in the hanging wall) that has been tilted southward.

A stack of N-dipping thrust sheets is exposed ~15 km north of Penbo (Fig. 2). One of these thrusts is S-directed and cuts strata as young as ca. 47 Ma in its footwall (He et al., 2007), whereas the structurally highest thrust with Paleozoic strata in the hanging wall is intruded by a suite of granites that has been dated to 57–50 Ma along strike to the west (Fig. 2). Preliminary observations suggest that the structurally highest thrust is a folded N-directed thrust (Fig. 3). Cretaceous and older strata were strongly folded prior to Linzizong volcanism. Whereas many of the folds are upright (Burg et al., 1983; Ratschbacher et al., 1992; Pan, 1993), hundreds-of-meter-wavelength overturned folds near Penbo show northward vergence (Fig. 3A). Cleavage planes in cataclasite within the structurally highest thrust fault zone dip more gently to the north than the fault plane (indicating a top-to-the-north sense-of-shear), and asymmetric mesoscopic folds in the hanging wall show northward vergence (Fig. 3B; He et al., 2007).

THRUST FAULTS IN THE NYAINQENTANGLHA RANGE

The Nyainqentanglha Range north of Damxung (Fig. 2) exposes metasedimentary rocks of previously inferred Paleozoic age (Kidd et al., 1988; Liu, 1988), although recent studies suggest that some of these rocks may be as young as Cretaceous (Edwards and Ratschbacher, 2005; Kapp et al., 2005a). Our mapping shows that metasedimentary rocks within the core of the range are regionally S-dipping and include Aptian-Albian metalimestone and >2 km of overlying metaclastic rocks. A U-Pb detrital zircon age spectrum for a metasandstone collected ~1.8 km tectonostratigraphically above the metalimestone (630041; Fig. 2) shows prominent Early Cretaceous and early Tertiary peaks (Fig. 4A). We interpret the Cretaceous-Tertiary zircons to have been derived from the Gangdese arc to the south and the peak age of the youngest zircon population (ca. 54 Ma) to provide a maximum depositional age. Within the late Cenozoic Damxung-Jiali shear zone to the south (Fig. 2; Edwards and Ratschbacher, 2005), the metaclastic rocks are exposed structurally beneath S-dipping Paleozoic metasedimentary rocks. We suggest that the Tertiary clastic rocks were initially juxtaposed against the Paleozoic rocks by a S-dipping, N-directed thrust (Figs. 2 and 3).

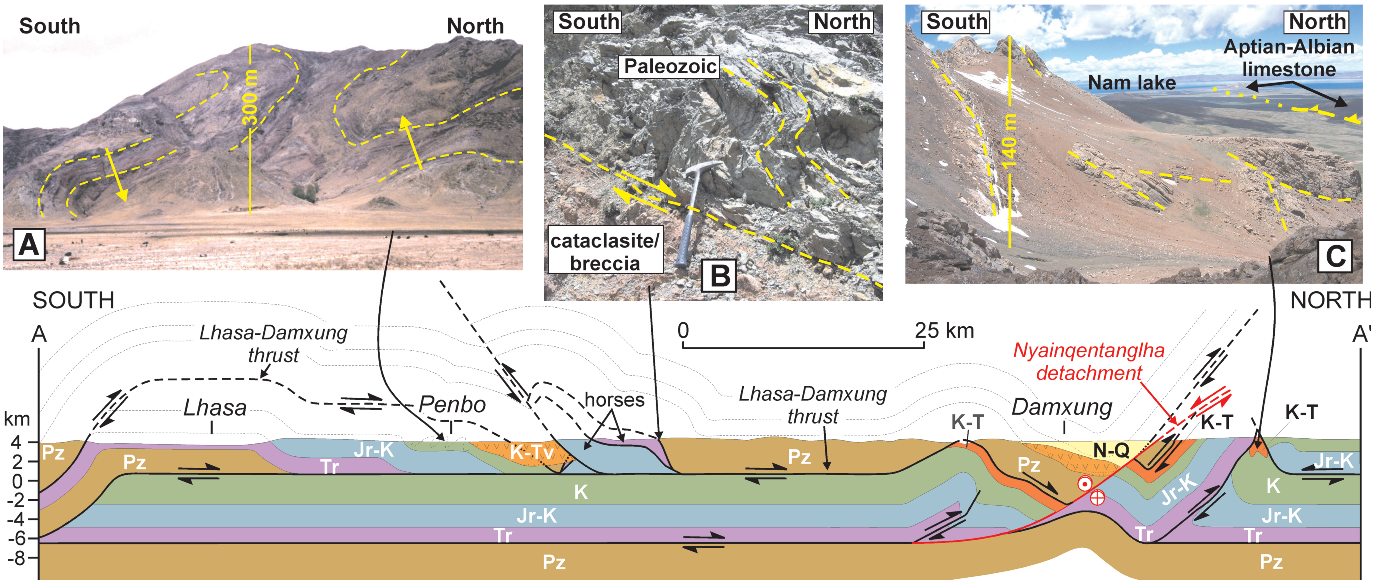

Figure 3. Cross section of the Lhasa region constructed from the simplified geological map and using unit abbreviations in Figure 2. For clarity, intrusive rocks are excluded. (A) Northward-verging folds in Cretaceous strata near Penbo. Arrows: stratigraphic facing direction. (B) Structurally highest N-dipping thrust fault north of Penbo. (C) Syncontractional, lower Eocene redbeds along the northern flank of the Nyainqentanglha Range.

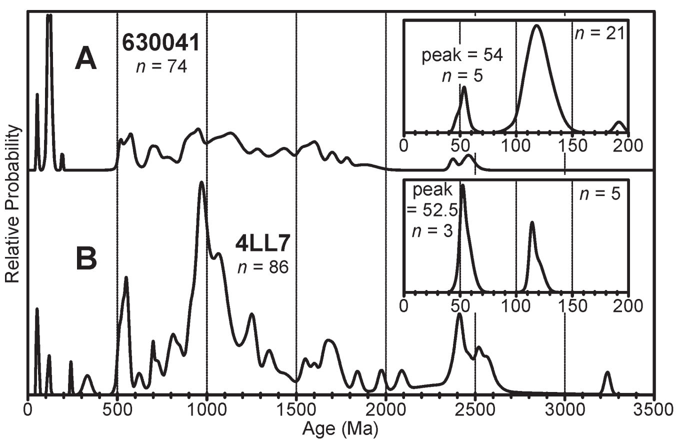

Figure 4. Relative probability detrital zircon age plots for (A) metaclastic sandstone and (B) redbeds within the Nyainqentanglha Range. The peak of the youngest age population of zircons provides a maximum depositional age and likely closely approximates the depositional age. Plotted ages are based on $^{206}Pb/^{238}U$ for grains <1000 Ma and $^{206}Pb/^{207}Pb$ for grains >1000 Ma. Spot analyses on individual zircon grains were made using a laser ablation, multicollector inductively coupled plasma mass spectrometer at the Arizona LaserChron Center. A tabulation of U-Pb data and a description of the analytical methods are provided in the GSA Data Repository (see text footnote 1).

Along the northern flank of the Nyainqentanglha Range, conglomeratic redbeds of previously inferred Cretaceous age are locally exposed in the footwall of a S-dipping thrust to the south and a N-dipping thrust to the north (Fig. 2). The conglomerates exhibit variable dips and intraformational unconformities (Fig. 3C), demonstrating that they are synkinematic, and are interpreted to have been deposited during slip on both the N- and S-directed faults (Fabijanic, 2005). These geological relations define a triangle zone, a structure common in the frontal parts of thrust belts (e.g., Jones, 1982; Vann et al., 1986). The depositional age of the redbeds, and hence the timing of contraction, is constrained by a U-Pb zircon date of 53 ± 2 Ma for an interbedded tuff layer (WP49A; Fig. 2) and the presence of detrital zircons of statistically indistinguishable age (4LL7; Figs. 2 and 4B). The GSA Data Repository[1] includes a description of the U-Pb analytical methods and a tabulation of the U-Pb data (Table DR1).

THE PROPOSED GANGDESE RETROARC THRUST BELT

A sequential restoration (Fig. 5) of the cross section of the Lhasa region (Fig. 3) shows that Late Cretaceous–Eocene contractional structures and clastic rocks in the Lhasa region formed in a northward directed and propagating retroarc thrust belt and foreland basin system. The largest displacement "Lhasa-Damxung thrust" carries Paleozoic strata in the hanging wall. This thrust (1) roots into the subsurface south of Lhasa, (2) was passively folded into an antiform between Lhasa and Penbo, (3) structurally overlies horses of Mesozoic strata north of Penbo, (4) has tectonic windows that expose footwall Cretaceous–lower Tertiary (?) redbeds between Penbo and Damxung, and (5) resurfaces in the Nyainqentanglha Range (Fig. 3). The youngest and most northward feature of the thrust belt is the lower Eocene triangle zone along the northern flank of the Nyainqentanglha Range (Fig. 3).

The kinematic history of the thrust belt during Takena deposition is unknown. At least 160 km of shortening is required to (1) account for the N-S length of Paleozoic strata carried in the hanging wall of the Lhasa-Damxung thrust, and (2) emplace underlying horses of Mesozoic strata (Fig. 5A). This shortening

[1]GSA Data Repository item 2007173, tabulation of U-Pb data and description of the analytical methods, is available at www.geosociety.org/pubs/ft2007.htm. You can also obtain a copy by writing to editing@geosociety.org.

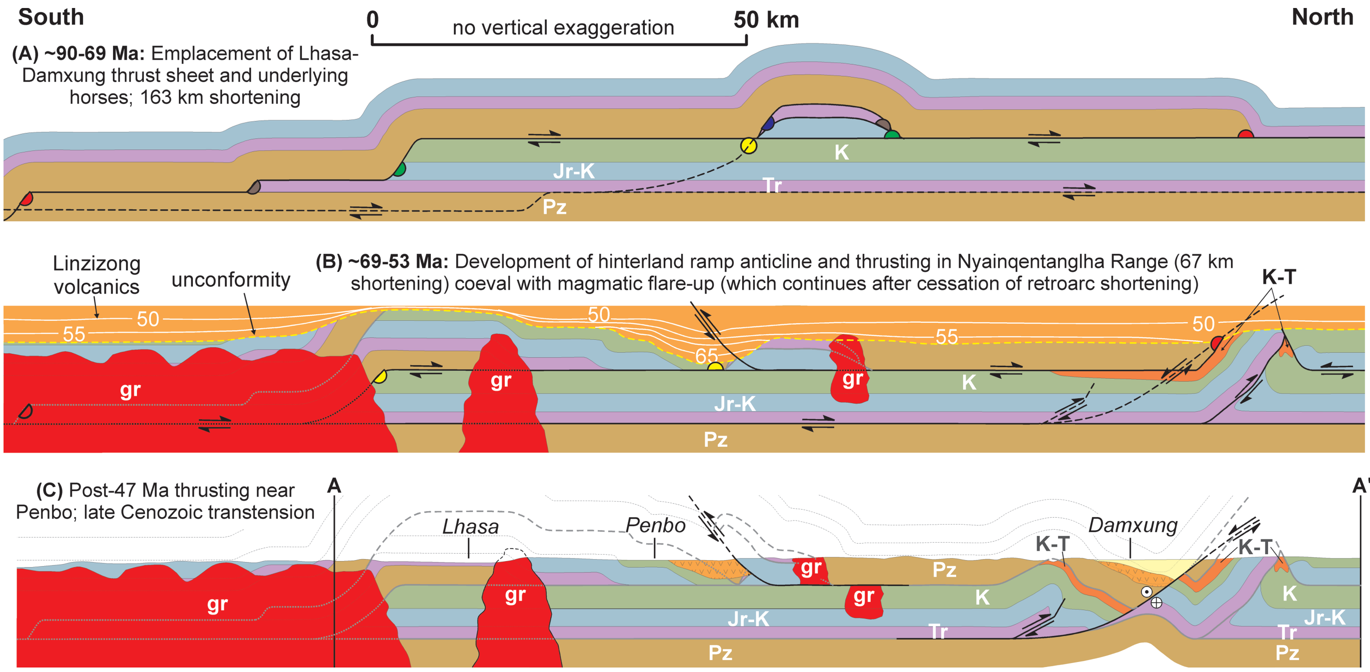

Figure 5. Proposed kinematic evolution of the Gangdese retroarc thrust belt. Unit abbreviations as in Figure 2. (A) Large magnitude and rapid N-directed shortening between ca. 90 and 69 Ma. (B) Development of hinterland ramp anticline during a phase of slower shortening rate. This deformation was coeval with the development of the basal Linzizong unconformity and widespread magmatism. White numbers and lines: speculated age distribution (in m.y.) of Linzizong volcanic rocks above the unconformity. (C) Present-day upper-crustal structure with cross-section lines from Figures 2 and 4.

occurred after deposition of the youngest Takena redbeds (ca. 90 Ma) and before the onset of Linzizong volcanism near Penbo ca. 69 Ma. The length of the horses shown is the minimum required to explain the map pattern (Fig. 2) and minimizes our shortening estimate; the horses could have extended much farther southward beneath the Lhasa-Damxung thrust, possibly even rooting into the structurally complex zone of metasedimentary rocks in the hanging wall of the Lhasa-Damxung thrust south of Lhasa (Fig. 2). The interpretation shown equates to a shortening rate of ~8 mm/yr, comparable to that estimated for the Andean thrust belt in Bolivia (5–10 mm/yr; e.g., McQuarrie, 2002).

There is no direct evidence for contraction between ca. 69 and ca. 53 Ma; however, during this time interval, arc magmatism swept northward (Fig. 6). This could have been due to shallowing of the subducting oceanic slab or shortening within the forearc; both scenarios are consistent with continued contraction. We suggest that between 69 and 53 Ma, slip along a S-dipping thrust in the hinterland produced a ramp anticline and passively folded the Lhasa-Damxung thrust (Fig. 5B). This slip, together with slip along a structurally lower décollement beneath Triassic strata, fed northward to thrusts that surfaced in the Nyainqentanglha Range.

A hinterland ramp anticline provides a simple explanation for the regional northward dip of Triassic–lower Tertiary strata in the Penbo region (Fig. 3). Growth of this anticline was coeval with deposition of the Linzizong Formation and should be recorded by lateral variations in the age and thickness of Linzizong strata (Fig. 5B). In fact, the oldest Linzizong volcanic rocks dated to the north of the anticline forelimb are 69–59 Ma, whereas those along the anticline crest in the Maqu area are ≤59 Ma (Fig. 2). Shortening during the 69–53 Ma time interval is estimated to be ~67 km (Fig. 5B), yielding an average shortening rate of ~4 mm/yr. More sophisticated interpretations to explain the structural relief in the hinterland will likely emerge; however, we assert that three conclusions are robust: (1) the structural culmination between Lhasa and Penbo grew in part coeval with Linzizong volcanism, (2) the magnitude and rates of shortening before 69 Ma were substantially greater than those after 69 Ma, and (3) the retroarc thrust

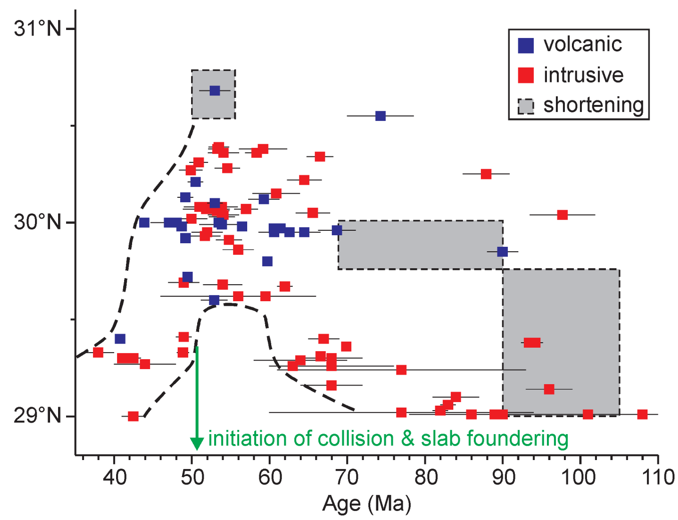

Figure 6. Temporal-spatial distribution of magmatism (from 85°E to 94°E) and documented shortening (Lhasa area) in the southern Lhasa terrane. The Indus-Yarlung suture is located at 29°N. Ages compiled from Maluski et al. (1982), Quidelleur et al. (1997), Harrison et al. (2000), and Wu et al. (2004), in addition to references cited in Figure 2 caption.

belt was not significantly disrupted during the Indo-Asian collision (Fig. 5C).

Remnants of the Gangdese retroarc thrust belt may be exposed over a distance of >1000 km along strike to the west of Lhasa. South of the town of Coqin (Fig. 1), Paleozoic strata are exposed in the hanging wall of a S-dipping thrust to the north and a N-dipping thrust to the south, both of which were active during the Cretaceous (Murphy et al., 1997). The Paleozoic strata were interpreted to core a pop-up structure between thrusts of opposing vergence. We favor an alternative interpretation in which the two faults form a single folded N-directed thrust that carries Paleozoic strata in the hanging wall (Fig. 1). This interpretation is consistent with the geology farther west near Shiquanhe (Fig. 1), where the Narangjiapo thrust emplaced Paleozoic strata northward over Cretaceous rocks during the Late Cretaceous (Fig. 1; Kapp et al., 2003).

DISCUSSION

Crowding and Removal of Lithosphere beneath the Gangdese Arc

By ca. 105 Ma, a Cordilleran-style margin was established in southern Tibet and, from south to north, included the Gangdese (Xigaze) forearc basin (e.g., Dürr, 1996), arc, and retroarc thrust belt and foreland basin system. Between 90 and 69 Ma, rapid (≥8 mm/yr) retroarc shortening resulted in southward underthrusting of a large volume of crust and mantle lithosphere beneath the arc (Fig. 7A). Crowding of lithosphere beneath the arc may have provided a resisting force to continued retroarc shortening, explaining the subsequent marked decrease in shortening rate. Between 69 and 62 Ma, ophiolites were obducted onto accretionary mélange within the Indus-Yarlung suture zone (Fig. 1), coeval with shortening and the development of an angular unconformity within the forearc (Fig. 7B; Ding et al., 2005). Ophiolite obduction required removal of upper plate mantle lithosphere. This could have occurred through tectonic erosion by the subducting slab and/or gravitational foundering of lithosphere beneath the arc (Fig. 7B). Concomitant upwelling of asthenosphere, in combination with partial melting of melt-fertile crust that was underthrust beneath the arc, can explain ignition of the 69 Ma and younger magmatic flare-up within the Gangdese arc (Fig. 7). Similar geodynamic processes have been invoked to explain correlations between the tempo of retroarc shortening and magmatism in the Cordillera of the western United Sates (e.g., Ducea, 2001; DeCelles, 2004).

Development of a "Lhasaplano"?

The proposed Gangdese retroarc thrust belt accommodated >230 km of shortening (>55%) in the Lhasa region. Crustal thickening and lithosphere removal in response to this shortening may have led to the development of a high-elevation "Lhasaplano" (Fig. 7B). The basal Linzizong unconformity is presently a gently dipping surface at similar elevations across much of the Lhasa terrane (Fig. 1), implying that a regional low-relief landscape was established prior to the Indo-Asian collision.

A major difference with an Andean-style margin is that the Gangdese retroarc thrust belt overlapped in age with the S-directed northern Lhasa terrane thrust belt to the north (Fig. 1; Murphy et al., 1997; Kapp et al., 2003, 2005b). Paleoaltimetric studies suggest that the northern Lhasa terrane achieved

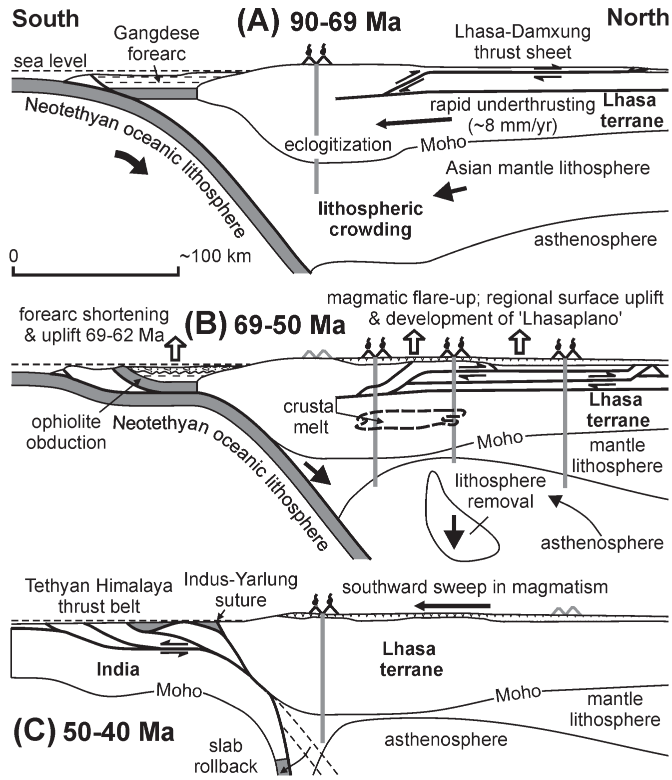

Figure 7. Proposed evolution of the Gangdese continental margin tectonic system. (A) Retroarc shortening results in underthrusting and crowding of lithosphere beneath the arc. (B) Shortening slows down in the retroarc region while it accelerates in the forearc region. Lithosphere removal beneath the arc ignites a magmatic flare-up. (C) India collides, the India-Asia convergence rate drops, the Neotethyan oceanic slab rolls back, and retroarc shortening ceases as shortening of Indian continental margin strata initiates in the Tethyan Himalaya.

near-modern elevations by the late Eocene (Rowley and Currie, 2006) and certainly no later than the late Oligocene (DeCelles et al., 2007). How much elevation was produced in this and other regions of Tibet by contractional tectonism prior to the Indo-Asian collision remains to be quantified.

Demise of Retroarc Shortening, Slab Rollback, and Collision

The cessation of major retroarc shortening at 50–55 Ma marked the initiation of a southward sweep in magmatism within the arc (Fig. 6) and Indo-Asian collision in south-central Tibet (e.g., Besse et al., 1984; Zhu et al., 2005). The magmatic sweep is interpreted to reflect rollback of the Neotethyan oceanic slab in response to a decrease in India-Asia convergence rate as the Indian continental margin entered the trench (Fig. 7C) (e.g., Patriat and Achache, 1984). Major upper crustal shortening during the early stages of collision was localized to the south in the Tethyan Himalaya (Fig. 7C; e.g., Ratschbacher et al., 1994) and to the north of the southern Qiangtang terrane (Fig. 1; e.g., Coward et al., 1988; Horton et al., 2002; Spurlin et al., 2005). The gravitational potential energy related to thick crust and high elevation in the Lhasa and southern Qiangtang terranes may, therefore, have been sufficient to inhibit major shortening in these areas and to focus contractional deformation along its lower elevation northern and southern margins (e.g., England and Searle, 1986).

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