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# Geometry and crustal shortening of the Himalayan fold-thrust belt, eastern and central Bhutan

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## ABSTRACT

We present a new geologic map of eastern and central Bhutan and four balanced cross sections through the Himalayan fold-thrust belt. Major structural features, from south to north, include: (1) a single thrust sheet of Subhimalayan rocks above the Main Frontal thrust; (2) the upper Lesser Himalayan duplex system, which repeats horses of the Neoproterozoic–Cambrian(?) Baxa Group below a roof thrust (Shumar thrust) carrying the Paleoproterozoic Daling-Shumar Group; (3) the lower Lesser Himalayan duplex system, which repeats horses of the Daling-Shumar Group and Neoproterozoic–Ordovician(?) Jaishidanda Formation, with the Main Central thrust (MCT) acting as the roof thrust; (4) the structurally lower Greater Himalayan section above the MCT with overlying Tethyan Himalayan rock in stratigraphic contact in central Bhutan and structural contact above the South Tibetan detachment in eastern Bhutan; and (5) the structurally higher Greater Himalayan section above the Kakhtang thrust. Cross sections show 164–267 km shortening in Subhimalayan and Lesser Himalayan rocks, 97–156 km structural overlap across the MCT, and 31–53 km structural overlap across the Kakhtang thrust, indicating a total of 344–405 km of minimum crustal shortening (70%–75%). Our data show an eastward continuation of Lesser Himalayan duplexing identified in northwest India, Nepal, and Sikkim, which passively folded the overlying Greater Himalayan and Tethyan Himalayan sections. Shortening and percent shortening estimates across the orogen, although minima, do not show an overall eastward increase, which may suggest that shortening variations are controlled more by the original width and geometry of the margin than by external parameters such as erosion and convergence rates.

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## INTRODUCTION

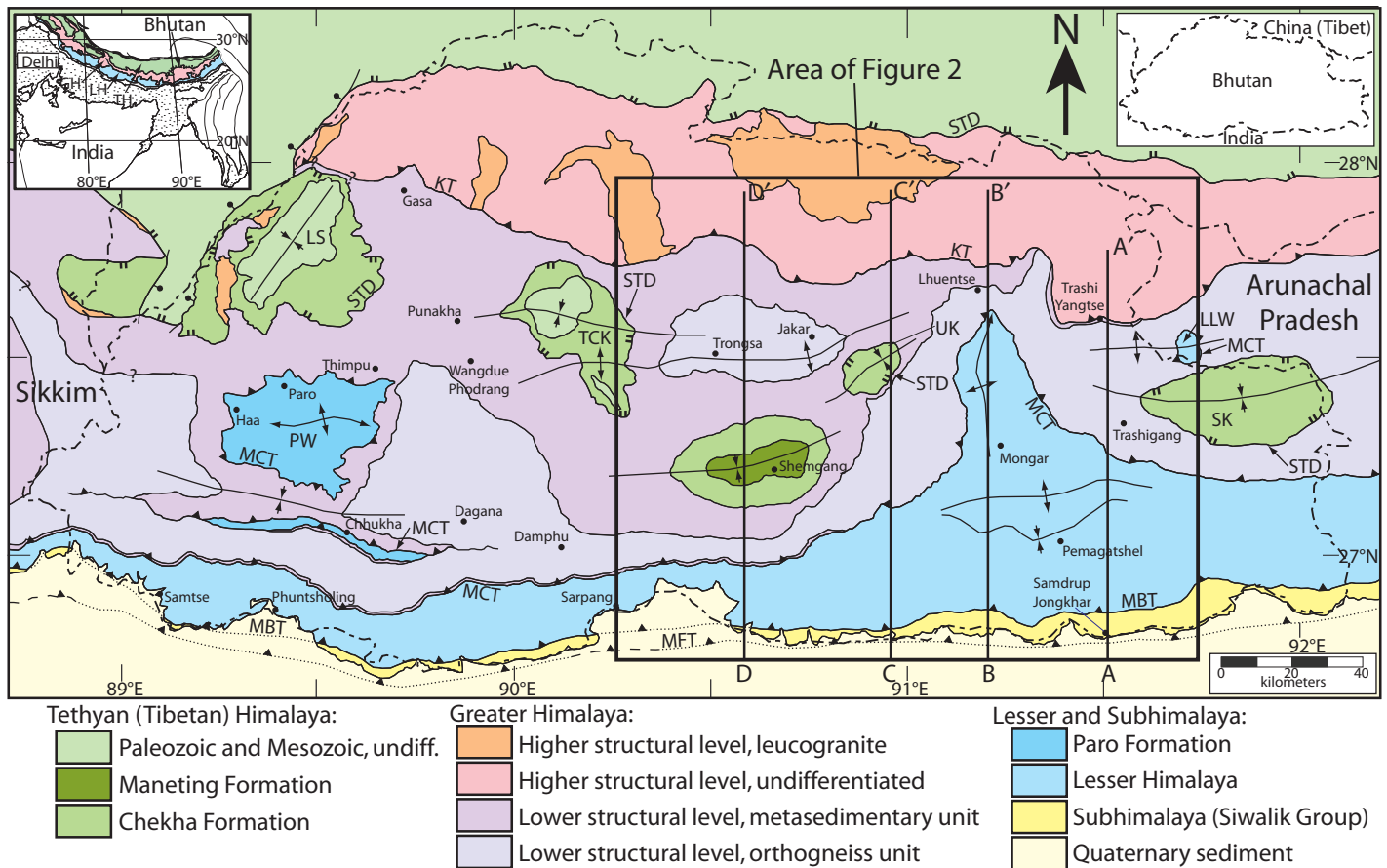
Collision between the Indian and Eurasian plates, which started in the Eocene (Yin and Harrison, 2000; Leech et al., 2005; Guillot et al., 2008) and continues today, produced the Tibetan-Himalayan orogenic system, our best example of modern continent-continent collision. Global positioning system (GPS) motion rates and neotectonic deformation rates show that approximately one-half (~20 mm/yr) of the convergence between these two plates may be accommodated through crustal shortening in the Himalayan fold-thrust belt (DeMets et al., 1994; Bilham et al., 1997; Larson et al., 1999; Lave and Avouac, 2000; Mugnier et al., 2003). This contraction of the northern Indian margin is accommodated by a series of south-vergent thrust faults, which detach and repeat the Proterozoic to Paleocene sedimentary cover (Gansser, 1964; Powell and Conaghan, 1973; LeFort, 1975; Mattauer, 1986; Hauck et al., 1998; Hodges, 2000; DeCelles et al., 2002; Murphy and Yin, 2003; Yin, 2006; Yin et al., 2010).

Determining the range of shortening magnitudes along the length of the Himalayan fold-thrust belt is essential for testing predictions of how convergence is accommodated throughout the orogen, and for estimating the budget of crustal material into the orogenic system. Predictions of first-order shortening variations along-strike include: (1) shortening and percent shortening should increase from west to east, as a result of postcollisional, counterclockwise rotation of India (Patriat and Achache, 1984; Dewey et al., 1989) or an eastward increase in convergence rates (Guillot et al., 1999) and erosion rates (Grujic et al., 2006; Yin et al., 2006); (2) shortening magnitude should mimic the width of the Tibetan Plateau measured in an arc-normal direction (DeCelles et al., 2002), or (3) shortening should be the greatest at the center of the orogen and decrease to the east and west (classic “bow-and-arrow” model of Elliott [1976]). To date, several studies have estimated Himalayan shortening with regional-

scale balanced cross sections. The majority of shortening estimates come from the central and western portions of the orogen, in Pakistan, northwest India, and central and western Nepal (Coward and Butler, 1985; Srivastava and Mitra, 1994; DeCelles et al., 1998, 2001; Robinson et al., 2006), where much of the previous work on Himalayan stratigraphy and structure has been focused (e.g., Srivastava and Mitra, 1994; Hodges et al., 1996; Upreti, 1996; Vannay and Hodges, 2003; Searle et al., 1997; DeCelles et al., 2000, 2001; Vannay and Grasmann, 2001; Richards et al., 2005; Robinson et al., 2006). These shortening estimates range between ~400 and 900 km (DeCelles et al., 2002; Robinson et al., 2006) and show a systematic increase from the western syntaxis to the midpoint of the Himalayan arc.

However, comparable shortening estimates for the eastern quarter of the Himalayan orogen are either lacking in key areas or based on preliminary efforts. The eastern Himalaya occupies a key position along the arc for testing the predictions of systematic shortening variation listed above, giving shortening estimates here a greater impact. However, in Sikkim, Bhutan, and Arunachal Pradesh (Fig. 1), accessibility for field research has only come recently, and minimal geologic mapping and stratigraphic data are available, particularly for the frontal Lesser Himalayan portion of the fold-thrust belt (e.g., Acharyya, 1980; Raina and Srivastava, 1980; Gansser, 1983; Bhargava, 1995; Kumar, 1997; Yin et al., 2006), inhibiting a rigorous evaluation of fold-thrust belt geometry. As a result, only preliminary studies illustrating geometry and estimating shortening are available from Sikkim (Mitra et al., 2010), Bhutan (McQuarrie et al., 2008), and Arunachal Pradesh (Yin et al., 2010).

In Bhutan (Fig. 1), most recent work has focused on determining the metamorphic and deformational history of the Greater Himalayan section, above the Main Central thrust (MCT) (Swapp and Hollister, 1991; Grujic et al., 1996, 2002; Davidson et al., 1997; Daniel et al., 2003; Hollister and Grujic, 2006; Long and McQuarrie,



**Figure 1.** Simplified geologic map of Bhutan and surrounding region, after Gansser (1983), Bhargava (1995), Grujic et al. (2002), and our own mapping. Locations of the four tectonostratigraphic zones shown, along with bounding structures. Area of detailed geologic map (Fig. 2) outlined, along with locations of lines of section for four balanced cross sections (Fig. 3). Upper left inset shows generalized geologic map of central and eastern Himalayan orogen (modified from Gansser, 1983). Structural detail left out of Tethyan Himalayan section north of Bhutan; map patterns of NE-striking, crosscutting normal faults northwest of Lingshi syncline (Yadong cross structure on fig. 1 of Grujic et al. [2002]) are simplified. Abbreviations: (1) inset: GH—Greater Himalaya; LH—Lesser Himalaya; TH—Tethyan Himalaya; (2) structures from north to south: STD—South Tibetan detachment; KT—Kakhtang thrust; MCT—Main Central thrust; MBT—Main Boundary thrust; MFT—Main Frontal thrust; (3) windows and klippen from west to east: LS—Lingshi syncline; PW—Paro window; TCK—Tang Chu klippe; UK—Ura klippe; SK—Sakteng klippe; LLW—Lum La window (location from Yin et al., 2009).

2010). However, recent studies that present new geologic mapping between the MCT and Main Frontal thrust (MFT) in eastern Bhutan, and an extensive U-Pb detrital zircon data set (McQuarrie et al., 2008; Long et al., 2010), have built a detailed stratigraphy for Subhimalayan and Lesser Himalayan rocks. The combined results of these foreland- and hinterland-focused studies facilitate, for the first time in Bhutan, a detailed study focused on the geometry, kinematics, and shortening of the Bhutan fold-thrust belt.

The main objective of this paper is to provide accurate estimates of shortening through the Himalayan fold-thrust belt in Bhutan. To accomplish this, we introduce a new, detailed geologic map of eastern and central Bhutan, based on mapping carried out in three separate field seasons, and four regional-scale, deformed and

retrodeformed, balanced cross sections, which illustrate the geometry of the fold-thrust belt, and provide minimum shortening estimates. These new shortening estimates fill a significant data gap for the eastern Himalaya, and allow for the first along-strike comparison of shortening estimates across the full length of the orogen. The second objective of this paper is to present an updated compilation of shortening and percent shortening estimates along the Himalayan arc, in order to test the predictions listed above of systematic variation along the orogen.

### GEOLOGIC BACKGROUND

Heim and Gansser (1939) and Gansser (1964) originally divided the Himalayan fold-thrust belt into four tectonostratigraphic zones

(Fig. 1), which represent distinct structural packages that have been imbricated and thrust to the south since the collision of India and Asia (e.g., Gansser, 1964; Powell and Conaghan, 1973; LeFort, 1975; Mattauer, 1986; Hodges, 2000; DeCelles et al., 2002; Murphy and Yin, 2003; Yin, 2006). From south to north, these are the Subhimalayan, Lesser Himalayan, Greater Himalayan, and Tethyan (or Tibetan) Himalayan zones. The Subhimalayan zone represents synorogenic rocks, and the Lesser Himalayan, Greater Himalayan, and Tethyan Himalayan zones represent packages of pre-Himalayan sedimentary and igneous rocks of Greater India.

The Lesser Himalayan zone consists of clastic and carbonate sedimentary rocks originally deposited on the northern margin of the Indian craton (Gansser, 1964; Schelling and Arita,

1991; Upreti, 1999; Yin, 2006). The Lesser Himalayan zone contains units as old as Paleoproterozoic (Parrish and Hodges, 1996; Upreti, 1999; DeCelles et al., 2000; Richards et al., 2005; McQuarrie et al., 2008; Long et al., 2010) that are exposed across the entire orogen (Kohn et al., 2010). Younger Lesser Himalayan strata include Mesoproterozoic rocks local to Nepal (Martin et al., 2005; Robinson et al., 2006), Neoproterozoic to Cambrian and locally Ordovician rocks in northwest India, Nepal, Sikkim, Bhutan, and Arunachal Pradesh (Valdiya, 1995; Myrow et al., 2003; Hughes et al., 2005; Richards et al., 2005; Shukla et al., 2006; McQuarrie et al., 2008; Schopf et al., 2008; Long et al., 2010) and Permian rocks across most of the length of the orogen (Brookfield, 1993; DeCelles et al., 2001; Najman et al., 2006; Robinson et al., 2006; Yin, 2006; Long et al., 2010). During Himalayan orogenesis, much of the Lesser Himalayan section was metamorphosed to greenschist facies (Gansser, 1964; Schelling and Arita, 1991; Robinson et al., 2003), and Lesser Himalayan rocks were internally deformed and thrust southward over the Subhimalayan zone across the Main Boundary thrust (MBT) (Gansser, 1964).

The Greater Himalayan zone consists of upper amphibolite facies (Gansser, 1964; LeFort, 1975; Harrison et al., 1997) metaigneous and metasedimentary rocks, and synorogenic intrusive igneous rocks, which structurally overlie the Lesser Himalayan zone across the Main Central thrust (MCT) (Heim and Gansser, 1939; Gansser, 1964). Sedimentary protoliths of Greater Himalayan metamorphic rocks range between Neoproterozoic and early Paleozoic in age (Parrish and Hodges, 1996; DeCelles et al., 2000; Gehrels et al., 2003; Martin et al., 2005; Myrow et al., 2009; Long and McQuarrie, 2010), and Cambrian–Ordovician orthogneiss units are present in the Greater Himalayan section throughout the orogen (Stocklin and Bhattarai, 1977; Stocklin, 1980; Parrish and Hodges, 1996; DeCelles et al., 2000; Gehrels et al., 2003; Martin et al., 2005; Cawood et al., 2007; Long and McQuarrie, 2010). Evidence for widespread Cambrian–Ordovician metamorphism and igneous activity has been interpreted as early Paleozoic orogenic activity that affected the Greater Himalayan section (DeCelles et al., 2000; Gehrels et al., 2003; Cawood et al., 2007). Since the contact between the Greater Himalayan and Lesser Himalayan sections is always the MCT, the original paleogeographic relationship between these two tectonostratigraphic zones is in question.

The Tethyan Himalayan zone consists of Neoproterozoic to Eocene sedimentary rocks that in most places sit structurally above the

Greater Himalayan zone across a top-to-the-north–sense shear zone and/or one or multiple top-to-the-north–sense detachment faults called the South Tibetan detachment system (Burg, 1983; Burchfiel et al., 1992). However, several studies throughout the Himalaya have interpreted a stratigraphic contact at the base of the Tethyan Himalayan section, where these rocks are preserved above lower-grade Greater Himalayan rocks in the frontal, southern portions of the orogen (Stocklin, 1980; Gehrels et al., 2003; Robinson et al., 2003; Long and McQuarrie, 2010). Stratigraphic evidence for Cambrian–Ordovician uplift, exhumation, and coarse-clastic deposition in northwest India and Nepal (Gehrels et al., 2003, and references therein) indicates that early Paleozoic orogenic activity also affected the Tethyan Himalayan section. This tectonic activity was succeeded by a passive margin setting on northern Greater India, represented by an Ordovician to Carboniferous shelf sequence that accumulated on the southern margin of the Paleotethys Ocean (Gaetani and Garzanti, 1991; Brookfield, 1993; Garzanti, 1999), and a Permian to Mesozoic passive margin sequence that accumulated on the southern margin of the Neotethys Ocean, which postdates the late Paleozoic breakup of Greater India and the northward migration of crustal fragments toward Asia (Yin and Harrison, 2000). South-vergent deformation of the Tethyan Himalayan zone commenced during the Eocene with the initiation of northward subduction of the Indian plate under Asia (Powell and Conaghan, 1973; Coward and Butler, 1985; Mattauer, 1986; Ratschbacher et al., 1994; Yin and Harrison, 2000; Ding et al., 2005; Leech et al., 2005; Aikman et al., 2008; Guillot et al., 2008).

The Subhimalayan zone consists of the Miocene to Pliocene Siwalik Group (Gansser, 1964; Tukuoka et al., 1986; Harrison et al., 1993; Quade et al., 1995; Burbank et al., 1996; DeCelles et al., 1998, 2001, 2004; Ojha et al., 2000; Huyghe et al., 2005; Robinson et al., 2006), and represents foreland basin deposits shed off of the actively growing Himalayan orogen. The Siwaliks are bound at their base by the MFT, which coincides with the present Himalayan topographic front, and bound at their top by the MBT. South of the MFT, modern Himalayan foreland basin sediments onlap onto cratonic rocks of northern India. While synorogenic units as old as Eocene have been recognized in Nepal, northwest India, and Arunachal Pradesh, they are structurally above the MBT and are mapped as part of the Lesser Himalayan zone (Acharyya, 1980; DeCelles et al., 1998, 2001, 2004; Richards et al., 2005; Robinson et al., 2006; Yin et al., 2006, 2009).

## MAPPING METHODS

This study presents new geologic mapping, which was undertaken in the field at a scale of 1:50,000, and is shown at 1:250,000 on Figure 2<sup>1</sup>. Mapping was focused between the MFT and the Kakhtang thrust. Map data from the structurally higher Greater Himalayan section above the Kakhtang thrust are projected from the geologic maps of Gansser (1983), Gokul (1983), and Bhargava (1995) (Fig. 2 [see footnote 1]). Map data were collected in four ~100-km-long, north-south traverses (Fig. 2), which provide data for four balanced cross sections (Fig. 3 [see footnote 1]). The four traverses, listed from east to west, are: (1) along roads south and north of the town of Trashigang; (2) along the Kuru Chu (note: chu means river), which was along roads north of 27°10'N and trails south of this latitude; (3) between the Kuru Chu and Bhumtang Chu, along a road between 27°40'N and 27°20'N, and along a trail that meets the Manas Chu at its southern end; and (4) on roads, north and south of the town of Trongsa, which pass through the town of Shemgang, and end in the south at the town of Geylegphug. Map data from these traverses were projected onto the Trashigang (A–A'), Kuru Chu (B–B'), Bhumtang Chu (C–C'), and Mangde Chu (D–D') cross sections, respectively (Fig. 3).

In addition, we collected map data in two along-strike transects, one on a trail between the Kuru Chu and the town of Pemagatshel, and another on the road connecting the towns of Trashigang, Mongar, Ura, Jakar, and Trongsa (Figs. 1 and 2). Our mapping was integrated with published geologic maps of Bhutan (Gansser, 1983; Gokul, 1983; Bhargava, 1995; Grujic et al., 2002), to help trace contacts and structures between traverses (see Fig. 2 caption).

The level of rock exposure in eastern Bhutan varies significantly with elevation and the presence or absence of road or trail cuts. In general, south of ~27°00'N, lower elevations and wetter climates resulted in much heavier vegetation cover, and discontinuous exposures of ~5- to 20-m-thick sections spaced apart ~250–500 m on average. Two exceptions to this were on the road north of Samdrup Jongkhar and the road north of Geylegphug, where roadcuts permitted exposures spaced every ~100–200 m. In general, north of 27°00'N, vegetation cover was much more sparse, and exposures were more closely spaced (~100–200 m).

<sup>1</sup>Figures 2 and 3 are on a separate sheet accompanying this issue.

**BHUTAN TECTONOSTRATIGRAPHY**

**Subhimalayan Zone**

The Siwalik Group coarsens upward from siltstone and claystone to sandstone and conglomerate, and has been divided into lower, middle, and upper members (Nautiyal et al., 1964; Jangpangi, 1974; Gansser, 1983; Lakshminarayana and Singh, 1995; McQuarrie et al., 2008; Long et al., 2010). Near Samdrup Jongkhar (Figs. 1 and 2), all three members are exposed, with a combined thickness of 5.6 km (Long et al., 2010) (Fig. 4). Along the Manas Chu (Fig. 2), only the lower and middle members are exposed, with a total thickness of 2.3 km.

**Lesser Himalayan Zone**

In eastern and central Bhutan, the Lesser Himalayan zone consists of six map units, with a combined thickness between 8 and 19 km (Fig. 4). Lesser Himalayan units can be divided into two stratigraphic successions: (1) the Paleoproterozoic lower Lesser Himalayan section, and (2) the Neoproterozoic–Paleozoic upper Lesser Himalayan section. Stratigraphy and deposition age constraints of Lesser Himalayan map units in Bhutan are discussed in detail in Long et al. (2010).

**Lower Lesser Himalayan Section**

The lower Lesser Himalayan section consists of the Paleoproterozoic Daling-Shumar Group, which displays a consistent two-part stratigraphy of quartzite of the Shumar Formation below schist, phyllite, and quartzite of the Daling Formation (McQuarrie et al., 2008; Long et al., 2010). Both units are metamorphosed to lower greenschist facies (Gansser, 1983). The lower contact is always the Shumar thrust, which places the Daling-Shumar Group over the Baxa Group (Ray et al., 1989; Ray, 1995; McQuarrie et al., 2008). The upper contact is an unconformity with the Jaishidanda Formation (Long et al., 2010). An upper stratigraphic contact with the Baxa Group is not observed, although this contact is documented in Sikkim (Bhattacharyya and Mitra, 2009; Mitra et al., 2010).

The Shumar Formation consists of thick-bedded quartzite, with schist and phyllite interbeds. The Shumar Formation is generally 1–2 km thick, but a 6-km-thick section is local to the Kuru Chu valley (Long et al., 2010). The Daling Formation overlies the Shumar Formation across a gradational contact, consists of green phyllite and schist with quartzite interbeds, and is 2.2–3.2 km thick. Granitic orthogneiss bodies are observed in variable stratigraphic

**Figure 4. Column showing tectonostratigraphy of central and eastern Bhutan. The four Himalayan tectonostratigraphic zones and positions of major bounding structures are shown. Lesser Himalayan unit ages from McQuarrie et al. (2008) and Long et al. (2010), unit ages for structurally lower Greater Himalayan section and Tethyan Himalayan units below Kakhtang thrust from Long and McQuarrie (2010), unit age range for Tethyan Himalayan units above Kakhtang thrust from Gansser (1983). Unit thickness range in km shown on right-hand side, from this study, McQuarrie et al. (2008), and Long et al. (2010), or as cited. See Figure 1 for structure abbreviations.**

Tethyan Himalaya	Undifferentiated - sedimentary rocks (Neoproterozoic–Mesozoic)		~7–13 (Hauck et al., 1998; Lin et al., 1989)
	<b>STD</b> ↙		
Greater Himalaya (structurally higher)	Undifferentiated - orthogneiss - metasedimentary rocks - leucogranite (Miocene)		>13
<b>KT</b> ↘			
Tethyan Himalaya	Maneting Fm. (Ordovician[?])		>1.0
	Chekha Fm. (age uncertain; Neoproterozoic to Ordovician[?]) <b>depositional or STD</b> ↙		2.2–4.0
Greater Himalaya (structurally lower)	Metasedimentary unit (Neoproterozoic–Ordovician[?])		0.5–6.7
	Orthogneiss unit (Cambrian–Ordovician) <b>MCT</b> ↘		1.5–8.0
<b>Total: 5.3–10.5 km</b>			
Lesser Himalaya	lower LH units Daling-Shumar Gp.	Jaishidanda Fm. (Neoproterozoic–Ordovician[?])	0.5–1.7
		Daling Fm. (Paleoproterozoic)	1.8–3.2
		Shumar Fm. (Paleoproterozoic) <b>ST</b> ↘	1.0–6.0
	upper LH units	Gondwana succession (Permian)	0.5–2.5
		Diuri Fm. (Permian)	2.4–3.0
	Baxa Gp. (Neoproterozoic–Cambrian[?]) <b>MBT</b> ↘	1.5–2.6	
Subhimalaya (Siwalik Gp)	upper member	(Miocene-Pliocene) undiff. 2.3–6.7 km <b>MFT</b> ↘	1.5
	middle member		1.0–1.3
	lower member		1.3–2.8

positions within the Daling-Shumar Group (Fig. 2). Based on intrusive contact relationships, the orthogneiss bodies are interpreted as granite intrusions originally emplaced in the Daling-Shumar Group (Long et al., 2010).

#### Upper Lesser Himalayan Section

The Neoproterozoic–Paleozoic upper Lesser Himalayan section consists of the four map units, the Baxa Group, Jaishidanda Formation, Diuri Formation, and Gondwana succession (Fig. 4).

The Neoproterozoic–Cambrian(?) Baxa Group consists of coarse-grained to conglomeratic quartzite, with common lenticular bedding and trough cross-bedding, interbedded with dark-gray phyllite and dolomite (McQuarrie et al., 2008; Long et al., 2010). Upper stratigraphic contacts with the Gondwana succession and Diuri Formation are observed on the Manas Chu and Kuru Chu transects, respectively (Fig. 2). The Baxa Group is 1.5–2.6 km thick (Along-Strike Variability of Lesser Himalayan Duplexing section).

The Neoproterozoic–Ordovician(?) Jaishidanda Formation unconformably overlies the Daling-Shumar Group under the MCT, and is not exposed within the upper Lesser Himalayan section below the Shumar thrust (Figs. 2 and 4) (Long et al., 2000; Bhargava, 1995). The Jaishidanda Formation consists of biotite-rich, locally garnet-bearing schist interbedded with biotite-rich quartzite, and ranges in thickness from 500 to 1700 m.

The Diuri Formation consists of pebble-clast diamictite (Jangpangi, 1974; Gansser, 1983; Tangri, 1995; McQuarrie et al., 2008; Long et al., 2010). The Diuri Formation is in stratigraphic contact above the Baxa Group in the southern Kuru Chu valley (Fig. 2), but all other contacts are tectonic. The Diuri Formation is 2.4–3.0 km thick, and pinches out east of the Manas Chu (Fig. 2). A ca. 390 Ma youngest detrital zircon (DZ) peak indicates a Devonian maximum deposition age (Long et al., 2010).

The Gondwana succession consists of sandstone, carbonaceous siltstone and shale, and coal (Gansser, 1983; Joshi, 1995; Lakshminarayana, 1995; McQuarrie et al., 2008; Long et al., 2010). The unit is 1.2–2.5 km thick in southeast Bhutan (Long et al., 2010), and a 500-m-thick section is exposed along the Manas Chu, in stratigraphic contact above the Baxa Group (Fig. 2). The Gondwana succession yields Permian fossils (Joshi, 1989, 1995; Lakshminarayana, 1995).

#### Greater Himalaya

The Greater Himalayan zone is divided into a lower structural level above the MCT and below the Kakhtang thrust, and a higher structural

level above the Kakhtang thrust and below the South Tibetan detachment (Figs. 1, 2, and 4) (Gansser, 1983; Grujic et al., 2002). The structurally higher section is at least 13 km thick, and consists of migmatitic orthogneiss and metasedimentary rocks and Miocene leucogranite (Figs. 2 and 4) (Gansser, 1983; Swapp and Hollister, 1991; Davidson et al., 1997; Grujic et al., 2002).

The structurally lower Greater Himalayan section consists of a lower orthogneiss unit and an upper metasedimentary unit (Long and McQuarrie, 2010) (Figs. 1 and 2). Together they are between 5.3 and 10.5 km thick (Figs. 3 and 4). In eastern Bhutan, both units display partial melt textures (granite-composition leucosomes) throughout the entire section (Grujic et al., 1996, 2002; Davidson et al., 1997; Daniel et al., 2003). However, south of Shemgang in central Bhutan (Figs. 1 and 2), beneath an erosional remnant of Tethyan Himalayan rocks, partial melt textures are only observed within the lower part of the orthogneiss unit, and much of the Greater Himalayan section was deformed at temperatures between ~450° and 500 °C (Long and McQuarrie, 2010). Throughout Bhutan, Greater Himalayan rocks just above the MCT are distinguished from Lesser Himalayan rocks below by the presence of kyanite, sillimanite, and granitic leucosomes (Grujic et al., 2002; Daniel et al., 2003; Long and McQuarrie, 2010).

The Greater Himalayan orthogneiss unit is 1.5–8.0 km thick, and consists of granitic orthogneiss with metasedimentary intervals <200 m thick. The Greater Himalayan metasedimentary unit is 0.5–6.7 km thick, and consists of quartzite, schist, and paragneiss. Circa 500 and 460 Ma youngest detrital zircon (DZ) peaks obtained from Greater Himalayan quartzite near Shemgang indicate that much of the Greater Himalayan metasedimentary unit in central Bhutan can only be as old as Cambrian–Ordovician (Long and McQuarrie, 2010). A ca. 900 Ma youngest DZ peak obtained from Greater Himalayan quartzite near Lhuentse (Figs. 1 and 2) indicates a Neoproterozoic lower deposition age for part of the section (Long and McQuarrie, 2010).

#### Tethyan Himalaya

Five isolated exposures of Tethyan Himalayan metasedimentary rocks are mapped on top of Greater Himalayan rocks in the axes of synclines (Fig. 1) (Gansser, 1983; Bhargava, 1995; Kellett et al., 2009). The two westernmost exposures contain Paleozoic to Mesozoic rocks above a basal quartzite unit called the Chekha Formation (Gansser, 1983; Bhargava, 1995; Tangri and Pande, 1995). The Chekha Formation lacks fossils, and is mapped stratigraphi-

cally below fossiliferous Cambrian units in the Tang Chu exposure (Bhargava, 1995; Tangri and Pande, 1995; Myrow, 2005; McKenzie et al., 2007), which has led to an inferred Neoproterozoic deposition age.

The three Tethyan Himalayan exposures in central and eastern Bhutan (Shemgang, Ura, and Sakteng) contain the Chekha Formation, and the Shemgang exposure contains the overlying Maneting Formation (Figs. 1 and 2). The Chekha Formation is 2.2–4.0 km thick (Figs. 3 and 4), and consists of thick-bedded, locally conglomeratic quartzite interbedded with biotite-muscovite-garnet schist. The Maneting Formation is at least 1.0 km thick, and consists of graphitic, biotite-garnet phyllite (Tangri and Pande, 1995; Long and McQuarrie, 2010). A ca. 460 Ma youngest DZ peak obtained from Chekha quartzite near Shemgang indicates an Ordovician maximum deposition age (Long and McQuarrie, 2010), and suggests along-strike variation in the age of the oldest Tethyan Himalayan strata. Differing age estimates between west-central and central Bhutan could indicate either: (1) structural complication that has telescoped the Tethyan Himalayan section, or (2) discrepancies in Tethyan Himalayan stratigraphy as currently defined, which have given the same name (Chekha Formation) and stratigraphic description to both Precambrian and Ordovician (or younger) quartzite.

Four of the five erosional remnants of Tethyan Himalayan rock have been interpreted as klippen above the South Tibetan detachment (Grujic et al., 2002). However, because no field observations were available at that time, a fault contact at the base of the Shemgang exposure was queried on the map of Grujic et al. (2002). Recent mapping in the Shemgang region indicates that the Chekha Formation is in interfingering depositional contact above the Greater Himalayan metasedimentary unit (Long and McQuarrie, 2010), similar to original mapping by Gansser (1983) and Bhargava (1995) (Figs. 1 and 2).

## BALANCED CROSS SECTIONS

### Methods

Four balanced cross sections were constructed based on field data projected from four north-south traverses (Figs. 2 and 3). From east to west, these are the Trashigang (A–A'), Kuru Chu (B–B'), Bhumtang Chu (C–C'), and Mangde Chu (D–D') cross sections. Deformed sections are shown at 1:300,000 scale, and restored sections are shown at 1:600,000 scale on Figure 3 (note different scale than Fig. 2). The lines of section are oriented N-S, which is parallel to the principal direction of Himalayan shortening

in Bhutan, as indicated by the regional strike of structures and N- and S-trending mineral stretching lineation (Fig. 5, stereonet O). Cross sections are constrained by surface data and earthquake seismology (Ni and Barazangi, 1984; Pandey et al., 1999; Mitra et al., 2005; Schulte-Pelkum et al., 2005) and seismic-reflection constraints (Hauck et al., 1998) that suggest an average dip of 4°N for the basal décollement, the Main Himalayan thrust (Fig. 3, #I).

Line lengths of thrust sheets measured on deformed sections were matched on restored sections (e.g., Dahlstrom, 1969). Apparent dips were calculated from surface data and projected along-strike to their position on the cross section. The orientations of fold axial planes were determined by bisecting the interlimb angle at fold hinges, and most axial planes were modeled as kink surfaces (e.g., Suppe, 1983). Areas of cross sections were divided into dip domains, based on the average apparent dips of surface data, and dividing lines between adjacent dip domains were also treated as kink-type fold hinges. No attempt was made to incorporate outcrop and smaller-scale folding, or to account for ductile deformation in Greater Himalayan rocks.

The main unknowns in the balancing process are the positions of hanging-wall cutoffs of Subhimalayan, Lesser Himalayan, and Greater Himalayan units that have passed through the erosion surface. We used conservative geometries that minimize shortening in all cases, which involved placing hanging-wall cutoffs just above the erosion surface in the case of Subhimalayan and most Lesser Himalayan units, or just beyond a unit's southernmost exposure in the case of the structurally lower Greater Himalayan section. At the north end of the restored sections, we interpret that the northernmost footwall ramp through the Daling-Shumar Group marks the northern extent of Lesser Himalayan units and the permissible southern extent of the lower Greater Himalayan section (Fig. 3, #XIV). Justifications for individual decisions on all cross sections are annotated on Figure 3.

## Structural Zones

### Main Frontal Thrust Sheet

The map pattern of the Siwalik Group varies significantly from east to west, from an ~8 km N-S exposure in southeast Bhutan, to an ~4 km N-S exposure at and west of the Manas Chu, and no exposure near Geylegphug (Fig. 2). The southern contact of the Siwaliks with Quaternary sediment, which covers the MFT, was drawn at the slope break between the foothills and the flat Brahmaputra plain. The location of the MFT is interpreted just to the south of

this slope break, except where located by offset terraces near Geylegphug (Gansser, 1983) (Fig. 2). In general, the Siwalik Group exhibits dips averaging between 35° and 50°N. We observed no structural repetition of the three-part Siwalik Group stratigraphy, and thus interpret the Subhimalayan zone as one thrust sheet, uplifted along the MFT (Fig. 3). The thickness of this thrust sheet varies between 2.3 and 6.7 km, and thins from east to west, in accord with the westward-narrowing map pattern. A lack of southward dips at the southern end of Siwalik Group exposures indicates that the hanging-wall cutoff has passed through the erosion surface on all four sections (Fig. 3, #III).

### Diuri Formation and Gondwana Succession Thrust Sheets

In southeast Bhutan, a 2- to 10-km-wide (N-S) exposure of the Gondwana succession is observed in thrust contact above the Siwalik Group across the MBT. The Gondwana succession is in thrust contact beneath the Diuri Formation, which is observed in a 4- to 8-km-wide (N-S) exposure, in thrust contact beneath the Baxa Group (Fig. 2). In map pattern, the surface exposures of both the Gondwana succession and Diuri Formation merge to the west, pinching out between the Kuru Chu and Bhumtang Chu transects (Fig. 2). The Gondwana succession carried in the MBT hanging wall is steeply north dipping (40°–50° average), and is 2.5 km thick on the Trashigang cross section (Fig. 3A) and 1.2 km thick on the Kuru Chu cross section (Fig. 3B). The extra length of the Gondwana succession shown above the erosion surface is necessary to align the northern end of the thrust sheet with footwall ramps through the Diuri Formation and Baxa Group on restored sections (Fig. 3, #I and #10).

On the Trashigang cross section (Fig. 3A), the Diuri Formation is folded into a syncline with 40°N and 40°S average limb dips, and is at least 2.4 km thick. One horse of the Gondwana succession and one horse of the Baxa Group are interpreted to fill space under the Diuri Formation, and provide a mechanism for passively folding the overlying thrust sheet. On the Kuru Chu cross section (Fig. 3B), the Diuri Formation dips 40°N on average, and is 3.0 km thick. On both the Trashigang and Kuru Chu cross sections, we interpret that the length of eroded Diuri Formation section that has passed through the erosion surface must equal the total restored length of duplexed Baxa Group horses (see Along-Strike Variability of Lesser Himalayan Duplexing section below), indicating that the majority of the original length of the Diuri thrust sheet has been removed by erosion (Fig. 3, #2 and #12).

### Upper Lesser Himalayan Duplex

Across southeastern and south-central Bhutan, the Baxa Group is exposed over a 16- to 29-km-wide N-S region that displays significant along-strike variation in width. At the southern extent of exposure, the Baxa Group is in thrust contact over the Diuri Formation in southeastern Bhutan, and over the Siwaliks across the MBT west of the Manas Chu (Fig. 2). At the northern extent, lower Lesser Himalayan rocks are thrust over the Baxa Group across the Shumar thrust (Figs. 6A and 6B) (Ray, 1989).

Klippen of the Daling Formation in flat-on-flat thrust contact over the Baxa Group are present on high ridgetops in the Kuru Chu valley (Figs. 2 and 6B). These klippen require that the lower Lesser Himalayan thrust sheet in the hanging wall of the Shumar thrust extends at least as far south as the southern limit of Baxa Group exposure. Observations of thrust contacts within the Baxa Group (Fig. 6D) and faults that place the Baxa Group over lowermost Diuri Formation on the southern Kuru Chu transect indicate that the same Baxa Group section is being structurally repeated (Figs. 2 and 3B). The Shumar thrust extends over multiple Baxa Group thrust sheets in the southern Kuru Chu valley (Fig. 2), which indicates that the structurally repeated Baxa Group sections are a duplex system that feeds slip into the Shumar thrust, defining it as a roof thrust. We call this duplex system the upper Lesser Himalayan duplex. Kinematic indicators observed in Baxa Group rocks include shear cleavage in phyllite interbeds (Figs. 6C and 6D), and consistently show a top-to-the-south sense of motion. We define shear cleavage as a C-type, shear-band cleavage (Passchier and Trouw, 1998) with secondary tectonic foliations (S surfaces) gently inclined relative to bedding planes or primary tectonic foliation (C surfaces).

From east to west, the Trashigang, Kuru Chu, Bhumtang Chu, and Mangde Chu transects expose continuous 11-, 6-, 7-, and 12-km-thick Baxa Group sections. However, based on the following stratigraphic, structural, and geomorphic observations, we argue that these thick sections represent the same 1.5- to 2.6-km-thick Baxa Group section being structurally repeated as multiple horses. On the Kuru Chu transect, a thickness of 2.6 km is calculated for the Baxa Group between lower thrust contacts and upper stratigraphic contacts with the Diuri Formation in two separate thrust sheets (Figs. 2 and 3B), and a minimum thickness of 2.5 km is exposed in the core of an anticline just below the Shumar thrust (Figs. 3B and 6B). The spacing of localized zones of deformation, which we interpret as the sites of intraformational thrust faults, provides further

Shortening and geometry of Bhutan fold-thrust belt

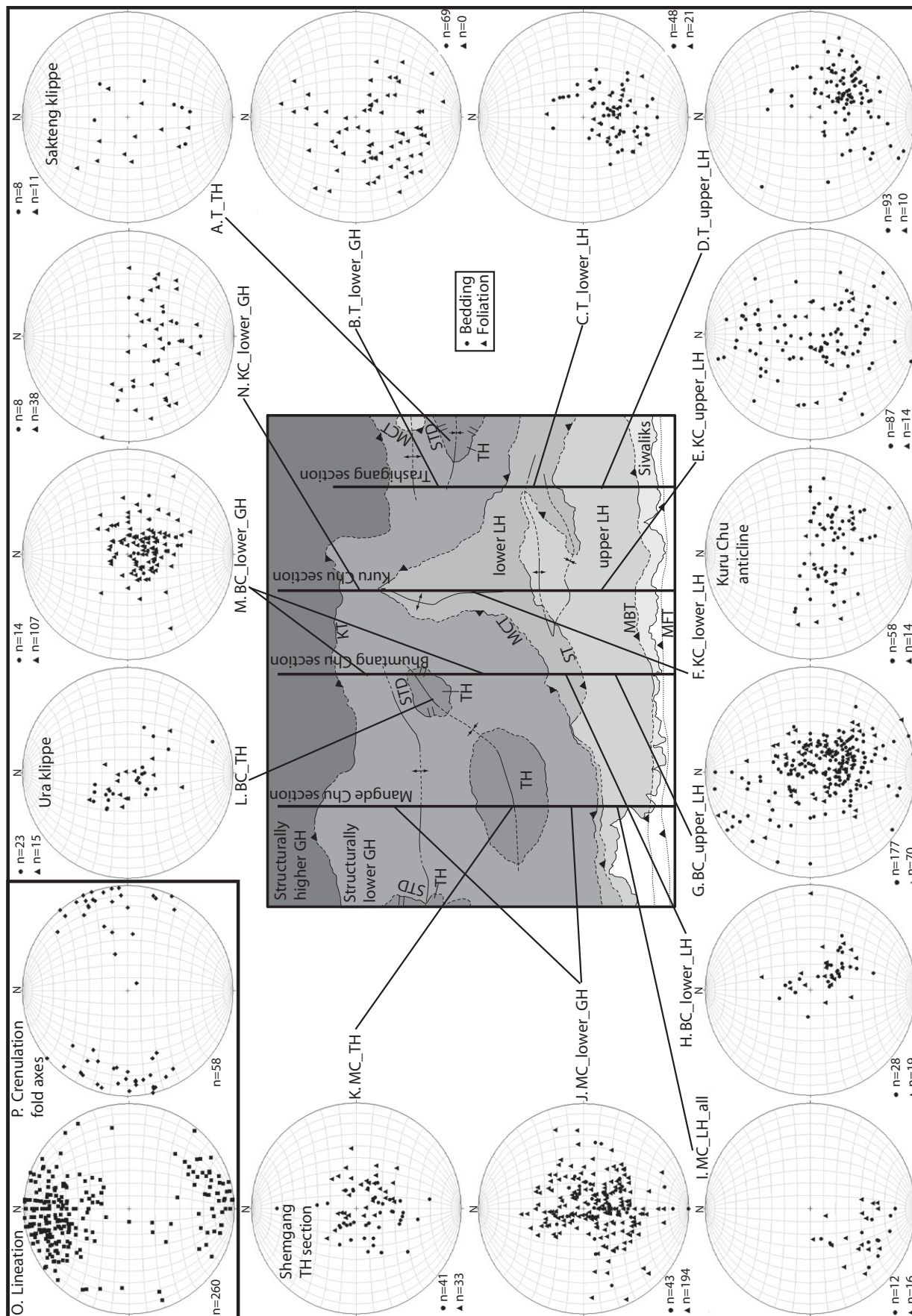
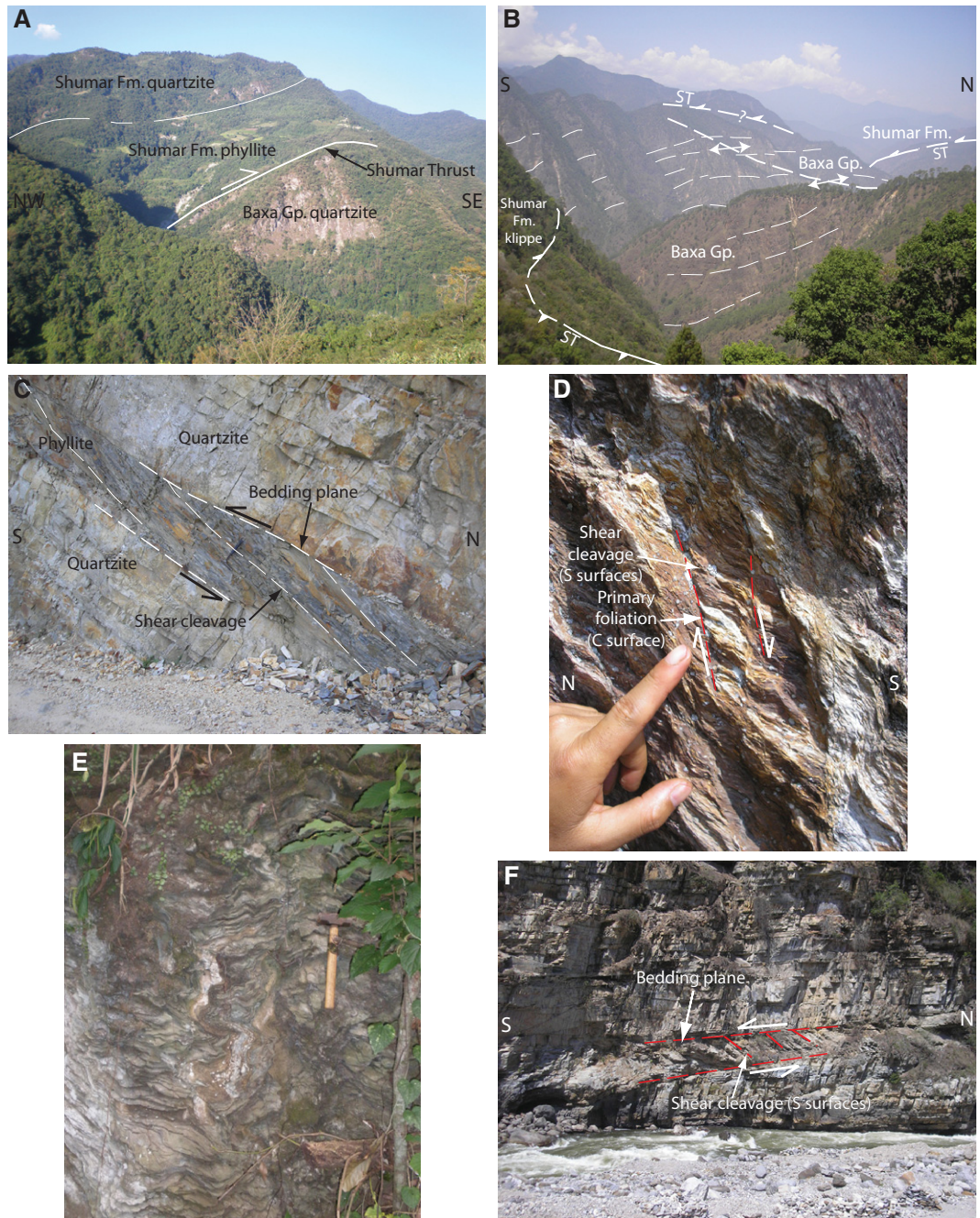


Figure 5. Equal-area stereonet plots of map data in eastern and central Bhutan. Stereonets A through N plot planar data (note different symbols for bedding and foliation) as poles to planes, and stereonets O and P plot linear data. Stereonets A through N are divided into structural zones (upper Lesser Himalayan [includes data from Siwaliks], lower Lesser Himalayan, structurally lower Greater Himalayan, and Tethyan Himalayan) for each cross section (T—Trashigang [A–A’]; KC—Kuru Chu [B–B’]; BC—Bhumtang Chu [C–C’]; MC—Mande Chu [D–D’]). Map data from structurally higher Greater Himalayan section are not plotted.



**Figure 6** (on this and following page). (A) Picture facing NE of Shumar Formation (Fm.) thrust over Baxa Group (Gp.) across Shumar thrust on Bhuntang Chu transect. Baxa Group quartzite cliffs are ~200 m high. (B) Picture facing NW of Shumar Formation thrust over folded Baxa Group across Shumar thrust, on Kuru Chu transect. Note klippe of Shumar Formation on south side. At least 2.5 km of Baxa Group strata are exposed in the center of the anticline; anticline axis marks northern extent of foreland-dipping part of upper Lesser Himalayan duplex. (C) Top-to-south-sense shear cleavage in phyllite interbed between quartzite layers of Baxa Group; location is just beneath Shumar thrust on Trashigang transect (30-cm hammer for scale). (D) Top-down-to-south-sense,  $\sigma$ -shaped shear cleavage in phyllite interval in Baxa Group. This is part of a ~10-m-thick interval of highly sheared and deformed phyllite interpreted as the site of an intraformational thrust on the Kuru Chu transect (Fig. 3, #15). Note that this is in the foreland-dipping part of the upper Lesser Himalayan duplex, and is interpreted to have been rotated to its top-down-to-south position by emplacement of subsurface Baxa Group horses (Fig. 7). (E) Picture of intensely folded Baxa Group dolomite, which is part of a ~25-m-wide zone that also exhibited hot springs and tufa precipitation, which we interpret as the location of an intraformational Baxa Group thrust fault on the Bhuntang Chu transect (Fig. 3, #20). (F) Top-to-south-sense shear cleavage in Shumar Formation quartzite in Kuru Chu valley. Outlined zone between bedding planes is ~2 m thick.

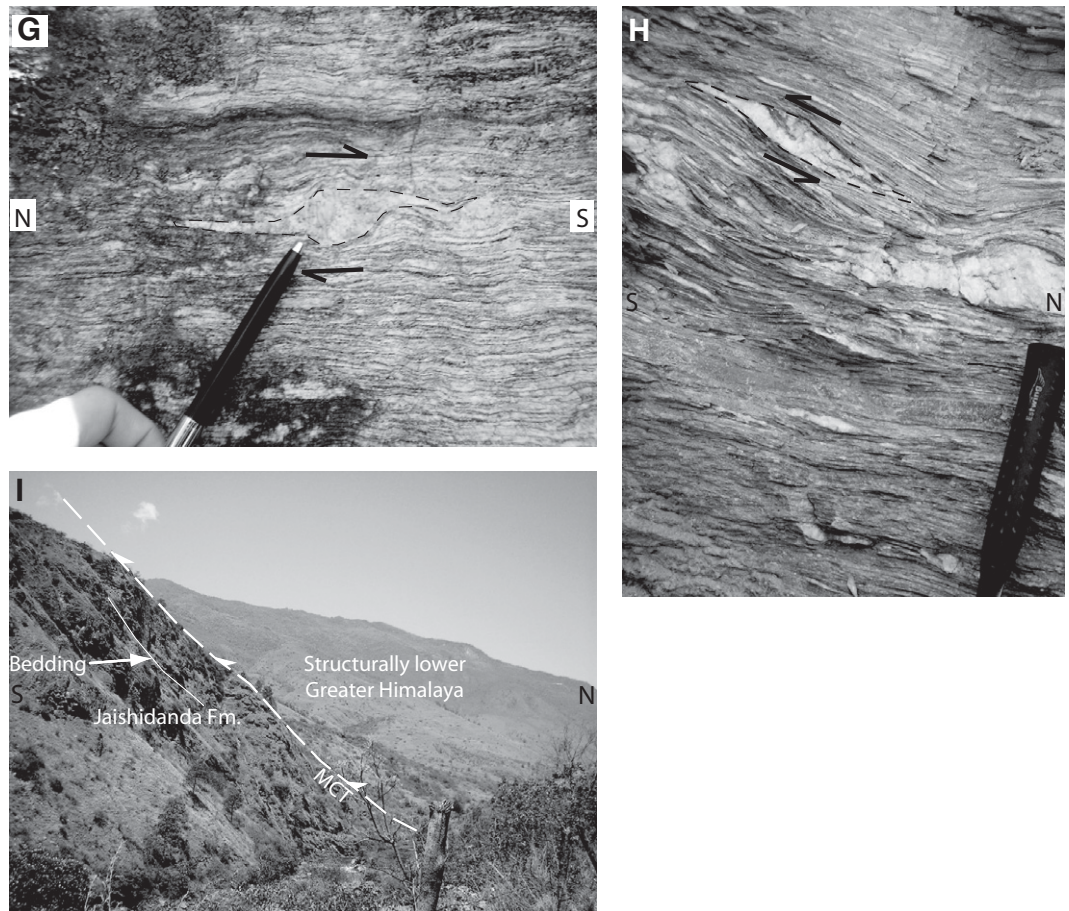


support for a 2.6-km-thick Baxa Group section on the Kuru Chu transect, and constrains the thickness of the Baxa Group section to 1.5 km on the Bhuntang Chu transect (Fig. 3C). These deformation zones include ~10- to 25-m-wide zones of highly sheared phyllite (Figs. 3 and 6D, #15), intensely folded dolomite with hot springs and tufa precipitation (Figs. 3 and 6E, #20), brecciated quartzite, brecciated dolomite, intensely sheared and folded phyllite, and a

sulfur-rich spring (Fig. 3, #21), isoclinally folded quartzite exhibiting outcrop-scale thrust faulting with an abrupt change in attitude (Fig. 3, #22), and folded, brecciated quartzite and intensely sheared phyllite with an abrupt change in attitude (Fig. 3C, #23). The abrupt attitude changes observed at these localized zones are in contrast to the generally homogeneously dipping Baxa Group strata observed between structures. On the Trashigang tran-

sect, prominent ENE-trending valleys and saddles spaced ~3 km apart north to south support dividing the exposed part of the Baxa Group into five 2.1-km-thick thrust-repeated sections (McQuarrie et al., 2008) (Fig. 3A, #5). Finally, on the Mangde Chu transect, the placement of five intraformational Baxa Group faults between the Shumar thrust and MBT was determined by interpreting six structural repetitions of a 2.1-km-thick Baxa Group section, which

Figure 6 (continued). (G) Top-to-south-sense feldspar augen  $\sigma$ -clast in orthogneiss body intruded into Daling Formation section in northern Kuru Chu valley (Fig. 2). (H) Top-to-south-sense sheared quartz vein boudin in Daling Formation phyllite just above Shumar thrust on Trashigang transect. Hammer handle is 20 cm long. (I) Picture facing NW of structurally lower Greater Himalayan section thrust over Jaishidanda Formation across Main Central thrust (MCT) in upper Kuru Chu valley, near Lhuentse (Fig. 2). Thickness of Jaishidanda section between highlighted bedding plane and MCT is  $\sim 25$  m.



is the average of the thicknesses observed on the other three transects (Fig. 3D, #28).

The geometry of the upper Lesser Himalayan duplex is predominantly hinterland-dipping. On the Trashigang transect, the five exposed Baxa Group horses dip  $30^\circ$  to  $40^\circ$  north on average (Fig. 5, stereonet D). On the Kuru Chu transect, the four southernmost horses (#1, #6, #7, and #8) dip  $40^\circ$  to  $50^\circ$  north on average (Fig. 3B), and the hanging-wall cutoffs of horses #1 and #7 pass through the erosion surface (Fig. 3, #V), which together with the Daling Formation klippen, constrain the position of the Shumar thrust. On the Bhumtang Chu transect, two syncline and two anticline axial traces are mapped in horse #5, which is attributed to passive folding above two horses (#6 and #7) interpreted in the subsurface. North of this folding (note that map data are projected from the transect east of the section line [Fig. 3, #23]), Baxa horses #1–#4 dip between  $20^\circ$  and  $35^\circ$  north on average (Fig. 5, stereonet G), and hanging-wall cutoffs for horses #1 and #2 pass through the erosion surface (Fig. 3C, #V), constraining the position of the Shumar thrust. On the Mangde Chu transect, the six Baxa Group horses dip  $50^\circ$  north on

average (Fig. 5, stereonet I) but are interpreted to flatten significantly in the subsurface, based on average foliation dips of  $20^\circ$ N in the overlying Greater Himalayan section (Fig. 3D).

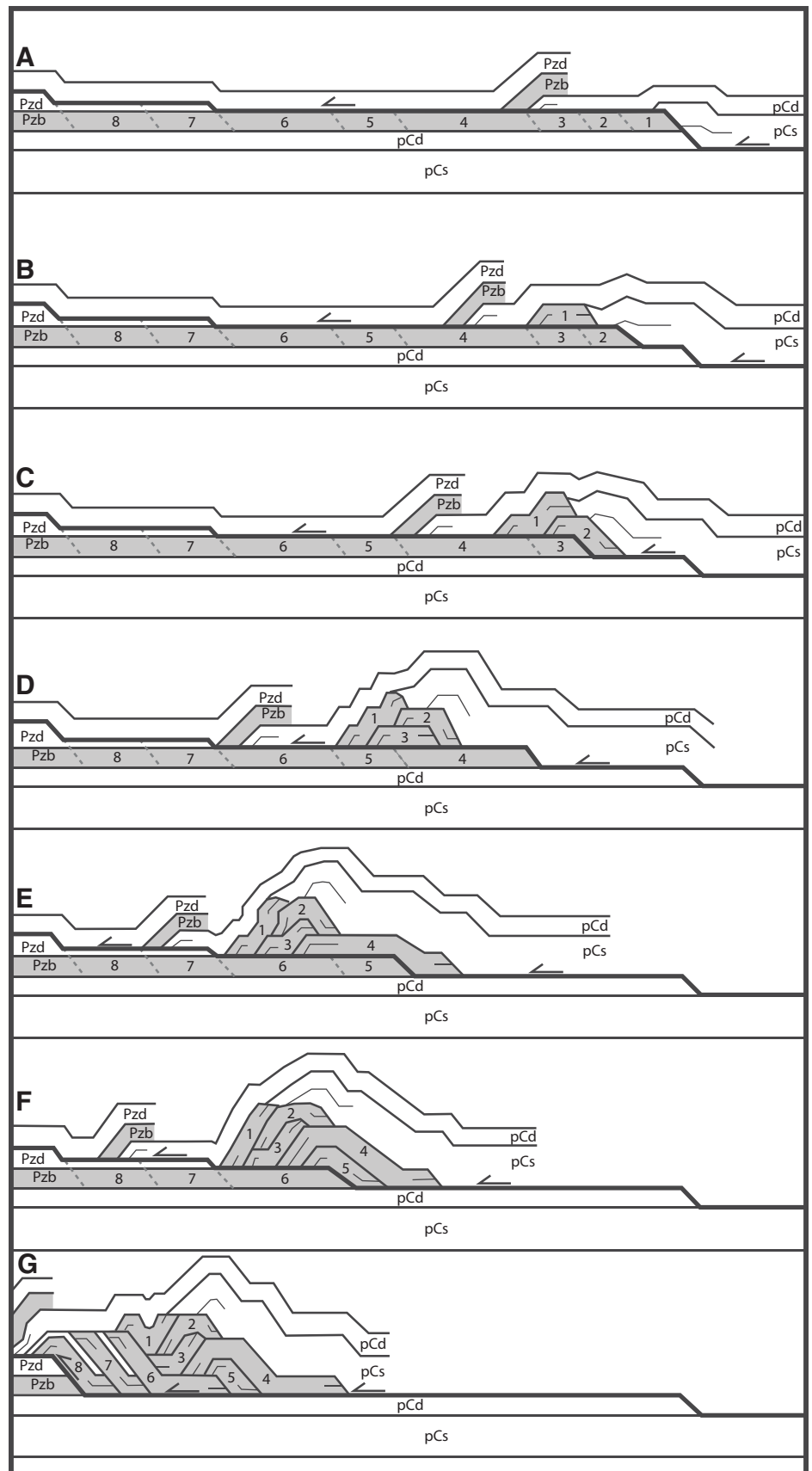
An east-trending syncline-anticline pair mapped in Baxa Group rocks immediately south of the Shumar thrust along the Kuru Chu transect can be traced along-strike to folded Daling-Shumar Group sections on the Trashigang and Bhumtang Chu transects (Fig. 2). These two folds are separated by a southward-dipping and southward-verging intraformational Baxa Group thrust mapped in the field (Fig. 6D), and require a foreland-dipping section of the upper Lesser Himalayan duplex in the Kuru Chu section (Fig. 3). These two fold traces are present east of the Kuru Chu section line, based on the geologic maps of Gokul (1983) and Bhargava (1995), and we connect them with an anticline-syncline pair that we map in the Daling-Shumar Group (Fig. 2). Here, two Baxa horses (#1 and #2) are inferred in the subsurface (Fig. 3, #6), with an interpreted antiformal stack geometry, which explains the folding observed in the overlying Daling-Shumar Group. This is consistent with map patterns showing the Baxa Group exposed

in the core of an anticline beneath the folded Shumar thrust just west of the section line (Gokul, 1983; Bhargava, 1995) (Fig. 2). We interpret the folding of the Shumar thrust and its hanging-wall section as the result of duplex geometries of Baxa Group horses that vary in size and displacement both along and across strike.

#### Lower Lesser Himalayan Duplex

Across eastern and central Bhutan, an exposure of the Daling-Shumar Group overlain by the Jaishidanda Formation is present above the Shumar thrust and below the MCT (Figs. 2, 6A, and 6B). The map pattern varies significantly along strike, and the N-S distance of exposure varies between  $\sim 15$  km on the Trashigang transect,  $\sim 50$  km in the Kuru Chu valley,  $\sim 11$  km west of the Kuru Chu valley, and  $\sim 1$ – $2$  km west of the Mangde Chu. In the Kuru Chu valley, where the trace of the MCT is shifted  $\sim 45$  km to the north relative to the east and west, we map two sections of the Daling-Shumar Group, which we interpret as structural repetition (McQuarrie et al., 2008) (Fig. 2). Map relationships showing only one lower Lesser Himalayan section under the MCT to the east and west of the Kuru Chu

**Figure 7.** Schematic cross sections showing sequential development of the upper Lesser Himalayan duplex in the Kuru Chu cross section (Fig. 3B). Active thrust faults for each increment shown in bold. (A) Lower Lesser Himalayan thrust sheet with thick Shumar Formation section begins to move over Daling-Baxa footwall ramp; (B) Baxa horse #1 translated farther than its length; (C) Baxa horse #2 translated less than its length, rotating horse #1 to foreland-dipping geometry; (D) Baxa horse #3 translated much farther than its length, further rotating horses #1 and #2; results in a hybrid anti-formal stack and foreland-dipping geometry. The long translation relative to horse length in this increment is necessary for development of the final duplex geometry in Figure 3B. Rapid forward propagation may have been facilitated by an increase in taper due to emplacement of the thick lower Lesser Himalayan thrust sheet; (E) Baxa horse #4 translated over what will become horse #5 and part of horse #6; (F) Baxa horse #5 translated less than its length, further rotating parts of older horses to foreland-dipping geometries; (G) limited translation of Baxa horses #6–#8 produces hinterland-dipping geometries, progressively rotating older horses. Geometry of schematic Baxa duplex contains both foreland- and hinterland-dipping geometries, and is similar to final geometry on Figure 3B.



valley (Fig. 2) suggest that the Greater Himalayan section overlaps thrusts that repeat the lower Lesser Himalayan section. Further support for thrust repetition of the lower Lesser Himalayan strata is found in regional-scale, long-wavelength, low-amplitude, east-west-trending folds defined by tectonic foliation and bedding measurements in Greater Himalayan and Tethyan Himalayan rocks (Gansser, 1983; Bhargava, 1995; our mapping) (Figs. 2 and 3). We suggest that these relationships indicate structural repetition of lower Lesser Himalayan thrust sheets in a thrust duplex system at depth (which we name the lower Lesser Himalayan duplex), with the MCT acting as the roof thrust (Fig. 3, #X). While Greater Himalayan and Tethyan Himalayan tectonic foliation and bedding locally display variable attitudes indicative of outcrop-scale folding, we used the average dip direction of the majority of measurements to define dip domains separated by fold axial traces on the map and cross sections (Figs. 2 and 3). Duplexing of lower Lesser Himalayan

thrust sheets in the subsurface is interpreted as the mechanism that forms the structural lows and highs in the folded Greater Himalayan and Tethyan Himalayan sections, and duplexed lower Lesser Himalayan thrust sheets are shown filling space under the Greater Himalayan section on all cross sections (Fig. 3).

The lower Lesser Himalayan thrust sheets display significant along-strike thickness variations. On the Trashigang section, the lower Lesser Himalayan thrust sheet is 5.4 km thick (Fig. 3A). On the Kuru Chu transect, the southern lower Lesser Himalayan thrust sheet is 9.2 km thick, with a 6.0-km-thick Shumar Formation section, and does not include the Jaishidanda Formation in the line of section (Figs. 2 and 3B). The northern lower Lesser Himalayan thrust sheet on the Kuru Chu transect is 7.0 km thick, with a 2.0-km-thick Shumar Formation section, which is attributed to a décollement high within a 6.0-km-thick Shumar Formation section, rather than a thinner Shumar Formation to the north. A 6.0-km-thick Shumar section that rapidly thins to the north under Greater Himalayan rocks near Lhuntse is another possible interpretation (Fig. 3, #18). On the Bhumtang Chu section, the lower Lesser Himalayan thrust sheet is 4.0 km thick (Fig. 3C). The thickness variations described above are interpreted as along-strike changes in depositional thickness (Himalayan river anticlines section). On the Mangde Chu section, the Shumar Formation and lower part of the Daling Formation are not exposed, and the thickness of the lower Lesser Himalayan thrust sheet is only 1.2 km (Fig. 3D). Since the Daling, Shumar, and Jaishidanda Formations with a combined thickness of 4.0 km are exposed 25 km along-strike to the east (Fig. 2), we interpret the missing stratigraphy and thin section observed along the Mangde Chu as the result of a lateral ramp of the Shumar thrust that cuts upsection to the west as well as in the direction of transport. The associated hanging-wall ramp through the lower Daling and Shumar sections is interpreted in the subsurface, making the northern extent of horse #5 3.3 km thick, which is similar to the exposed thickness on the Bhumtang Chu section (Fig. 3D). The location of the hanging-wall ramp corresponds to the syncline axial trace in the center of the Shemgang Tethyan Himalayan exposure (Fig. 2). Finally, since the Jaishidanda Formation is not present in the upper Lesser Himalayan section south of the trace of the Shumar thrust, it is interpreted to pinch out to the south, and its southern extent is queried above the erosion surface on all cross sections (Fig. 3, #VIII).

Kinematic indicators from lower Lesser Himalayan units consistently display top-to-the-south motion senses, and include shear cleavage

in quartzite (Fig. 6F), feldspar augen  $\sigma$ -clasts in orthogneiss bodies (Fig. 6G), and sheared and rotated quartz vein boudins in Daling Formation schist and phyllite (Fig. 6H) and Jaishidanda schist. In thin section, Shumar, Daling, and Jaishidanda samples display dynamically recrystallized quartz microstructure (Grujic et al., 1996; Long et al., 2010), with quartz crystallographic-preferred orientation (Grujic et al., 1996) and mineral stretching lineation (Figs. 2, 5O) indicating a N-S transport direction. These observations argue against thickening via E-W-oriented ductile flow of Lesser Himalayan rocks, and support our interpretation for differences in original depositional thickness across eastern Bhutan.

Throughout eastern Bhutan, the lower Lesser Himalayan duplex is generally hinterland-dipping, but the geometry and number of horses varies along-strike. On the Trashigang section, the exposed lower Lesser Himalayan thrust sheet dips 30°N (Figs. 3B and 5C), except for a 25°S-dipping section that is interpreted as folding above subsurface Baxa Group horses (Along-Strike Variability of Lesser Himalayan Duplexing section below). Two additional lower Lesser Himalayan horses are interpreted under the Greater Himalayan section (Fig. 3A), and coincide with fold axial traces observed in Greater Himalayan tectonic foliations (Fig. 2), including a synclinal trace that projects along-strike to the Sakteng klippe (Grujic et al., 2002), and an anticlinal trace that projects along-strike to the Lum La window (Yin et al., 2010). On the Kuru Chu transect, the southern lower Lesser Himalayan thrust sheet decreases in dip from 30°N to 4°N from south to north (Figs. 3B and 5F). The 4°N-dipping section corresponds to a décollement at the top of the Diuri Formation at depth (Fig. 3, #16). The northern lower Lesser Himalayan thrust sheet on the Kuru Chu transect steepens in dip from 4°N to 35°N from south to north (Figs. 3B and 5F), which constrains the position of a footwall ramp through the Diuri Formation and Baxa Group at depth (Fig. 3, #16 and #17). On the Bhumtang Chu section, the exposed lower Lesser Himalayan thrust sheet (#5) has a 20°N average dip (Figs. 2, 3C, and 5H), and four additional lower Lesser Himalayan horses (#1, #2, #3, and #4) are inferred in the subsurface (Fig. 3, #X). These horses define a hinterland-dipping duplex that coincides with a broad synform in the center of the Ura klippe and an antiform observed to the north in the Greater Himalayan section. We interpret a similar geometry for the Mangde Chu cross section, with four lower Lesser Himalayan horses (#1, #2, #3, and #4) that define a hinterland-dipping duplex coincident with a broad antiform in the Greater Himalayan and Tethyan Himalayan sections.

Bedding and tectonic foliation from both lower Lesser Himalayan thrust sheets in the Kuru Chu valley define a north-trending-, north-plunging anticline (Fig. 5, stereonet F), which we name the Kuru Chu anticline. This structure is responsible for the ~45 km northward shift of the MCT trace centered on the Kuru Chu valley.

### Main Central Thrust Sheet

The structurally lower Greater Himalayan section is exposed above the MCT (Fig. 6I), and sits either structurally below (across the South Tibetan detachment) or stratigraphically below isolated Tethyan Himalayan exposures (Long and McQuarrie, 2010), and structurally beneath the Kakhtang thrust on its northern end (Grujic et al., 2002). North to south (across-strike) surface exposure varies between a maximum of ~90 km in central Bhutan and a minimum of ~14 km in the Kuru Chu valley (Fig. 2).

The structurally lower Greater Himalayan section displays significant across-strike gradients in pressure and temperature conditions, as recorded by metamorphic mineral assemblages, the presence or absence of partial melt textures, and quartz deformation microstructure (Long and McQuarrie, 2010). In eastern Bhutan, on the Trashigang, Kuru Chu, and Bhumtang Chu transects, kyanite and partial melt textures (deformed granitic leucosomes) are present throughout the section, and peak pressure and temperature conditions are estimated at 8–12 kbar and 750–800 °C (Daniel et al., 2003). In contrast, in central Bhutan, on the Mangde Chu transect, partial melt textures are absent or only present near the base of the Greater Himalayan section, a biotite-muscovite-garnet mineral assemblage dominates the majority of the Greater Himalayan section and entire Tethyan Himalayan section, with no observed change across the Greater Himalayan–Tethyan Himalayan contact, and quartz and feldspar microstructure indicates deformation temperatures between 450 and 500 °C (Long and McQuarrie, 2010). In the lower-grade Greater Himalayan section observed in central Bhutan, quartzite preserves original sedimentary structures, including bedding, compositional laminations, and upright cross-bedding. Quartzite bedding and schist, phyllite, and paragneiss foliation are approximately parallel, and low-strain magnitudes show that bedding has not been transposed (Long and McQuarrie, 2010) (Fig. 5, stereonets B, J, M, and N).

The structurally lower Greater Himalayan section is shown in cross section as a 5.3- to 10.5-km-thick thrust sheet. However, since this section is bound by ductile shear zones at its base and top, and pervasive fabrics throughout the section indicate penetrative ductile deformation (Grujic et al., 1996, 2002; Daniel et al.,

2003; Hollister and Grujic, 2006; Long and McQuarrie, 2010), we emphasize that interpreting these rocks as a thrust sheet with a discrete thrust at the base provides a minimum estimate of displacement. On all transects, tectonic foliation in Greater Himalayan rocks just above the MCT is parallel to bedding and tectonic foliation of Lesser Himalayan rocks just below. This relationship can be traced at the surface for an across-strike distance of ~45 km in the Kuru Chu valley (Figs. 2 and 3). This regional-scale, flat-on-flat relationship is shown in cross section as a hanging-wall flat over a footwall flat (Fig. 3). Parallel dips above and below the MCT also indicate that the hanging-wall cutoff for the Greater Himalayan section has passed through the erosion surface on all transects. On the cross sections, the MCT trace is projected from its southernmost extent on either side of the Kuru Chu valley (Fig. 3, #IX), and the hanging-wall cutoff through the Greater Himalayan section is positioned just to the south, to minimize structural overlap across the MCT (Fig. 3, #IX). Our cross sections show a westward-increasing minimum structural overlap between 97 and 156 km across the MCT (Table 1).

Based on our mapping, the structurally lower Greater Himalayan section is ~8 km thick across eastern Bhutan. On the Trashigang section, at least 7.0 km of lower Greater Himalayan rocks are exposed, and the complete lower Greater Himalayan section is shown as 8.5 km thick between the MCT and South Tibetan detachment based on projection of the Sakteng klippe above the erosion surface (Fig. 3A). On the Kuru Chu section, the Greater Himalayan section is 8.1 km thick between the MCT and Kakhtang thrust (Fig. 3B). On the Bhumtang Chu transect, the structurally lower Greater Himalayan section is 8.2 km thick south of the Ura klippe, and the Greater Himalayan metasedimentary unit thickens significantly to the north between the Ura klippe and the Kakhtang thrust (Fig. 3, #25). In cross section, the Greater Himalayan orthogneiss unit is interpreted as thinning to the north in the subsurface, which keeps the total thickness of the Greater Himalayan section nearly constant (Fig. 3C). In central Bhutan, on the Mangde Chu transect, the lower Greater Himalayan section thickens to the north, from 5.3 km between the MCT and the base of the Shemgang Tethyan Himalayan exposure to 10.5 km between Trongsa and the Kakhtang thrust (Fig. 3D). In cross section, most of the thickness change is attributed to northward thickening of the metasedimentary unit (Fig. 3, #29). Note that the thinnest Greater Himalayan section, between the MCT and Shemgang, also corresponds to the coolest temperature and highest viscosity Greater Himalayan section studied

TABLE 1. SHORTENING AND FAULT DISPLACEMENT ESTIMATES FOR EASTERN AND CENTRAL BHUTAN

	(A-A') Trashigang	(B-B') Kuru Chu	(C-C') Bhumtang Chu	(D-D') Mangde Chu
LH length deformed (km)	135	139	148	164
LH length restored (km)*	401	406	312	342
LH shortening (km)*	266	267	164	178
LH shortening (%)*	66	66	53	52
Minimum MCT overlap (km)	97	107	140	156
Minimum KT overlap (km)	42	31	40	53
Total length restored (km)**	540	544	492	551
Total shortening (km)	405	405	344	387
Total shortening (%)	75	74	70	70
<b>Subhimalayan zone</b>				
Shortening (km)	5	7	5	5
LH shortening (%)	2	3	3	3
Total shortening (%)	1	2	1	1
<b>Diuri-Gondwana thrust sheets</b>				
Shortening (km)	29	21	—	—
LH shortening (%)	11	8	—	—
Total shortening (%)	7	5	—	—
<b>Upper LH duplex</b>				
Shortening (km)	166	137	107	67
LH shortening (%)	62	51	65	38
Total shortening (%)	41	34	31	17
<b>Lower LH duplex</b>				
Shortening (km)	66	102	52	106
LH shortening (%)	25	38	32	60
Total shortening (%)	16	25	15	27
<b>GH lower structural level</b>				
Minimum MCT overlap (km)	97	107	140	156
Total shortening (%)	24	26	41	40
<b>GH higher structural level</b>				
Minimum KT overlap (km)	42	31	40	53
Total shortening (%)	10	8	12	14
MFT displacement (km)	9	9	6	6
MBT displacement (km)	34	67	5	13
ST displacement (km)	49	79	40	40
STD displacement (km)	—	—	20	13

Note: Abbreviations: GH—Greater Himalaya; KT—Kakhtang thrust; LH—Lesser Himalaya; MBT—Main Boundary thrust; MCT—Main Central thrust; MFT—Main Frontal thrust; SH—Subhimalaya; ST—Shumar thrust; STD—South Tibetan detachment.

\*LH length and shortening estimates include SH zone.

\*\*Includes restored length from LH-SH, MCT overlap, and KT overlap.

thus far in Bhutan (Long and McQuarrie, 2010). In this region the Tethyan Himalayan section at Shemgang is in depositional contact above the structurally lower Greater Himalayan section (Long and McQuarrie, 2010), making the Greater Himalayan and Tethyan Himalayan sections part of the same thrust sheet (Fig. 3D).

### Tethyan Himalayan Klippen

Grujic et al. (2002) provided field evidence for top-to-the-north-sense shear zones correlated with the South Tibetan detachment at the base of the Chekha Formation. This interpretation was based on structures observed at the base of the Ura and Sakteng Tethyan Himalayan exposures in eastern Bhutan (Fig. 2). Because no field observations were available at that time, the southernmost Tethyan Himalayan exposure at Shemgang (Fig. 2) was inferred to be the Black Mountain klippe (Grujic et al., 2002). New mapping in the Shemgang region shows an interfingering depositional contact between the Chekha Formation and Greater Himalayan metasedimentary rocks

indicating the original stratigraphic relationship between the Chekha Formation and the structurally lower Greater Himalayan section (Long and McQuarrie, 2010).

The Sakteng klippe is exposed in the core of a syncline with ~30°N- and S-dipping limbs (Fig. 5, stereonet A), and although Chekha Formation bedding and tectonic foliation are variable, the majority of measurements are sub-parallel to the tectonic foliation of Greater Himalayan rocks below (Fig. 3A), indicating that hanging-wall and footwall cutoffs of the South Tibetan detachment are above the erosion surface to the south. The Ura klippe displays two synclinal traces and an anticlinal trace, with ~20°N- and S-dipping limbs (Fig. 5, stereonet L). The southern contact of the Chekha Formation with the Greater Himalayan metasedimentary unit shows a flat-on-flat relationship across the South Tibetan detachment, while the northern contact displays a distinct change in bedding orientation from NE-dipping strata below to SE-dipping strata above (Long and McQuarrie,

2010). Approximate locations for footwall and hanging-wall ramps through the Chekha Formation are shown on the Bhumtang Chu section (Fig. 3C). These features are shown at their maximum permissible southern and northern extents, respectively, which are constrained between the along-strike projection of the Shemgang Tethyan Himalayan exposure, where the Chekha Formation is in depositional contact above the Greater Himalayan section (Long and McQuarrie, 2010), and the southern extent of the South Tibetan detachment at the Ura klippe, where a flat-on-flat relationship shows that the hanging-wall cutoff must be above the erosion surface to the south (Fig. 3, #26). These geometries constrain displacement on the South Tibetan detachment to ~20 km (Long and McQuarrie, 2010) (Table 1). On the Mangde Chu section, a similar geometry for hanging-wall and footwall cutoffs of Tethyan Himalayan units is shown, with the along-strike position of the Ura klippe projected above the erosion surface (Fig. 3, #30).

Our mapping in central Bhutan has implications for tectonic models that interpret the South Tibetan detachment as a passive roof thrust (Webb et al., 2007). Our interpreted geometry for Greater Himalayan and Tethyan Himalayan units in central Bhutan (Fig. 3D), with detailed observations presented in Long and McQuarrie (2010), shows the South Tibetan detachment cutting downsection to the north through the Maneting Formation and Chekha Formation. This geometry is compatible with a top-to-the-north-sense normal fault, and is not compatible with a top-to-the-north-sense thrust fault. For the South Tibetan detachment to be a passive roof thrust above a Greater Himalayan wedge, rocks we map as Greater Himalayan south of Shemgang (Fig. 2) would have to be reinterpreted as Tethyan Himalayan rocks, requiring the South Tibetan detachment to merge with the MCT between the Bhumtang Chu (high-grade Greater Himalayan rocks displaying kyanite and partial melt textures) and the Mangde Chu (lower-grade Greater Himalayan rocks), and requiring the MCT to cut upsection from Greater Himalayan strata to Tethyan Himalayan strata south of Shemgang. The passive roof duplex model would also require the trace of the South Tibetan detachment to be exposed between Trongsa and Shemgang. We have mapped and sampled a transect south of Trongsa in detail (Fig. 2), and observe only top-to-the-south-sense structures in outcrop and thin section (Long and McQuarrie, 2010).

#### ***Kakhtang Thrust Sheet***

The structurally higher Greater Himalayan section is exposed above the Kakhtang thrust and below the South Tibetan detachment across

Bhutan (Figs. 1 and 2), and is shown on the cross sections as a thrust sheet (Fig. 3), similar to the structurally lower Greater Himalayan section. Note that surface data and cross-section lines terminate within the structurally higher Greater Himalayan section, so only minimum thicknesses are shown on the cross sections. On the Kuru Chu and Trashigang sections, the higher Greater Himalayan section is at least 13 km thick (Fig. 4). Map data from the higher Greater Himalayan section are projected from the maps of Gansser (1983), Gokul (1983), and Bhargava (1995) (Fig. 3, #XI), and show that tectonic foliation dips 20°–40°N on average (Fig. 2), subparallel to dips of the structurally lower Greater Himalayan section beneath the Kakhtang thrust, indicating that the hanging-wall cutoff has passed through the erosion surface. Assuming that the hanging-wall cutoff is just above the erosion surface, and that the Kakhtang thrust roots into the Main Himalayan thrust at depth (e.g., Nelson et al., 1996), we measure structural overlap across the Kakhtang thrust from its trace to the footwall cutoff of the structurally lower Greater Himalayan section (Fig. 3, #XIII). This provides minimum shortening estimates for the Kakhtang thrust, which vary between 31 and 53 km (Table 1). Just like the lower Greater Himalayan section, fabrics indicative of penetrative ductile deformation are observed throughout the higher Greater Himalayan section (Gansser, 1983; Swapp and Hollister, 1991; Davidson et al., 1997; Daniel et al., 2003; Hollister and Grujic, 2006), so we emphasize that structural overlap across the Kakhtang thrust is only a minimum estimate for the amount of strain that these rocks have accommodated.

#### **Crustal Shortening Estimates and Along-Strike Variation**

##### ***Shortening Estimates by Tectonostratigraphic Zone***

Our four deformed and restored, balanced cross sections (Fig. 3) allow estimation of the minimum shortening accommodated by the Lesser Himalayan and Subhimalayan zones in Bhutan to be 164–267 km, or 52%–66% (Table 1). At the northern end of the restored cross sections, the footwall ramp through the northernmost lower Lesser Himalayan thrust sheet is interpreted to mark the northernmost extent of Lesser Himalayan rocks, and the permissible southernmost ramp for the structurally lower Greater Himalayan section (Fig. 3, #XIV). By adding in the structural overlap across the MCT (97–156 km) and across the Kakhtang thrust (31–53 km), the minimum contributions of shortening of the structurally lower and higher Greater Himalayan sections

can be included in our shortening estimates. Our estimate for the total minimum shortening accommodated by the Subhimalayan, Lesser Himalayan, and Greater Himalayan zones is 344–405 km, or 70%–75% (Table 1).

Shortening data for each structural zone are also listed on Table 1. The Subhimalayan zone accommodates only 5–7 km of shortening, 1%–2% of the total. The upper Lesser Himalayan duplex accommodates 67–166 km, or 17%–41% of the total on individual sections, and the lower Lesser Himalayan duplex accommodates 52–106 km, or 15%–27% of the total on individual sections. Together, duplexing of Lesser Himalayan units accommodates 159–239 km, or 44%–59% of the total shortening estimated on individual sections. Finally, structural overlap across the MCT on individual sections accounts for 24%–41%, and across the Kakhtang thrust accounts for 8%–14% of the total shortening, although these estimates do not account for internal strain within the Greater Himalayan zone.

##### ***Along-Strike Variability of Lesser Himalayan Duplexing***

At the scale of Bhutan, there are significant along-strike variations observed in the geometry, number of horses, overall shortening, and relative shortening contributions of Lesser Himalayan duplexes. This variation indicates that along-strike horse width is on the order of the distance between adjacent cross sections (25 km average). The amount of shortening in the upper Lesser Himalayan duplex decreases significantly from east to west (Table 1). Partially, this is taken up by an increase in shortening in the lower Lesser Himalayan duplex. However, the total shortening in the lower Lesser Himalayan duplex does not show such a clear along-strike trend. The relative shortening contributions of the upper and lower Lesser Himalayan duplexes could be controlled by the ratio of décollement strength to taper angle through time. As an example, the presence of a foreland-dipping duplex on the Kuru Chu section, which contains a locally thick lower Lesser Himalayan section (Fig. 3B), may illustrate the control of original basin geometry on later deformation. The sequential development of this duplex is illustrated on Figure 7. The foreland-dipping geometry results from a translation of three Baxa horses (#1–#3) that is greater than their individual lengths, most importantly the very long translation of horse #3 shown in increment D. We suggest that the significant forward propagation during this increment was facilitated by an increase in taper due to emplacement of the locally thick lower Lesser Himalayan thrust sheet (Lower Lesser Himalayan duplex

section) over a footwall ramp, highlighting the control that original basin geometry can exert on final deformation geometry.

At the scale of the Himalayan orogen, duplexing of Lesser Himalayan units accommodates significant shortening across the majority of the arc. Lesser Himalayan duplexing most likely represents a hinterland taper-building mechanism in response to either rapid forward propagation of the deformation front or rapid removal of material by erosion. An along-strike comparison of Lesser Himalayan duplexing is discussed in detail in Mitra et al. (2010). Not surprisingly, the thickness and relative translation of individual horses involved in building the Lesser Himalayan duplex, as well as the area that needs to be filled between the décollement and the roof thrust, have the largest effect on shortening magnitude. The former two are a response to original basin geometry, while the latter is dictated by taper, and may be a function of basin geometry or external processes such as erosion. In northwest India and western Nepal, the Lesser Himalayan duplex is primarily hinterland-dipping, and repeats multiple horses below the roof thrust, the Ramgarh thrust (RT) (Srivastava and Mitra, 1994; Robinson et al., 2006). In this region, from west to east,

the thickness of duplexed strata decreases and the vertical distance between the décollement and the roof thrust increases, resulting in a three- to four-fold increase in percent shortening. In Sikkim, Paleoproterozoic and Paleozoic units are repeated in a duplex with a hybrid hinterland-dipping and antiformal stack geometry beneath the Ramgarh thrust, and thicker Paleoproterozoic thrust sheets are repeated in a hinterland-dipping duplex above the Ramgarh thrust and below the MCT (Bhattacharyya and Mitra, 2009; Mitra et al., 2010). The two-duplex system in Sikkim is very similar to what we observe in eastern and central Bhutan. The Shumar thrust occupies a similar role as roof thrust that the Ramgarh thrust performs in duplexes further to the west. Note that offset on the Shumar thrust varies between 40 and 79 km across Bhutan, but the Ramgarh thrust in Sikkim has much more offset (164 km) (Mitra et al., 2010).

## DISCUSSION

### Shortening along the Himalayan Arc

A compilation of shortening estimates obtained across the ~2500 km arc-length of the Himalayan orogen is shown in Figure 8A, with

the data from individual studies listed in Table 2. Figure 8A and Table 2 are modeled after the compilation originally presented in DeCelles et al. (2002), but are updated to include more recent studies, in particular new data from the eastern Himalaya.

Other than Coward and Butler (1985), who presented a balanced cross section across the entire fold-thrust belt in Pakistan, the remaining studies compiled on Figure 8A present cross sections and shortening estimates for the Subhimalayan, Lesser Himalayan, and Greater Himalayan zones only, and not the Tethyan Himalayan zone. These studies include, from west to east, Srivastava and Mitra (1994) in northwest India, Robinson et al. (2006) in western Nepal, Schelling (1992) in east-central Nepal, Schelling and Arita (1991) in eastern Nepal, Mitra et al. (2010) in Sikkim, this study in central and eastern Bhutan, and Yin et al. (2009) in western Arunachal Pradesh. Note that shortening estimates from DeCelles et al. (1998; 2001) are replaced by updated estimates from Robinson et al. (2006), and the preliminary estimate from McQuarrie et al. (2008) is replaced by the data from this study.

For shortening estimates across the entire fold-thrust belt, the results from the studies listed

TABLE 2. COMPILATION OF SHORTENING ESTIMATES FOR THE HIMALAYAN FOLD-THRUST BELT

Reference in Figure 8A	Reference	Location	Structural boundaries	Tectonostratigraphic zones	Shortening (km)
1	Coward and Butler (1985)	Pakistan	MMT-MFT	GH, LH, SH	470
2	Srivastava and Mitra (1994)	India, Kumaon and Garhwal	STD-MCT	GH (includes Almora thrust sheet)	193–260
3	Srivastava and Mitra (1994)	India, Kumaon and Garhwal	MCT-MFT	LH, SH	161
	DeCelles et al. (1998)	Western Nepal	MCT-MFT	LH, SH	228
	DeCelles et al. (2001)	Western Nepal	STD-MCT	GH (includes Dadeldhura thrust sheet)	131–206
	DeCelles et al. (2001)	Western Nepal	MCT-MFT	LH, SH	287
4	Robinson et al. (2006)	Western Nepal	STD-MCT	GH (includes Dadeldhura thrust sheet)	111–221
5	Robinson et al. (2006)	Western Nepal	MCT-MFT	LH, SH	374–522
	Kohn et al. (2004)	East-central Nepal	STD-MCT	GH	200
6	Schelling (1992)	East-central Nepal	STD-MCT	GH	140–210
7	Schelling (1992)*	Central Nepal	MCT-MFT	LH, SH	70
8	Schelling and Arita (1991)	Eastern Nepal	STD-MCT	GH	140–175
9	Schelling and Arita (1991)*	Eastern Nepal	MCT-MFT	LH, SH	45–70
10	Mitra et al. (2010)	Sikkim	STD-MCT	GH	249
11	Mitra et al. (2010)	Sikkim	MCT-MBT	LH, SH	253
12	<b>This study</b>	Central and eastern Bhutan	STD-MCT	GH	138–209
13	<b>This study</b>	Central and eastern Bhutan	MCT-MFT	LH, SH	164–267
	McQuarrie et al. (2008)	Eastern Bhutan	STD-MCT	GH	133
	McQuarrie et al. (2008)	Eastern Bhutan	MCT-MFT	LH, SH	226
14	Yin et al. (2010)	Western Arunachal Pradesh	STD-MCT	GH	207
15	Yin et al. (2010)**	Western Arunachal Pradesh	MCT-MFT	LH, SH	308
	Searle (1986)	India, Zaskar and Ladakh	ISZ-MMT	TH	126
16	Searle et al. (1997)	India, Zaskar and Ladakh	ISZ-MCT	TH	150–170
17	Corfield and Searle (2000)	India, Zaskar and Ladakh	ISZ-STD	TH	85
	Steck et al. (1993)	India, Zaskar and Ladakh	ISZ-STD	TH	87
18	Murphy and Yin (2003)	Tibet, Mount Kailas region	ISZ-STD	TH	112
19	Murphy and Yin (2003)	Tibet, Mount Kailas region	ISZ-STD	TH + SZ	176
20	Ratschbacher et al. (1994)	Tibet, north of Arun River	ISZ-MCT	TH	133
21	Ratschbacher et al. (1994)	Tibet, north of Sikkim	ISZ-MCT	TH	139

Note: Data accompany Figure 8A. Individual estimates are listed for each tectonostratigraphic zone (note that LH and SH zones are grouped together). Note that not all studies are referenced on Figure 8A. Augmented estimates marked with asterisk are discussed in the section "Shortening along the Himalayan arc". Abbreviations: GH—Greater Himalaya; LH—Lesser Himalaya; SH—Subhimalaya; ISZ—Indus-Yalu suture zone; MBT—Main Boundary thrust; MCT—Main Central thrust; MFT—Main Frontal thrust; MMT—Main Mantle thrust; STD—South Tibetan detachment; TH—Tethyan Himalaya.

\*Projection of Ramgarh thrust into eastern Nepal would increase LH shortening by 122–193 km (DeCelles et al., 2001; Pearson, 2002).

Note that these offsets are similar to the 164 km slip on the Ramgarh thrust reported from Sikkim (Mitra et al., 2010).

\*\*50 km northward shift of northernmost ramp on Yin et al. (2010). Figures 4F–4G would decrease LH shortening by 75 km.

above must be combined with shortening estimates for the Tethyan Himalayan zone. Several Tethyan Himalayan estimates are available from northwest India (Searle, 1986; Steck et al., 1993; Searle et al., 1997; Corfield and Searle, 2000). The minimum (Corfield and Searle, 2000) and maximum (Searle et al., 1997) of these estimates are added to the estimates of Srivastava and Mitra (1994). Minimum and maximum estimates from Murphy and Yin (2003), obtained north of western Nepal, are added to the estimates of Robinson et al. (2006). Data from Ratschbacher et al. (1994) from a transect north of east-central Nepal are added to the estimates of Schelling (1992). Data from Ratschbacher et al. (1994) from a transect north of Sikkim represent the easternmost available shortening estimate for the Tethyan Himalayan zone, and are added to the shortening estimates from eastern Nepal, Sikkim, Bhutan, and Arunachal Pradesh. The data listed in Table 2 split out the range of shortening estimates individually by tectonostratigraphic zone. For each study site, the column on the left represents a total of the minimum estimates for each zone, and the column on the right represents a total of the maximum estimates for each zone, after DeCelles et al. (2002). For this reason, the totals may be different from shortening estimates listed for individual cross sections in these studies.

To be able to directly compare shortening magnitudes, there are three places where we calculate shortening estimates that are different than published values (marked with asterisk). It is important to mention that the estimates we obtain in this manner are approximate. In eastern Nepal, the shortening estimates of Schelling (1992) and Schelling and Arita (1991) are significantly smaller than those reported farther west in Nepal and to the east in Bhutan, particularly for the Lesser Himalayan zone. DeCelles et al. (2002) attributed this to a lack of identification of important structures in these cross sections, most notably the Ramgarh thrust. Subsequent studies have identified an along-strike equivalent of the Ramgarh thrust in eastern Nepal (Pearson, 2002; Pearson and DeCelles, 2005), and this structure is also identified to the east in Sikkim (Bhattacharyya and Mitra, 2009; Mitra et al., 2010). Projecting maximum and minimum displacements estimated for the Ramgarh thrust would add 122 km (DeCelles et al., 2001) to 193 km (Pearson, 2002) shortening to the Lesser Himalayan zone (Table 2; Fig. 8A). Note that these offset estimates are similar to the 164 km estimate obtained in Sikkim (Mitra et al., 2010).

Estimates from western Arunachal Pradesh, presented in Yin et al. (2009), are accompanied by deformed and restored cross sections that

include (1) an estimate with ~18 km of pre-Himalayan topography on the basal décollement (figs. 4D and 4E of Yin et al., 2009), and (2) an estimate with no pre-Himalayan deformation (flat-lying strata) (figs. 4F and 4G of Yin et al., 2009). Since the space between the erosion surface and the décollement exerts one of the largest controls on shortening magnitude, we use the latter estimate of Yin et al. (2010); this estimate minimizes shortening (515 km). In addition, for cross sections to balance, hanging-wall ramps and décollements must match footwall ramps and décollements in both the deformed and restored sections (e.g., Woodward et al., 1985). This constraint requires a ~50 km northward shift of the northernmost décollement ramp on Yin et al. (2010) figure 4F, and suggests that the minimum estimate of Lesser Himalayan shortening in Arunachal Pradesh is 440 km (Fig. 8A; Table 2).

With new data from western Nepal, our augmented estimates for eastern Nepal and Arunachal Pradesh, and the addition of new data from Sikkim and Bhutan, for the first time we can compare along-strike shortening variations across the entire Himalayan arc (Fig. 8A). This allows us to evaluate the validity of the predictions of systematic shortening variation across the orogen listed above in the Introduction. The data compiled on Figure 8A suggest that the greatest amount of shortening is accommodated in the central part of the orogen, as first discussed in DeCelles et al. (2002). Compared to western Nepal, shortening estimates from eastern Nepal, Sikkim, Bhutan, and Arunachal Pradesh are incompatible with an overall eastward increase in shortening as suggested by the convergence history or increase in erosion (Guillot et al., 1999; Yin et al., 2006). Maximum shortening estimates for the eastern half of the orogen are very similar (ca. 580–640 km), and fall 280–340 km short of the maximum estimate in western Nepal. While not a perfect match for either, the data shown in Figure 8A are more compatible with the “bow-and-arrow” model (Elliott, 1976), or the hypothesis that shortening should mimic the width of the Tibetan Plateau (DeCelles et al., 2002), which is indicated by the dashed black line. The maximum shortening estimates from the majority of compiled studies fall very close to this line. However, exceptions that stand out are (1) the maximum estimate from western Nepal (Robinson et al., 2006), which exceeds the Tibetan Plateau width by ~250 km, and (2) the maximum augmented estimates from eastern Nepal (Schelling and Arita, 1991; Schelling, 1992), which fall short of the Tibetan Plateau width by ~100 km. The estimates from eastern Nepal are ~30–60 km less than estimates just to the east, falling short of

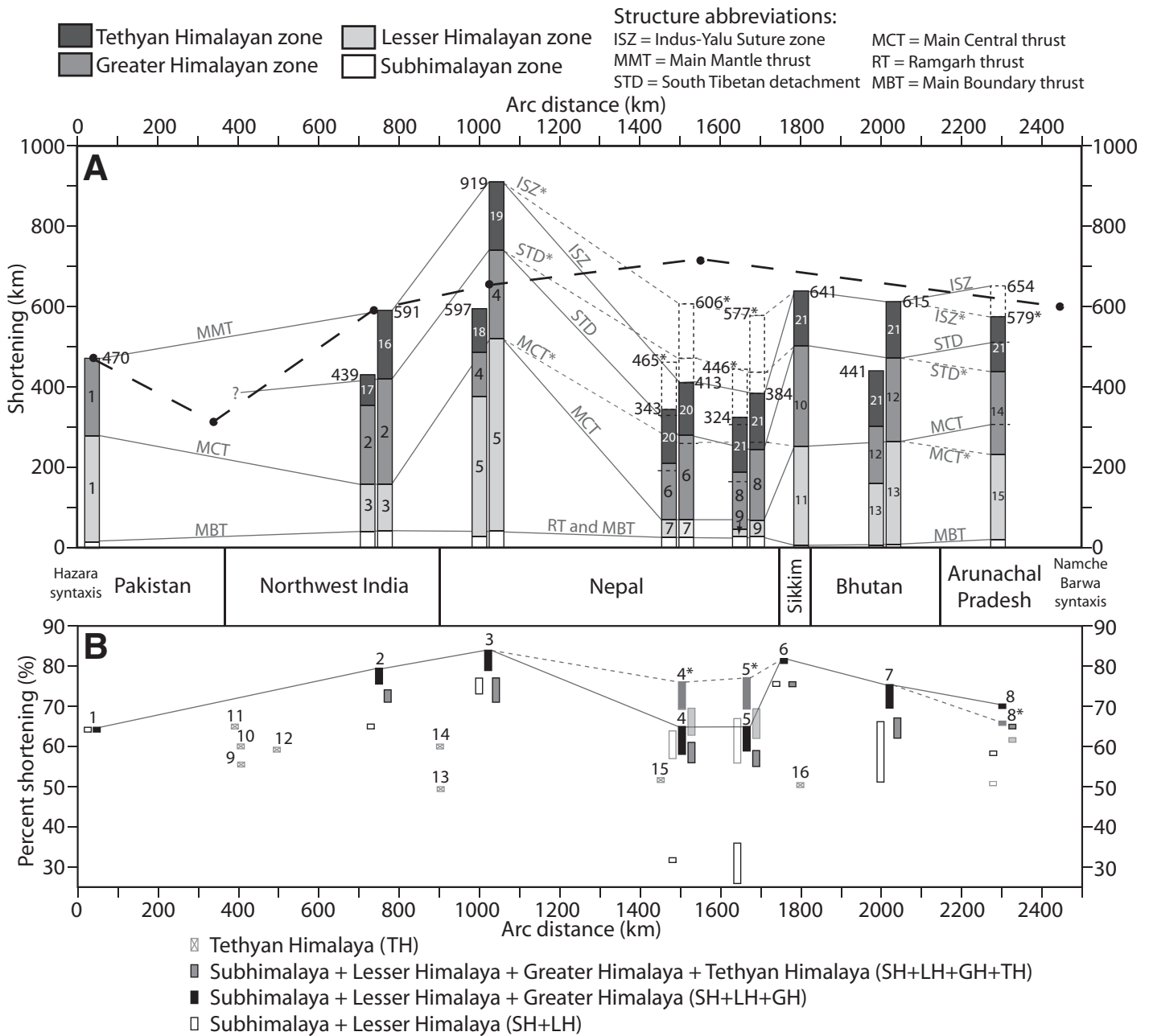
the estimates predicted by a simple “bow-and-arrow” model where shortening is greatest at the center of the orogen (Elliott, 1976). However, since our augmented estimates are not based on new cross sections that incorporate the Ramgarh thrust, future work in eastern Nepal could significantly refine and update these estimates allowing for a more robust comparison.

It is important to reemphasize that our shortening estimates from Bhutan, as with the rest of the shortening estimates compiled above, are minima. Several factors could increase shortening estimates, including: (1) increasing the depth of the basal décollement (e.g., figs. 4D and 4E of Yin et al., 2010); (2) replacing thicker strata with thrust repetition of thinner stratigraphic units (e.g., addition of Ramgarh thrust to Schelling [1992] and Schelling and Arita [1991]); (3) greater displacement on thrust sheets where hanging-wall cutoffs have been eroded; or (4) incorporating penetrative strain or small-scale folding and faulting. For factor 1, earthquake seismology (Ni and Barazangi, 1984; Pandey et al., 1999; Mitra et al., 2005) and seismic reflection studies (Hauck et al., 1998) have imaged a consistent, flat, gently north-dipping basal décollement across the Himalayan orogen, removing significant changes in the décollement as a mechanism for increasing shortening. Factor 2 depends on the level of detail of mapping, and the ability to delineate individual thrust-repeated units. In the case of our Bhutan cross sections, we see stratigraphic and structural evidence for repeated Baxa Group horses (Along-Strike Variability of Lesser Himalayan Duplexing section) and a consistent two-part stratigraphy of the Daling-Shumar Group allows mapping of separate thrust sheets (Lower Lesser Himalayan duplex section). Factors 3 and 4 pose the biggest unknown for Subhimalayan, Lesser Himalayan, and Greater Himalayan shortening estimates across the Himalaya, because hanging-wall cutoffs are rarely exposed, and because of the degree of ductile deformation, particularly in Greater Himalayan rocks. In Bhutan, klippen of lower Lesser Himalayan rock in the Kuru Chu valley allow constraint of the amount of erosion of Baxa Group horses. However, fortuitous map relationships such as this are not present in every study site across the orogen. Finally, one of the largest uncertainties in the composite estimates we compile above may be shortening in the Tethyan Himalayan zone, particularly east of Sikkim.

#### **Percent Shortening along the Himalayan Arc**

Precipitation from the Indian monsoon has been documented to increase significantly from the western to the eastern Himalaya (e.g.,





**Figure 8. (A)** Compilation of shortening estimates from west to east across the Himalayan fold-thrust belt after DeCelles et al. (2002) but modified and updated to incorporate recent work. Black dots connected with dashed line correspond to arc-normal width of Tibetan Plateau on five transects shown on figure 1 of DeCelles et al. (2002). Small numbers within colored boxes are referenced to data sources listed on Table 2. Left column shows minimum estimates, and right column shows maximum estimates for all tectonostratigraphic zones, except where only one estimate is available. Numbers with asterisk refer to augmented shortening estimates in eastern Nepal and Arunachal Pradesh (connected with adjacent estimates by dashed gray lines); changes listed in Table 2 and discussed in the “Shortening along the Himalayan arc” section. **(B)** Compilation of percent shortening ranges across the Himalayan arc. Data are totals for tectonostratigraphic zones listed below figure. Numbers are referenced to data sources listed on Table 3. Gray line connects maximum percent shortening from Greater Himalayan, Lesser Himalayan, and Subhimalayan zones. Numbers with asterisk (connected with dashed gray line) refer to augmented estimates in eastern Nepal and Arunachal Pradesh, as listed in Figure 8A and Table 2.

## Shortening and geometry of Bhutan fold-thrust belt

Finlayson et al., 2002; Bookhagen et al., 2005). If the amount of precipitation can be directly related to erosion magnitude, as has been suggested by studies in the eastern Himalaya (Grujic et al., 2006; Yin et al., 2010) and northwest India (Thiede et al., 2005), and if erosion exerts a fundamental control on the width of orogens (e.g., Beaumont et al., 1992, 2001; Zeitler et al., 1993, 2001; Willett, 1999; Whipple and Meade, 2004), then the documented precipitation gradient should be reflected in an overall increase in percent shortening from the western to the eastern Himalaya (e.g., McQuarrie et al., 2008).

Oxygen isotope records of sediments in Tibet (Dettman et al., 2003) and Nepal (Dettman et al., 2001) and foraminifera (Kroon et al., 1991) and diatom (Burckle, 1989) records from the northern Indian Ocean have been used to document a late Miocene (ca. 10–12 Ma) onset age for the Indian monsoon. Paleoelevation studies indicate that the High Himalaya and southern Tibet had achieved similar elevations to the present by approximately the same time (ca. 10–12 Ma) (Garzzone et al., 2000a, 2000b; Rowley et al., 2001), indicating an orographic barrier had been established by the late Miocene. Since the majority of deformation in the Tethyan Himalayan zone occurred between Paleocene and Oligocene time (Ratschbacher et al., 1994; Harrison et al., 2000; Wiesmayr and Grasemann, 2002; Murphy and Yin, 2003; Ding et al., 2005; Aikman et al., 2008), percent shortening estimates for the Miocene Himalayas (shortening in the Greater Himalayan, Lesser Himalayan, and Subhima-

layan zones from the Miocene to the present) (e.g., Hodges et al., 1996; DeCelles et al., 2001; Grujic et al., 2002; Daniel et al., 2003; Searle et al., 2003; Kohn et al., 2004; Vannay et al., 2004; Robinson et al., 2006; Yin et al., 2009) would be the most representative standard for along-strike comparison of percent shortening.

Table 3 is a compilation of available percent shortening estimates for the Himalayan fold-thrust belt, which are shown graphically in Figure 8B. These data were either originally presented in their source study, or were calculated from the balanced cross sections accompanying those studies. Data for the total percent shortening in the Greater Himalayan, Lesser Himalayan, and Subhimalayan zones are shown by red boxes and connected with a gray line on Figure 8B. Since the shortening estimates that generate percent shortening ranges are most likely minima, the gray line connects the maximum estimates. Augmented estimates for eastern Nepal and for Arunachal Pradesh, calculated as discussed above (Shortening along the Himalayan arc), are shown as transparent boxes, and are marked with an asterisk and connected with a dashed gray line. Figure 8B shows that percent shortening in the Greater Himalayan, Lesser Himalayan, and Subhimalayan zones varies between 64% near the western syntaxis, increases to a maximum of 84% near the center of the orogen in western Nepal, and decreases to 76%–77% at the augmented estimates in eastern Nepal, increases to 82% in Sikkim, and decreases to 75% in Bhutan and 66% in Arunachal Pradesh.

Although this is only based on eight studies distributed across the ~2500 km arc-length of the orogen, our compilation does not support the prediction of an overall west-to-east increase in percent shortening, indicating a lack of first-order correlation between precipitation magnitude, shortening, and width in the Himalayan orogen. However, since the timing of deformation initiation of Greater Himalayan rocks extends back to the early Miocene (e.g., Daniel et al., 2003; Robinson et al., 2006), which predates the late Miocene onset of the Indian monsoon, this along-strike comparison of percent shortening should be viewed as a preliminary effort. A more robust test of the relationship of percent shortening to along-strike precipitation variations would require more precise timing constraints of late Miocene and younger shortening magnitudes in the Lesser Himalayan and Subhimalayan zones in multiple along-strike locations. Finally, note that percent shortening across the arc smooths out the large variations in shortening amount, which may suggest that shortening variations may be controlled more by the original width and geometry of the northern Indian margin than by external features such as precipitation and convergence rate.

## Himalayan River Anticlines

The observation that many major Himalayan rivers, including the Sutlej River in northwest India, the Arun River in eastern Nepal, and the Kuru Chu in Bhutan, flow parallel to the hinges

TABLE 3. COMPILATION OF PERCENT SHORTENING ESTIMATES FOR THE HIMALAYAN FOLD-THRUST BELT

Reference in Figure 8B	Reference	Location	SH + LH (%)	SH + LH + GH (%)	Total: SH + LH + GH + TH (%)
1	Coward and Butler (1985)	Pakistan	64	64	—
2	Srivastava and Mitra (1994)	India, Kumaon and Garhwal	65	76–79	72 <sup>1</sup> –74 <sup>2</sup>
3	Robinson et al. (2006)	Western Nepal	74–77	79–84	72 <sup>3</sup> –77 <sup>4</sup>
4	Schelling (1992)	East-central Nepal	32	58–65	56–61 <sup>5</sup>
4*	Schelling (1992)*	East-central Nepal	57–64	69–76	63–69 <sup>6</sup>
5	Schelling and Arita (1991)	Eastern Nepal	26–36	59–65	55–59 <sup>6</sup>
5*	Schelling and Arita (1991)*	Eastern Nepal	56–67	70–77	63–69 <sup>6</sup>
6	Mitra et al. (2010)	Sikkim	76	82	76 <sup>6</sup>
7	This study	Central and eastern Bhutan	52–66	70–75	63–67 <sup>6</sup>
8	Yin et al. (2010)	Western Arunachal Pradesh	58	70	65 <sup>6</sup>
8**	Yin et al. (2010)	Western Arunachal Pradesh	51	66	62 <sup>6</sup>
Reference in Figure 8B	Reference	Location	TH (%)		
9	Searle (1986)	India, Zaskar and Ladakh	56		
10	<sup>1</sup> Searle et al. (1997)	India, Zaskar and Ladakh	60		
11	<sup>2</sup> Corfield and Searle (2000)	India, Zaskar and Ladakh	65		
12	Steck et al. (1993)	India, Zaskar and Ladakh	59		
13	<sup>3</sup> Murphy and Yin (2003)	Tibet, Mount Kailas region	49		
14	<sup>4</sup> Murphy and Yin (2003)	Tibet, Mount Kailas region	60 (w/ISZ)		
15	<sup>5</sup> Ratschbacher et al. (1994)	Tibet, north of Arun River	52		
16	<sup>6</sup> Ratschbacher et al. (1994)	Tibet, north of Sikkim	51		

Note: Abbreviations: GH—Greater Himalaya; ISZ—Indus suture zone; LH—Lesser Himalaya; SH—Subhimalaya; TH—Tethyan Himalaya. Data accompany Figure 8B. Maximum and minimum percent shortening are listed as totals for the indicated tectonostratigraphic zones. Superscripts in Total (SH + LH + GH + TH) column are referenced to the specific TH study used. Augmented estimates marked with asterisk are discussed in sections “Shortening along the Himalayan arc” and “Percent shortening along the Himalayan arc” and are matched with superscripts in “Reference” column.

\*Calculated by adding 122–193 km shortening to LH zone (see Table 2).

\*\*Calculated by subtracting 75 km shortening from LH zone (see Table 2).

of orogen-perpendicular anticlines, has led to a number of studies searching for a folding mechanism (Bordet, 1955; Krishnaswamy, 1981; Oberlander, 1985; Meier and Hiltner, 1993; Johnson, 1994; Burg et al., 1997; DiPietro et al., 1999; Montgomery and Stolar, 2006). However, no general consensus has been reached. Lateral ramps in major Himalayan thrusts and accretion of lenticular horses are two possible explanations (Johnson, 1994). In a recent study of the Arun River valley in eastern Nepal, Montgomery and Stolar (2006) argued that the observed spatial correlation between higher rainfall and the river valley itself supports the interpretation that Himalayan river anticlines are the result of “focused rock uplift in response to significant differences between net erosion along major rivers and surrounding regions” (Montgomery and Stolar, 2006).

An alternative explanation is that preexisting structures and accompanying sedimentary thickness variations (i.e., paleogeography) may control the development of the north-trending Himalayan anticlines. The 9-km-thick section of the Daling-Shumar Group that we observe is local to an ~35-km-wide (east-west) area centered on the Kuru Chu valley (Fig. 2), and the thickness of the group decreases to ~4 km to the east and west. Since the lower contact is the Shumar thrust, these are minimum thicknesses. However, we assume that the faults detach the Shumar Formation at the base of the section. Displacing this locally thick section southward over the Baxa Group adds an extra ~5 km of structural elevation compared to the east and west (Figs. 3A–3C), creates two lateral ramps to the east and west, and as a result creates a structural high localized on the Kuru Chu valley. Note that the axis of the anticline does not continue below the Shumar thrust in the Baxa Group exposure to the south (Fig. 2), which provides further support for association with the thick Daling-Shumar Group section in the Shumar thrust hanging wall. Along strike through the eastern Himalaya, several north-trending folds are present, including the Arun antiform centered on the Arun River valley in eastern Nepal. This area also contains a thick (12–13 km) Lesser Himalayan section (Schelling and Arita, 1991; Schelling, 1992) when compared to the 3–4.5 km thickness of correlative Lesser Himalayan units in central and western Nepal (Robinson et al., 2006).

Locally thick Lesser Himalayan sections trending perpendicular to the Greater Indian continental margin could have been generated from preexisting or syntectonic irregularities, such as at the intersections of transform systems with the continental margin. While significant along-strike synrift sediment thickness changes at the scale of salients and re-

entrants in continental margins have been identified (e.g., Thomas, 1977), thick, smaller-scale, margin-perpendicular, basin-fill sections are also documented. Thomas (1991) observed abrupt along-strike thickness changes of synrift rocks in the Appalachian-Ouachita continental margin, including a 65-km-wide, margin-perpendicular graben, localized along a synrift transform fault interpreted to have propagated onto the continent. Francheteau and Le Pichon (1972) also document similar deep, margin-perpendicular coastal basins interpreted to have formed where transform fracture zones intersected the east coast of Argentina.

## CONCLUSIONS

A new 1:250,000-scale geologic map and four balanced cross sections through the Himalayan fold-thrust belt in eastern and central Bhutan allow us to conclude the following.

(1) Major structural features of the fold-thrust belt include: (a) the ~2- to 7-km-thick Main Frontal thrust sheet; (b) the upper Lesser Himalayan duplex, which structurally repeats ~2- to 3-km-thick horses of the Baxa Group, with the Shumar thrust acting as the roof thrust; (c) the lower Lesser Himalayan duplex, which repeats ~4- to 9-km-thick thrust sheets of the Daling-Shumar Group and Jaishidanda Formation, which passively folds the roof thrust, the MCT, and the structurally lower Greater Himalayan section; (d) the ~5- to 11-km-thick, structurally lower Greater Himalayan thrust sheet above the MCT and below the South Tibetan detachment; (e) Tethyan Himalayan rock in stratigraphic contact above the lower Greater Himalayan section in central Bhutan and in structural contact above the South Tibetan detachment in eastern Bhutan; and (f) the >13-km-thick, structurally higher Greater Himalayan thrust sheet above the Kakhtang thrust.

(2) In the Subhimalayan and Lesser Himalayan zones, 164–267 km of minimum shortening, or 52%–66%, is recorded. Structural overlap across the MCT and Kakhtang thrust varies between 97 and 156 km and 31 and 53 km, respectively. Total minimum shortening of the Himalayan fold-thrust belt between the MFT and the South Tibetan detachment ranges between 344 and 405 km, or 70% to 75%. The Subhimalayan zone only accounts for 5–7 km, or 1%–2% of the total. The upper and lower Lesser Himalayan duplexes together account for 159–239 km of shortening, or 44%–59% of the total. When combined with observations from northwest India, Nepal, and Sikkim, this indicates that Lesser Himalayan duplexing accommodates significant shortening across much of the Himalayan orogen.

(3) A compilation of shortening estimates across the length of the orogen does not indicate a systematic west-to-east increase, as predicted by the obliquity of Indian-Asian convergence, or increased erosion in the east. Although not a perfect fit to either, the shortening data are more compatible with classic “bow-and-arrow” models (e.g., Elliott, 1976), and the hypothesis that shortening magnitude should mimic the arc-normal width of the Tibetan Plateau, as predicted by DeCelles et al. (2002). Finally, although precipitation increases from west to east across the Himalayan front, a compilation of the percent shortening across the length of the orogen does not indicate a systematic west-to-east increase, which would be predicted if precipitation, erosion magnitude, and shortening were all positively correlated. We suggest that the original width and geometry of sedimentary basins on the northern Indian margin may exert a stronger control on shortening across the arc than external features such as precipitation and convergence rate.

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## Shortening and geometry of Bhutan fold-thrust belt

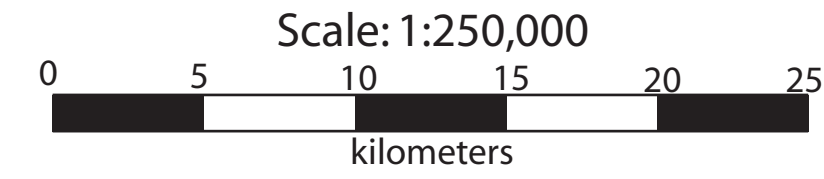
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# Geologic Map of Eastern and Central Bhutan

S. Long, N. McQuarrie, T. Tobgay, and D. Grujic



## Stratigraphy

- Qs Modern sediment (Quaternary)
- Subhimalaya**
- Ts Siwalik Group (Miocene–Pliocene) - lower (Tsl), middle (Tsm), upper (Tsu)
- Tibetan (Tethyan) Himalaya**
- Pzm Maneting Formation (Ordovician[?])
- Pzc Chekha Formation (age uncertain; Neoproterozoic to Ordovician[?])
- Greater Himalaya**
- GHhm Structurally higher metasedimentary unit
- GHho Structurally higher orthogneiss unit
- GHhg Structurally higher leucogranite (Miocene)
- GHlm Structurally lower metasedimentary unit (Neoproterozoic–Ordovician[?])
- GHlo Structurally lower orthogneiss unit (Cambrian–Ordovician)
- Lesser Himalaya**
- Pzg Gondwana succession (Permian)
- Pzd Diuri Formation (Permian)
- Pzj Jaishidanda Formation (Neoproterozoic–Ordovician[?])
- Pzb Baxa Group (Neoproterozoic–Cambrian[?])
- Dolomite
- pCd Daling Formation (Paleoproterozoic)
- pCs Shumar Formation (Paleoproterozoic)
- pCg Orthogneiss (Paleoproterozoic)

## Symbols

- Geological symbols published online on 26 January 2011 at [www.lyellcollection.org](http://www.lyellcollection.org)
- Thrust fault (teeth on upper plate)
  - Detachment fault (ticks on upper plate)
  - Anticline
  - Syncline
  - Strike and dip of bedding and foliation
  - Structural data from Bhargava (1995)
  - Structural data from Gansser (1983)
  - Structural data from Gokul (1983)
  - Horizontal bedding
  - Mineral stretching lineation
  - Crenulation fold axis
  - Town
  - Road
  - River
  - Contour line (elevation in meters)

## Structures (North to South)

- KT Kakhtang thrust
- STD South Tibetan detachment
- MCT Main Central thrust
- ST Shumar thrust
- MBT Main Boundary thrust
- MFT Main Frontal thrust

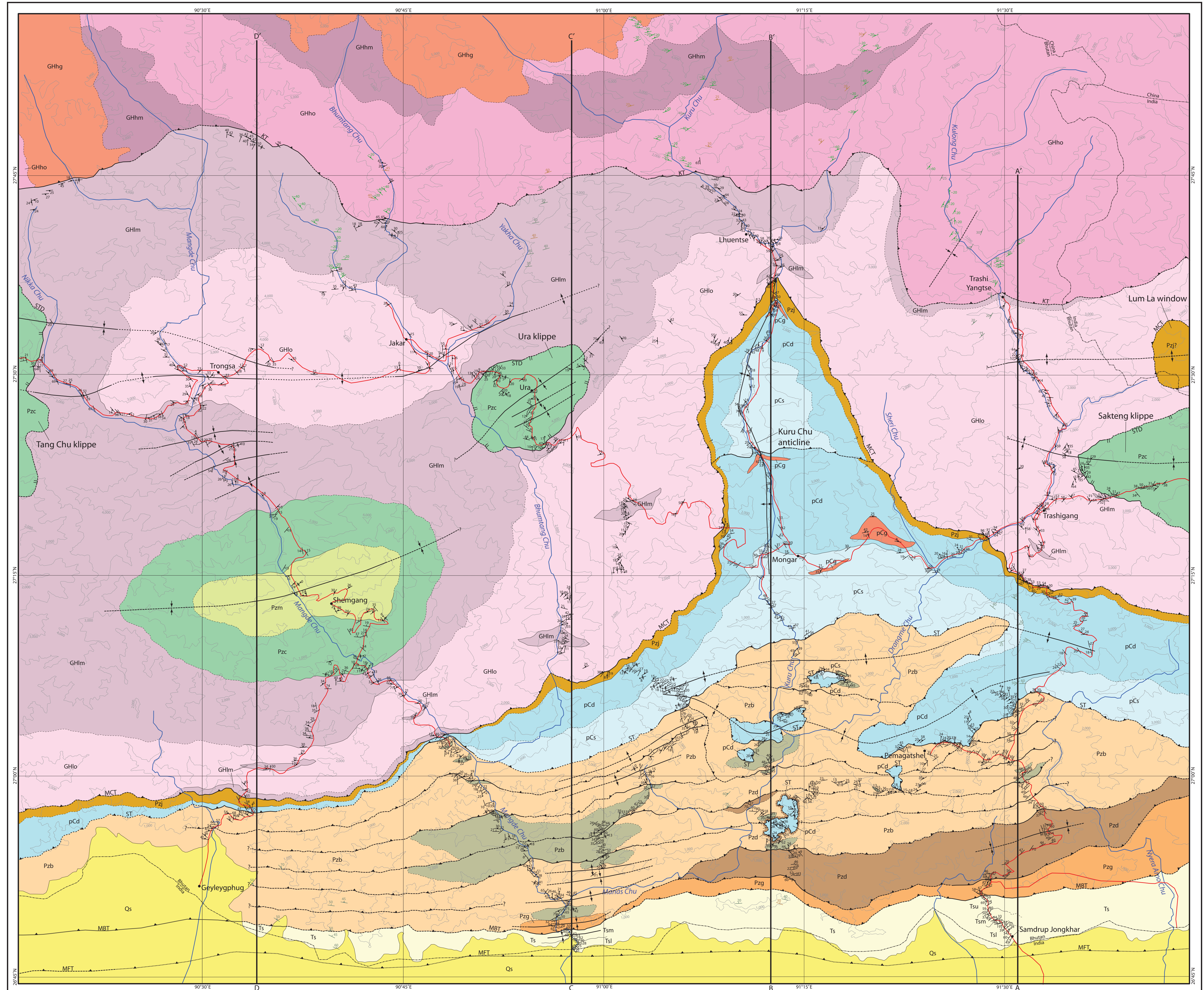


Figure 2. Geologic map of eastern and central Bhutan (scale 1:250,000). Location shown on Figure 1. Stratigraphy, unit abbreviations, structure abbreviations, sources of map data, and symbols shown in legend. The following data sources were used to trace contacts between our traverses: locations of Main Boundary thrust (MBT), Kakhtang thrust, Main Central thrust (MCT) east of Trashingang traverse, Tang Chu klippe, and all structurally higher Greater Himalayan unit contacts from Gansser (1983); locations of Shumar thrust (ST); folded Shumar thrust in eastern Kuru Chu valley from Gokul (1983); most Lesser Himalayan unit contacts, and MCT from Bhargava (1995); location of Shumar thrust east of Trashingang traverse matches along-strike of location of Bomdilla thrust from Yin et al. (2010); location of Lum La window from Yin et al. (2010).

Geometry and crustal shortening of the Himalayan fold-thrust belt, eastern and central Bhutan  
Long et al.  
Plate 1  
Supplement to: *Geological Society of America Bulletin*, doi: 10.1130/B30203.S1  
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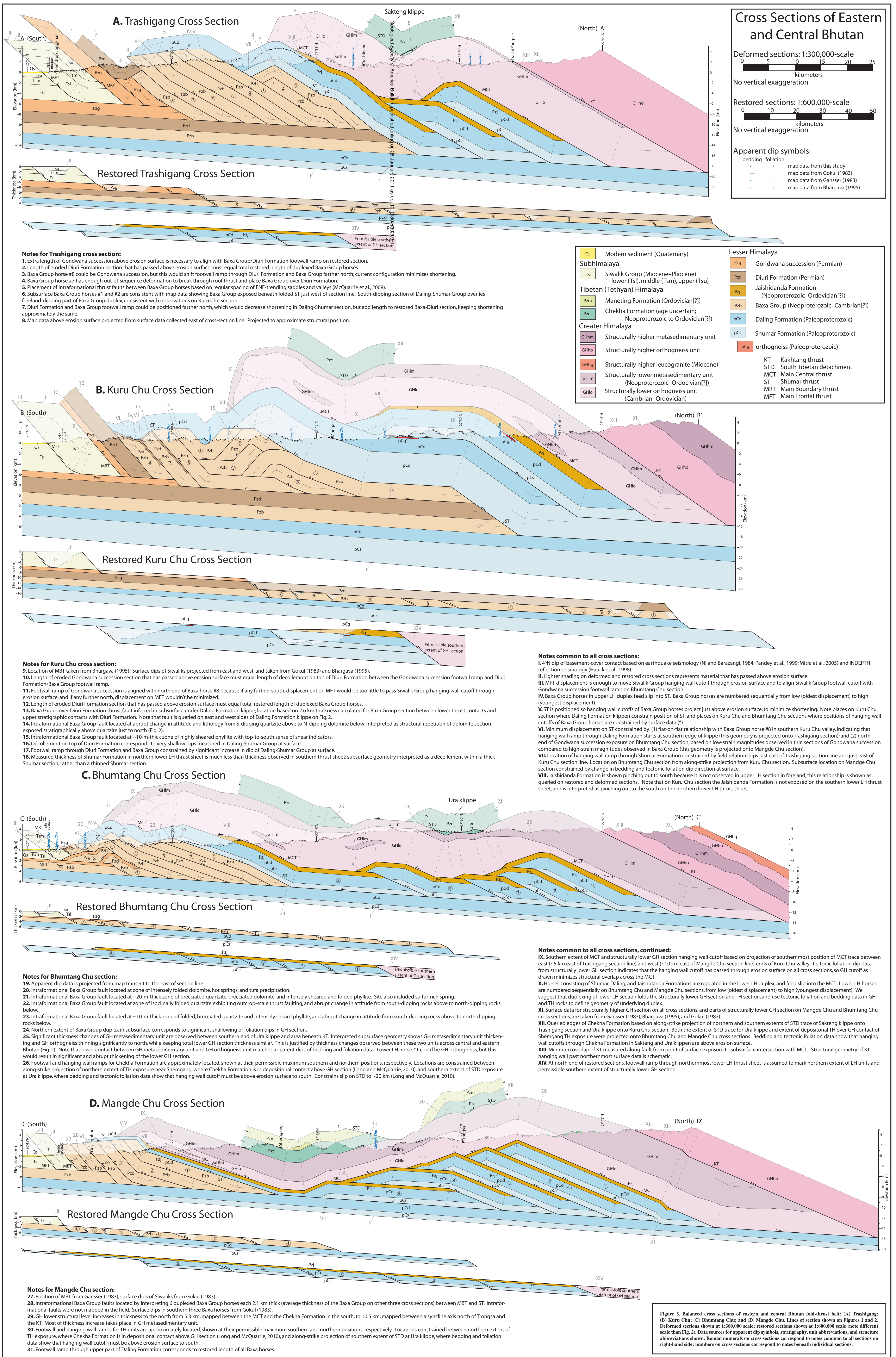


Figure 3. Balanced cross sections of eastern and central Bhutan fold-thrust belt: (A) Trashigang; (B) Kuru Chu; (C) Bhumtang Chu; and (D) Mangde Chu. Lines of section shown on Figures 1 and 2. Deformed sections shown at 1:300,000 scale; restored sections shown at 1:600,000 scale (note different scale than Fig. 2). Data sources for apparent dip symbols, stratigraphy, unit abbreviations, and structure abbreviations shown. Roman numerals on cross sections correspond to notes common to all sections on right-hand side; numbers on cross sections correspond to notes beneath individual sections.