

## Geological Society of America Bulletin

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*Geological Society of America Bulletin* 2003;115, no. 1;21-34  
doi: 10.1130/0016-7606(2003)115<0021:SEASOT>2.0.CO;2

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#### Notes

# Structural evolution and sequence of thrusting in the Tethyan fold-thrust belt and Indus-Yalu suture zone, southwest Tibet

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## ABSTRACT

Regional mapping of a north-south traverse from the India-Nepal-China border junction to Mount Kailas in southwest Tibet—combined with previously published geochronologic and stratigraphic data—is the basis for an incremental restoration of the Tethyan fold-thrust belt and deformation along the Indus-Yalu suture zone. From north to south, the major structural features are (1) the Indus-Yalu suture zone, composed of five south-dipping thrust faults involving rocks interpreted to represent parts of the former Indian passive margin and Asian active margin, (2) the Tethyan fold-thrust belt, composed of a dominantly north-dipping system of imbricate thrust faults involving Precambrian through Upper Cretaceous strata, and (3) the Kioagar-Jungbwa thrust sheet. A line-length cross-section reconstruction indicates a minimum of 176 km of north-south horizontal shortening partitioned by the Tethyan fold-thrust belt (112 km) and Indus-Yalu suture zone (64 km). Sequential restoration of the cross section shows that the locus of shortening prior to the late Oligocene occurred significantly south (possibly >60 km) of the Indus-Yalu suture zone within the Tethyan fold-thrust belt and that a significant amount of unsubducted oceanic lithosphere was present south of the suture in southwest Tibet until that time. An implication of this result is that postcollision (Oligocene/Miocene) high-K, calc-alkaline magmatism may be explained by melting due to active subduction of oceanic crust beneath the Kailas magmatic complex until the late Oligocene. A regional profile across the Tibetan-Himalayan orogen from

the Subhimalaya to the Gangdese Shan (Transhimalaya), along with previously reported shortening estimates in the central Himalaya, yields a minimum shortening estimate across the orogen of ~750 km.

**Keywords:** Tethys, Himalayan orogeny, Tibetan plateau, suture zones, thrust faults.

## INTRODUCTION

The deformation histories of suture zones are in general tremendously complex because they are commonly modified by multiple generations of syncollisional faulting (e.g., Dewey, 1977; Yin et al., 1994; Puchkov, 1997). The major tectonic elements of a “model” suture zone are well preserved, however, along a segment of the Indus-Yalu suture (also known as Indus-Yarlung suture) in southwest Tibet. This suture zone separates rocks with an Asian affinity to the north from those with an Indian affinity to the south. Plate-tectonic reconstructions of the Tibetan-Himalayan collision zone suggest that ~1000 km of shortening has been accommodated between southern Tibet and the Indian Shield (Patriat and Achache, 1984; Dewey et al., 1989; Chen et al., 1993; Patzelt et al., 1993) since the initial collision between India and Asia at ca. 55–50 Ma (Patriat and Achache, 1984; Rowley, 1996; de Sigoyer et al., 2000) or earlier (Yin and Harrison, 2000). Attempts to corroborate this total estimate with field-based structural studies have viewed the Tibetan-Himalayan collision zone as consisting of three belts that could have absorbed a significant proportion of the convergence: (1) the Himalayan fold-thrust belt (Gansser, 1964; Sinha, 1986; Schelling, 1992; DeCelles et al., 1998, 2001), (2) the Tethyan fold-thrust belt (Burg and Chen, 1984; Searle, 1986, 1996a; Steck et al., 1993; Ratschbacher et al., 1994), and (3) the Indus-Yalu suture zone (Heim and Gansser, 1939; Gansser, 1964; Burg and Chen, 1984; Yin et

al., 1994, 1999; Harrison et al., 2000) (Figs. 1A and 1B).

Although constraints have been placed on the magnitude of shortening of the Tethyan Sedimentary Sequence in the northwestern Tethyan Himalaya (Zanskar) and eastern Tethyan Himalaya in southern Tibet (Searle, 1986; Burg et al., 1987; Ratschbacher et al., 1994), there have been no estimates of Cenozoic shortening for the central Tethyan Himalaya in southwest Tibet. This paper presents a first attempt to better understand the sequence of Cenozoic thrusting in southwest Tibet and to quantify the magnitude of contraction within the Tethyan fold-thrust belt and Indus-Yalu suture zone between the Mount Kailas region in the north and the Nepal-India-China border junction to the south in southwest Tibet.

## REGIONAL GEOLOGY

The Himalayan fold-thrust belt lies between the Indian shield to the south and the Indus-Yalu suture zone to the north (Figs. 1A and 1B). It consists of four lithotectonic units bounded by four north-dipping Cenozoic fault systems: the Main Frontal Thrust, the Main Boundary Thrust, the Main Central Thrust, and the South Tibetan Detachment System, from south to north. Immediately south of the study area, in the Garhwal Himalaya, the Main Central Thrust and South Tibetan Detachment System correlate with the Vaikrita thrust and Malari fault, respectively (Valdiya, 1981, 1989) (Figs. 1A and 1B). The Lesser Himalaya is the structurally lowest thrust slice. It is bounded at the base by the Main Boundary Thrust and at the top by the Main Central Thrust and consists of Middle Proterozoic metasedimentary rocks, Paleozoic to Eocene sedimentary and volcanic rocks, and Cambrian–Ordovician granitic rocks (Brookfield, 1993; Parrish and Hodges, 1996; DeCelles et al., 2000). The Greater Himalaya Crystalline Sequence (also known as the High Himalayan

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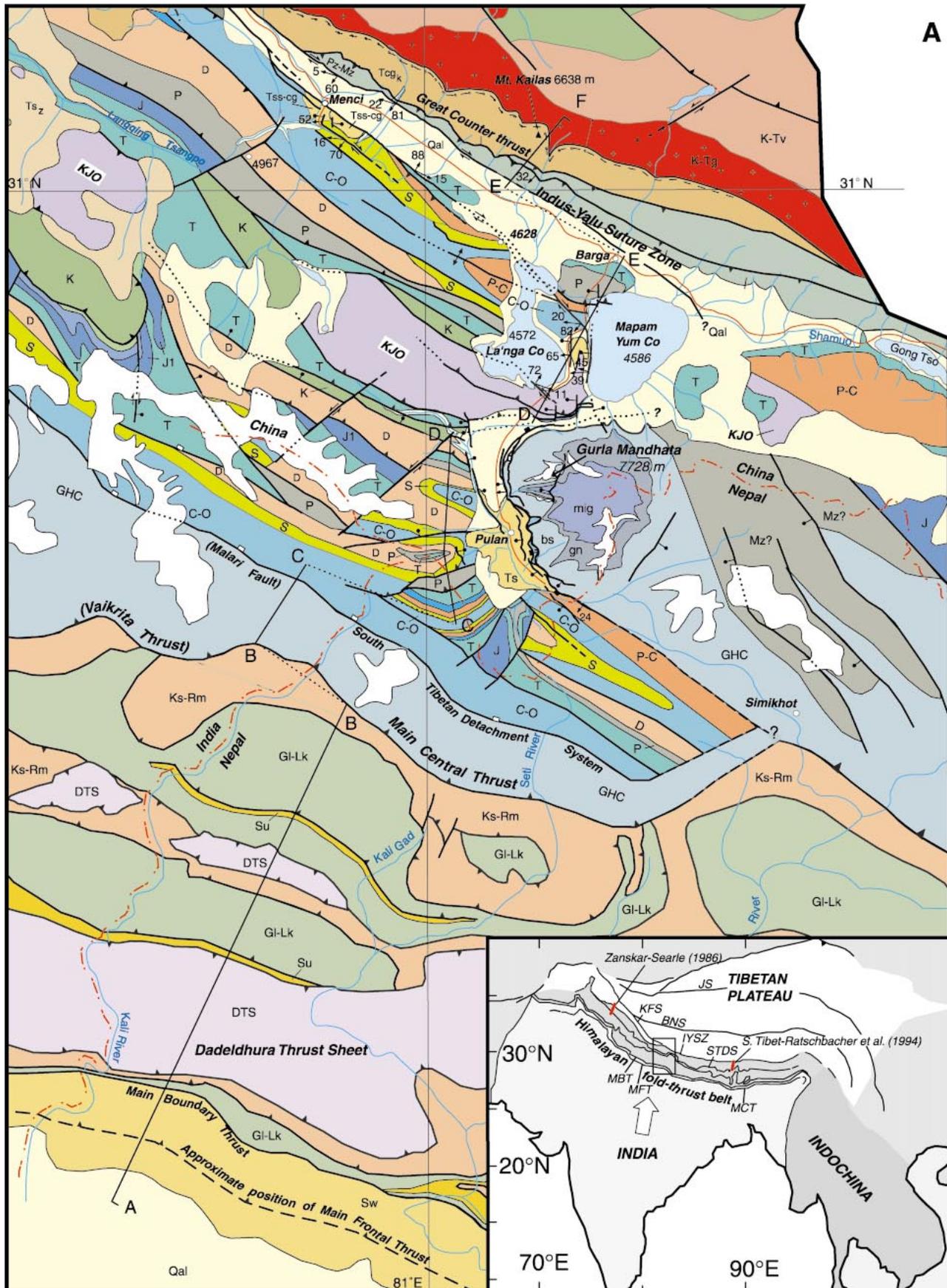
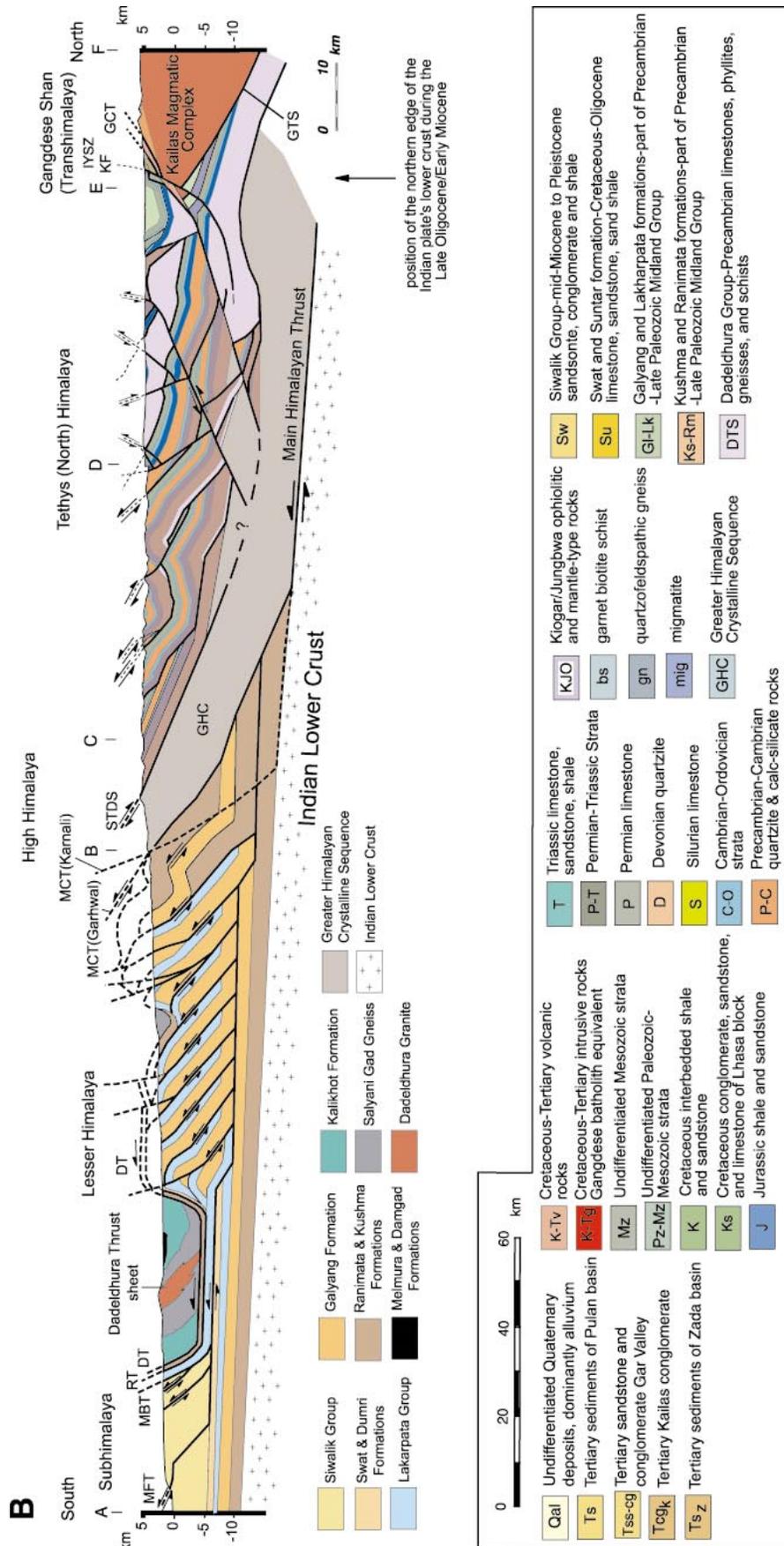


Figure 1.



**Figure 1. (Continued.)** (A) Regional geologic map of southwest Tibet and northwestern Nepal compiled from Heim and Gansser (1939), Valdiya (1981), Cheng and Xu (1987), Shrestha et al. (1987), DeCelles et al. (1998), Yin et al. (1999), and Murphy et al. (2000). Location of regional cross-section line (A–F) extending from the Subhimalaya to the Gangdese Shan (Transhimalaya) (Fig. 1B) is shown. The A–B segment of the regional cross section is taken directly from DeCelles et al. (1998). Inset shows location of study area and cross sections from Searle (1986) in Zaskar and Ratschbacher et al. (1994) in south Tibet. Abbreviations: JS—Jinsha suture; KFS—Ka rakoram fault system; BNS—Bangong-Nujiang suture zone; IYSZ—Indus-Yalu suture zone; STDS—South Tibetan Detachment System; MBT—Main Boundary Thrust; MFT—Mai Frontal Thrust; MCT—Main Central Thrust. (B) Regional cross section across the Himalaya on the basis of profiles published in Heim and Gansser (1939), DeCelles et al. (1998), and this study. Additional abbreviations: RT—Ramgarh thrust; DT—Dadeldhura thrust; KF—Karakoram fault; GCT—Great Counter Thrust; GT S—Gangdese thrust system. Formations in the Tethys Himalaya and Gangdese Shan (between C and F on the cross-section) correlate to those shown in Figure 2. Two different orientations are shown for the Main Central Thrust, on the basis of observations in the Garhwal and in the Karnali. We estimate 763 km of horizontal shortening between the Subhimalaya and the Indus-Yalu suture zone. If the displacement on all thrusts south of and including the Main Central Thrust is assumed to have fed into the Main Himalayan Thrust and underthrusting is assumed to have begun at 20 Ma, the leading edge of the Indian plate's lower crust would have been positioned beneath the Kailas magmatic arc complex shortly thereafter, thereby implying that oceanic lithosphere had been subducted beneath Asia until that time.

Crystalline Sequence) is bounded by the Main Central Thrust below and the South Tibetan Detachment System above (Burg and Chen, 1984; Burchfiel et al., 1992) and is composed of Neoproterozoic to lower Paleozoic meta-sedimentary, granitic, and volcanic rocks, and Tertiary granitic rocks (Le Fort, 1986; Parrish and Hodges, 1996; DeCelles et al., 2000). The Tethyan (or North) Himalaya lies between the South Tibetan Detachment System and the Great Counter Thrust, a major north-directed thrust system located along the Indus-Yalu suture zone (Heim and Gansser, 1939; Ratschbacher et al., 1994; Yin et al., 1999). It consists of late Precambrian to lower Paleozoic sedimentary and metasedimentary rocks (Gansser, 1964; Yin et al., 1988; Burchfiel et al., 1992; Brookfield, 1993; Garzanti, 1999) and thick Permian to Upper Cretaceous continental-margin sequences (Cheng and Xu, 1987; Brookfield, 1993; Garzanti, 1999). The entire sequence is commonly referred to as the Tethyan Sedimentary (or metasedimentary) Sequence.

Sedimentologic characteristics, trace-element isotope data, and U-Pb detrital zircon ages place the Greater Himalayan Crystalline Sequence north of, and partially at a higher stratigraphic level than, the Lesser Himalayan Sequence (Brookfield, 1993; Parrish and Hodges, 1996; DeCelles et al., 2000). A provenance study by DeCelles et al. (2000) suggested on the basis of U-Pb detrital zircon ages and Nd model ages that the Greater Himalayan Crystalline Sequence was accreted onto the Indian plate during Late Cambrian–Early Ordovician time along a paleosuture marked by the present Main Central Thrust. Sedimentologic characteristics, trace-element isotope data, and U-Pb detrital zircon ages suggest that the Greater Himalayan Crystalline Sequence may have served as the basement to the Paleozoic–Mesozoic succession of the Tethyan Sedimentary Sequence (Brookfield, 1993; Parrish and Hodges, 1996; DeCelles et al., 2000). Cenozoic convergence between India and Asia has resulted in shortening of the Tethyan Sedimentary Sequence across the entire Himalayan thrust front, forming the Tethyan fold-thrust belt (Fig. 1A inset map). Although schists and gneisses do exist in the Tethyan Himalaya, most are interpreted to have been exhumed by motion on syncollisional extensional structures (e.g., Gurla Mandhata—Murphy et al. [2002]; Kangmar dome—Chen et al. [1990]; Lee et al. [2000]) that postdate the Tethyan fold-thrust belt, therefore indicating that the thrust belt may be thin-skinned. If so, the basal detachment may be located along the contact between the Tethyan Sedimentary Se-

quence and the Greater Himalayan Crystalline Sequence.

The magnitude of shortening within the Himalayan fold-thrust belt is undoubtedly underestimated because of the lack of hanging-wall cutoffs and pervasive penetrative deformation within the hanging wall of the Main Central Thrust (e.g., Gansser, 1964; Brunel and Kienast, 1986; MacFarlane et al., 1992; Schelling, 1992; Hodges et al., 1996; DeCelles et al., 2001). Nonetheless, minimum shortening estimates north of the Main Boundary Thrust, but excluding the Tethyan fold-thrust belt, range from 193 to 260 km in the northwestern Himalaya of northern India (Srivastava and Mitra, 1994), 316 km in the western Nepal Himalaya (DeCelles et al., 2001), and 175–210 km in the eastern Nepal Himalaya (Schelling, 1992). Field studies suggest that the Tethyan Sedimentary Sequence has been shortened 100–126 km in the Zaskar region (Searle, 1986, 1996a; Steck et al., 1993) and 60 km (Hauck et al., 1998), 139 km (Ratschbacher et al., 1994), and 325 km (Burg et al., 1987) in south-central Tibet.

Over the past decade, field investigations and thermochronologic studies along the Indus-Yalu suture zone have recognized two phases of north-south shortening (Harrison et al., 1992, 2000; Ratschbacher et al., 1994; Yin et al., 1994, 1999; Quidelleur et al., 1997). The earlier phase (30–23 Ma) is associated with the south-directed Gangdese thrust system, resulting in juxtaposition of Gangdese granitoids in its hanging wall over the Tethyan Sedimentary Sequence in its footwall (Yin et al., 1994; Harrison et al., 2000). Modification of this earlier configuration occurred between 19 and 13 Ma in southwest Tibet and is associated with thrusting toward the north along the Great Counter Thrust (Yin et al., 1999), also referred to as the South Kailas thrust in southwest Tibet (Cheng and Xu, 1987; Murphy et al., 2000), the backthrust system (Ratschbacher et al., 1994), and the Renbu-Zedong thrust in southeast Tibet (Yin et al., 1994; Quidelleur et al., 1997; Harrison et al., 2000). Where observed, the thrust places the Tethyan Sedimentary Sequence in its hanging wall above the Gangdese batholith in its footwall. The Gangdese thrust system does not crop out in southwest Tibet (Yin et al., 1999). However, thermal modeling of  $^{40}\text{Ar}/^{39}\text{Ar}$  step-heating results from K-feldspar in a granite from the Kailas magmatic complex indicates a rapid cooling event between 30 and 25 Ma (Yin et al., 1999). In the absence of extensional structures of such age cutting the Gangdese batholith, the cooling ages may best be explained by slip on a structure equivalent to the Gangdese thrust system in southwest Tibet (Yin et

al., 1999). Thermal modeling of the Gangdese hanging wall in the Zedong area of southeast Tibet yields a slip rate of 7 mm/yr between 30 and 23 Ma, placing a minimum constraint on its displacement of ~50 km (Harrison et al., 2000). Thermal modeling of the hanging wall of the younger Great Counter Thrust in the Lian Xian area, east of Zedong in southeast Tibet, by Quidelleur et al. (1997) places a minimum constraint on the total displacement of 12 km. The total displacement on the Great Counter thrust in southwest Tibet has not been investigated prior to this study.

## GEOLOGY OF SOUTHWEST TIBET

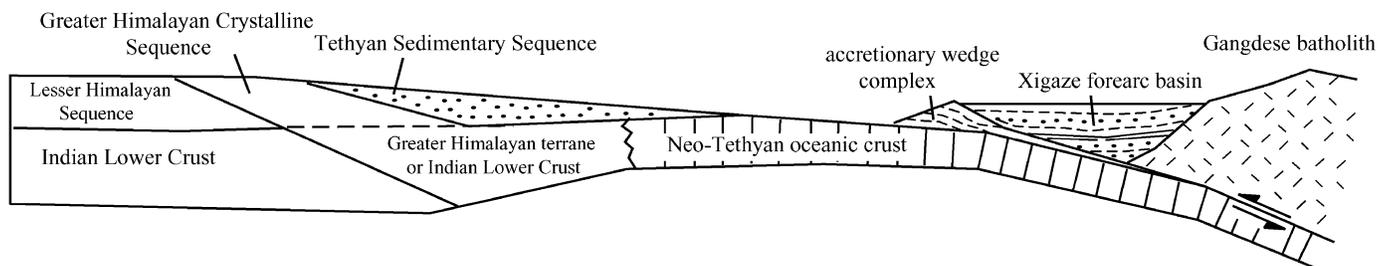
In the following section, we summarize the geologic relationships between the Mount Kailas area in the north and the China-Nepal-India border junction in the south (Fig. 2<sup>1</sup>), based on observations by Heim and Gansser (1939), Cheng and Xu (1987), Yin et al. (1999), and our recent field work in the region. Several components of the former Indian passive continental margin and Asian active margin are exposed along this profile. They are, from south to north, (1) the Tethyan Sedimentary Sequence (Indian passive-margin sequence), (2) the Kiogar-Jungbwa ophiolite (Neotethyan oceanic lithosphere), (3) the Indus-Yalu suture zone (Triassic–Cretaceous mélange and accretionary-wedge materials), (4) the Xigaze Group (forearc basin deposits), and (5) the Gangdese batholith (magmatic arc), which is also called the Kailas magmatic complex (Figs. 1–3). Figure 3 shows a schematic profile displaying the inferred tectonic framework across the India-Asia convergent margin prior to collision.

### Tethyan Sedimentary Sequence

On the basis of stratigraphic data collected by the Tibetan Bureau of Geology and Mineral Resources (Cheng and Xu, 1987) and our own geologic mapping (Fig. 2), we have compiled stratigraphic thicknesses of the Precambrian–Cretaceous units (Fig. 4). Although the total thickness of the units in the study area is nearly constant (9.6–9.3 km from south to north), the thickness of individual units does vary (Cheng and Xu, 1987).

Precambrian–Devonian strata are well exposed in the southern part of the study area, near Pulan (Figs. 1A and 2). These rocks consist of quartzites, calc-silicates, and minor limestone and dolostone, ~4.9 km thick (Fig. 4). Carboniferous–Permian strata are variably

<sup>1</sup>Figure 2 is on a separate sheet accompanying this issue.



**Figure 3.** Schematic north-south profile showing the major tectonic elements of the northern (passive) margin of the Indian plate and the southern (active) margin of the Asian plate prior to the onset of collision. Position of Lesser Himalayan Sequence, Greater Himalayan Crystalline Sequence, Indian plate's lower crust (Indian Shield-type rocks), and Tethyan Sedimentary Sequence after DeCelles et al. (2000).

exposed in southwest Tibet. Carboniferous strata are missing south of the Kiogar-Jungbwa ophiolite sheet, and only 333 m of Permian limestone is present in the thrust belt immediately west of Pulan (Cheng and Xu, 1987). North of the Kiogar-Jungbwa ophiolite thrust sheet, both Carboniferous and Permian strata are present and are as thick as 2100 m (Figs. 1A and 2). Elsewhere in the Tethyan Himalaya, two regional unconformities have been observed in the Upper Carboniferous (Pennsylvanian)–Lower Permian strata that have been attributed to rifting of the Lhasa block off the margin of India or other part of Gondwanaland (Leeder et al., 1988; Brookfield, 1993; Le Fort, 1996), which may explain missing Lower Carboniferous (Mississippian) strata along the southern part of the traverse. No Paleozoic rift-related structures have been observed in southwest Tibet, although they are probably present below the younger Mesozoic strata. The Triassic strata (1000 to 1122 m thick) were deposited in a shallow-marine environment and consist of interbedded silty limestone and fine-grained sandstone, containing abundant ammonites particularly to the west of Pulan (Fig. 4). The Jurassic through Cretaceous strata (3400–2250 m thick) consists of shale and minor siltstone, sandstone, and limestone. The Jurassic strata, south of the Kiogar-Jungbwa ophiolite thrust sheet, contain bivalves that indicate that a shallow-marine environment prevailed on the Indian passive margin at least until this time. The upper part of the Jurassic strata are dominated by fine-grained sandstone and shale. Tertiary strata within the Tethyan Himalaya are only present in the Pulan basin, which postdates thrusting and is interpreted to be related to late Miocene slip on the Gurla Mandhata detachment system (Fig. 1A).

#### ***Kiogar-Jungbwa Ophiolite***

Between Mapam Yum Co and La'nga Co ("Co" is "Lake" in Tibetan) on their south side (Figs. 1 and 2), a north-dipping thrust

places nearly unaltered norite and mantle-type rocks (dunite and harzburgite) in its hanging wall over fossiliferous sandstone, siltstone, and minor limestone of Jurassic to Cretaceous age in its footwall (Fig. 2). At the base of the thrust sheet is a foliated cataclasite containing numerous veins of calcite. Field evidence from slickensides, foliation patterns, chatter marks, and offset lithologic markers define three sets of faults: east-trending thrust faults, north-trending normal faults, and northwest-trending right-slip faults (Fig. 2). Faults displaying north-trending striations are cut by those displaying east-trending lineations. We interpret strike-slip and extensional structures within the thrust sheet to be related to recent slip on the Karakoram fault system and Gurla Mandhata detachment system (Murphy et al., 2002). The thrust sheet is poorly exposed near Mapam Yum Co (Fig. 2), and we therefore were unable to recognize any complete rock sequence. A more complete section of the thrust sheet was observed by Augusto Gansser (Heim and Gansser, 1939) near the southwest corner of La'nga Co (Fig. 1A). Gansser documented a north-dipping thrust sheet floored by an ~200-m-thick flysch sequence consisting of a Cretaceous limestone, Jurassic sandstone matrix, and blocks of Triassic carbonates and andesite of unknown age. Gabbroic rocks lie in tectonic contact above the flysch sequence (Gansser, 1979). Gansser (1979) linked the Cretaceous limestone with the flysch sequence, therefore placing a maximum age constraint on the emplacement of the ophiolitic rocks. Farther north, we observed that peridotite crops out for nearly 10 km. Unlike other ophiolite exposures in the Tethyan Himalaya, such as the Spontang ophiolite in Zanskar (Searle, 1986; Searle et al., 1997) or the Xigaze ophiolite in southern Tibet (Nicolas et al., 1981), a metamorphic sole at the base of the thrust sheet was not found. The fact that the flysch sequence documented by Gansser near La'nga Co is missing near Mapam Yum Co farther to the east suggests that

the thrust may have been reactivated, resulting in excision of the flysch sequence along strike (Fig. 1A). Moreover, the Kiogar-Jungbwa thrust sheet is bounded both to the south and north by Tethyan Sedimentary Sequence rocks, suggesting out-of-sequence-thrusting, similar to the Spontang thrust sheet (Searle, 1986; Searle et al., 1997). As mentioned already, the upper age constraint on slip along the Kiogar-Jungbwa thrust sheet is Cretaceous. In southeast Tibet, constraints on the crystallization age of the Indus-Yalu suture ophiolites are similar (late Albian–early Cenomanian according to Marcoux et al. [1981];  $119 \pm 25$  Ma according to Allègre et al. [1984]).

#### ***Indus-Yalu Suture Zone***

The boundary between rocks with an Asian affinity and those with an Indian affinity is currently defined by a south-dipping thrust system referred to as the Great Counter Thrust (Heim and Gansser, 1939; Yin et al., 1999) (Figs. 1A and 2); it has been referred to locally as the South Kailas thrust (Cheng and Xu, 1987). The Great Counter Thrust is a thrust system composed of at least five south-dipping thrust faults in southwest Tibet. From south to north, they place phyllitic schist over a sequence of limestone and sandstone that may be part of the Tethys Sedimentary Sequence. In the hanging wall of this thrust, serpentinized ophiolitic rocks are thrust over the phyllitic schist unit. We speculate, on the basis of the rock types juxtaposed, that the thrust is an older, folded, south-directed thrust that separates an accretionary-wedge complex above from metamorphosed Triassic turbidites below. Fault-slip analysis by Ratschbacher et al. (1994) determined that the transport direction on this fault is toward the southwest. Approximately 2 km to the north, a north-directed thrust places a folded limestone unit over purple sandstone. The limestone is in turn thrust northward over a >1-km-thick sequence of Cretaceous limestone and sandstone referred



to as the Yiema Formation by Cheng and Xu (1987) and correlated to the Xigaze forearc basin deposits by Liu (1988). The Yiema Formation is thrust northward over the Kailas conglomerate. Ratschbacher et al. (1994) determined a compression direction trend of  $033^\circ$  for the northernmost and southernmost backthrust. Yin et al. (1999) investigated the general stratigraphic framework of the Kailas conglomerate. They advocated a two-phase history, with the deposition of its lower section coeval with slip on a south-directed thrust equated to the Gangdese thrust system (Yin et al., 1994), whereas its upper section records north-directed motion on the Great Counter Thrust. Fault-slip data collected by Ratschbacher et al. (1994) (stations 8–9F and KAF) from the northernmost backthrust can be interpreted to record two deformation events, an earlier south-directed thrusting event followed by a later northwest-directed thrusting event. The earlier south-directed thrusting event may reflect motion along a fault equivalent to the Gangdese thrust. A late Oligocene–late Miocene age of the Kailas conglomerate is defined by  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages of both clasts and their apparent source in the Gangdese batholith (Harrison et al., 1993; Yin et al., 1999). The Kailas conglomerate lies unconformably above a granite that is a part of the Kailas magmatic complex (Honegger et al., 1982) correlated with the Gangdese batholith (Cheng and Xu, 1987; Liu, 1988).

### South Tibetan Detachment System

The main trace of the South Tibetan Detachment System crops out  $\sim 20$  km south of the study area. It is a down-to-the-north, low-angle normal-fault system that is traceable along the length of the Himalaya (Burg and Chen, 1984; Burchfiel et al., 1992). This feature places generally low-grade Tethyan metasedimentary rocks against the Greater Himalaya crystalline basement with variably deformed leucogranites commonly exposed in the footwall of the detachment system (Burg and Chen, 1984; Herren, 1987; Burchfiel et al., 1992; Edwards et al., 1996; Hodges et al., 1996). Augusto Gansser mapped such a relationship along the Kali river in Nepal, where the fault dips  $\sim 40^\circ$  to the north (Heim and Gansser, 1939). Within our study area, due west of the town of Pulan, we speculate that, on the basis of similar orientations, the top-to-the-north normal fault may be part of the South Tibetan Detachment System (Fig. 2). The timing of slip on the South Tibetan Detachment System in southwest Tibet is unknown. Elsewhere, however, U-Th-Pb dating of accessory minerals from synkinematic

dikes yields crystallization ages between 21 and 12 Ma (e.g., Zanskar—Noble and Searle [1995]; Shisha Pangma—Searle et al. [1997]; Nyalam—Scharer et al. [1986] and Xu [1990]; Rongbuk valley—Hodges et al. [1998] and Murphy and Harrison [1999]; Dinggye—Xu [1990]; Wagye La—Wu et al. [1998]; Gonta La—Edwards and Harrison [1997]).

### Karakoram-Gurla Mandhata Fault System

The dextral strike-slip Karakoram fault system and Gurla Mandhata detachment system merge within the study area (Figs. 1A and 2). On the basis of offset of recent geomorphic features, both faults are considered active (Karakoram fault—Molnar and Tapponnier [1978], Armijo et al. [1989], Liu [1993], Ratschbacher et al. [1994], Searle [1996b], and Murphy et al. [2000]; Gurla Mandhata detachment system—Ratschbacher et al. [1994], Yin et al. [1999], and Murphy et al. [2002]). Movement on them likely began in the late Miocene to early Pliocene in southwest Tibet (Ratschbacher et al., 1994; Searle, 1996b; Yin et al., 1999; Murphy et al., 2000). The Karakoram fault system extends into our study area as an  $\sim 36$ -km-wide zone of northwest-striking dextral strike-slip faults (Fig. 2). On the basis of timing, kinematics, and net-slip estimates, Murphy et al. (2002) suggested that the Karakoram fault system is linked to the Gurla Mandhata detachment system, thus making a large right step in the fault system (Fig. 1). The slip direction on the two fault systems is nearly coincident. The mean slip direction of the Karakoram fault system at its southern end, near Mount Kailas, is  $N70^\circ\text{W}$ ,  $30^\circ$  ( $\alpha_{95}$  confidence cone,  $30^\circ$ ). The mean slip direction of the Gurla Mandhata detachment is  $N80^\circ\text{W}$ ,  $20^\circ$  ( $\alpha_{95}$  confidence cone,  $10^\circ$ ). The magnitude of slip on the Karakoram fault system at its southern end is estimated to be 66 km on the basis of offset of the Great Counter Thrust. The footwall of the Gurla Mandhata detachment systems contains rocks that can be correlated with both the Greater Himalayan Sequence and Lesser Himalayan Sequence on the basis of their Sr-Nd isotopic ratios, implying these rocks originated below the Tethyan Sedimentary Sequence. Consideration of GASP (garnet-aluminosilicate-quartz-plagioclase) and GARB (garnet-biotite) thermobarometric results yields equilibration depths for the footwall rocks between 13.3 and 26.7 km, if a lithostatic gradient of 0.275 kbar/km (Murphy et al., 2002) is assumed. The shallowest equilibration depth imposes a limit to the maximum depth of the Tethyan Sedimentary Sequence. Moreover, considerations for the

original dip angle of the Gurla Mandhata detachment during exhumation of the footwall yield total-slip estimates of between 66 and 35 km across the Gurla Mandhata detachment system (Murphy et al., 2002).

### CROSS-SECTION RECONSTRUCTION

In order to better understand the structural relationship between these lithotectonic zones in southwest Tibet in the vicinity of the Indus-Yalu suture zone and their original paleogeographic position, we have restored a regional cross section (Fig. 5). Our geologic map is compiled from mapping by Augusto Gansser (Heim and Gansser, 1939), the Tibetan Bureau of Geology and Mineral Resources (Cheng and Xu, 1987), A. Yin and M.A. Murphy in 1995 (Yin et al., 1999), and field mapping by M.A. Murphy during 1997 and 1998 field seasons (Fig. 2). We make four general assumptions in our cross section: (1) The transport direction of the Tethyan fold-thrust belt was perpendicular to the trend of axial hinges of thrust-related asymmetric folds, i.e.,  $203^\circ$  (Fig. 2). The transport direction of the Great Counter Thrust system (Fig. 6), which was determined from the orientations of compression-related structures (Fig. 2) and fault-slip analysis (Ratschbacher et al., 1994), was toward  $033^\circ$ . The transport direction for the Kiogar-Jungbwa ophiolite thrust sheet is assumed to be parallel to the Tethyan fold-thrust belt, although measured thrust-related striations indicate a north-south motion. (2) The fold-thrust belt is thin-skinned, and the basal thrust (décollement) lies between the Tethyan Sedimentary Sequence and the Greater Himalayan Crystalline Sequence. (3) Thrusts propagated toward the foreland within the Tethyan fold-thrust belt, with the exception of the thrust directly north of the Kiogar-Jungbwa ophiolite thrust sheet. (4) Out-of-plane motion is not considered (Fig. 2). The cross section is length-balanced. Figures 5A through 5G summarize our proposed sequential development of the Tethyan fold-thrust belt and Indus-Yalu suture zone beginning with the precollisional setting. Figure 5G indicates 112 km of horizontal shortening in the Tethyan Sedimentary Sequence and 64 km of horizontal shortening in the Indus-Yalu suture zone. As no subsurface data exist, stratigraphic and structural relationships shown in the reconstruction are a first-order approximation at best. Moreover, because we do not take into account internal deformation (stylolites, cleavage, and isoclinal folding) within thrust sheets, our shortening estimate should be viewed as a minimum.

### Stage A (Early Cretaceous to Late Cretaceous)

The Neotethys oceanic lithosphere subducts beneath the Asian active margin (Fig. 5A). The configuration of the Asian active margin prior to collision is defined by those tectonic units exposed in the Great Counter Thrust system near Mount Kailas and in south-central Tibet where the Xigaze forearc basin deposits (Xigaze Group) are better exposed. U-Pb zircon data from the Kailas magmatic complex indicate that arc-related magmatism was occurring by the Early Cretaceous (120 Ma—Miller et al., 2000) in southwest Tibet. Farther to the east, geochronologic data indicate an older age for arc-related magmatism (130 Ma—Lhasa area, Harris et al., 1988; 147 Ma—Coqin area, 31° N, 85° E, Murphy et al., 1997). We assume the existence of a forearc basin in southwest Tibet prior to the India-Asia collision, although its present exposure is small compared to south-central Tibet (Liu, 1988). The discontinuous occurrence of the Xigaze Group along strike of the Indus-Yalu suture zone has been interpreted in two different ways. Yin et al. (1994) suggested that the Xigaze Group is preserved in south-central Tibet because the Gangdese thrust system outcrops to the south. In the Mount Kailas area, Yin et al. (1999) inferred the existence of an equivalent structure on the basis of thermal modeling results from the Kailas magmatic complex. Alternatively, Einsele et al. (1994) suggested that primary pinching out of trapped oceanic or transitional crust in the forearc could have controlled the occurrence of forearc basin deposits. On the basis of the limited occurrence of forearc deposits in southwestern Tibet, Einsele et al. (1994) interpreted very little, if any, oceanic or transitional crust to be trapped in the forearc. Although their model does offer an alternative explanation for the limited occurrence of forearc deposits in southwestern Tibet, the strong correlation between missing Xigaze forearc deposits and significant tectonic denudation of the Gangdese arc led us to favor the interpre-

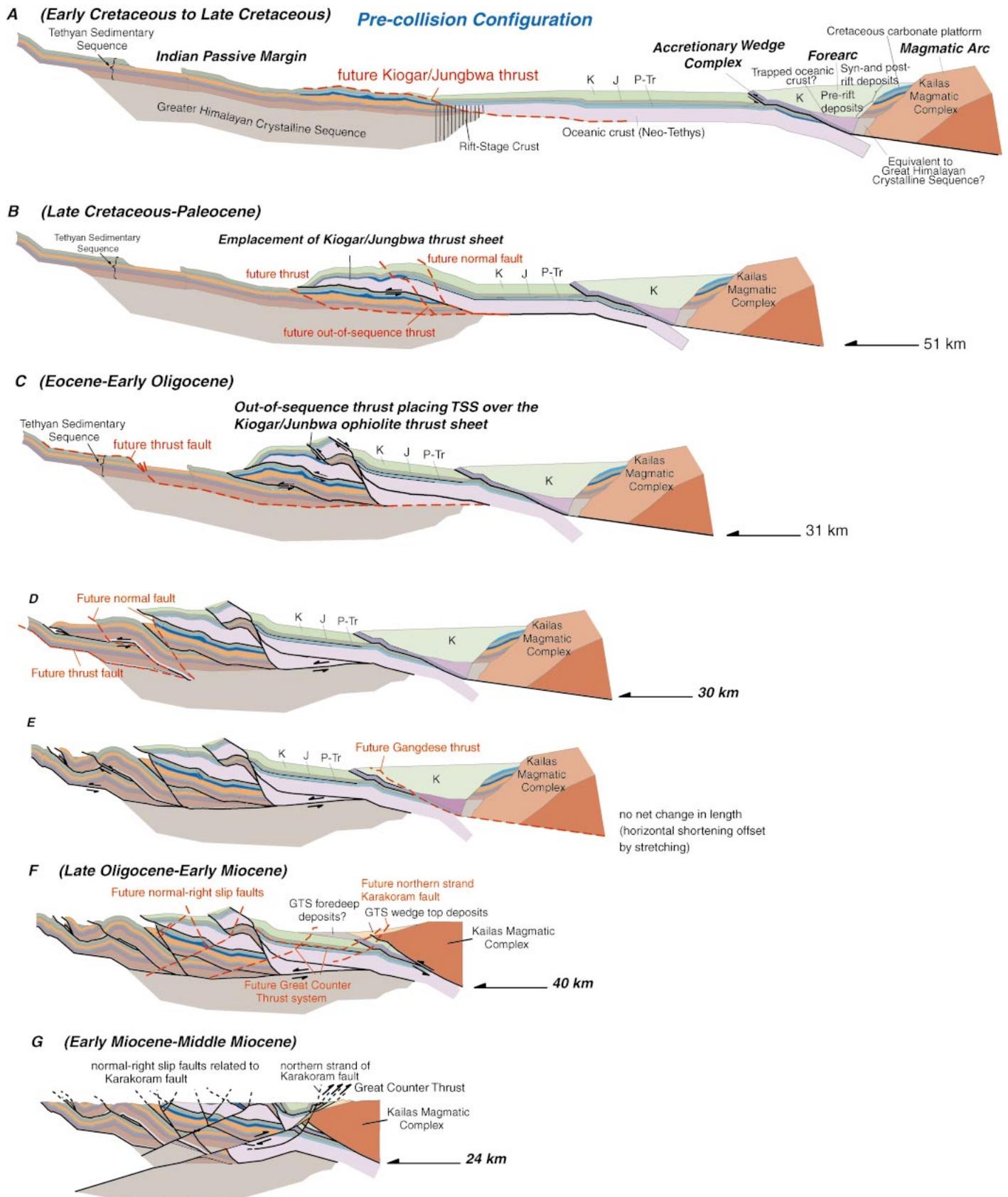
tation that the Xigaze forearc strata have been underthrust below the Gangdese batholith. The dimensions of the forearc shown are calculated from stratigraphic studies and structural reconstructions of the Xigaze Group in south-central Tibet (Ratschbacher et al., 1992; Dürr, 1993, 1996; Einsele et al., 1994; Dürr et al., 1995). Between Xigaze (82°52' E) and directly north of Saga (85°10' E), the overall structure of the Xigaze Group is a large synclinorium (Burg et al., 1987; Ratschbacher et al., 1992; Einsele et al., 1994). In the Jianguqinze area (88°10' E), the Xigaze Group restores to an original north-south length of ~65 km, implying a similar width of the forearc basin (Einsele et al., 1994). Burg et al. (1987) estimated a higher predeformational width of 80–100 km for the forearc basin in south-central Tibet. Measured stratigraphic sections in the Xigaze area by Dürr (1996) indicate that the original thickness of the Xigaze Group was ~12 km. It should be noted that these forearc basin dimensions are minimum values, as the margin of the forearc basin may have been removed by tectonic and erosional processes. As discussed in the next section, the Kailas magmatic complex is differentially denuded from south to north, which is consistent with a tilted thrust hanging wall over a ramp. In constructing the early cross sections, we have added a volume of granite to the Kailas magmatic complex (light red rocks in Fig. 5A) equal to that which, on the basis of thermochronology data presented in Yin et al. (1999), we estimate to have been removed by erosion. The accretionary-wedge complex is shown to be rather small (Fig. 5A). Its minimum thickness is defined by a separate reconstruction of the Great Counter Thrust (Fig. 6).

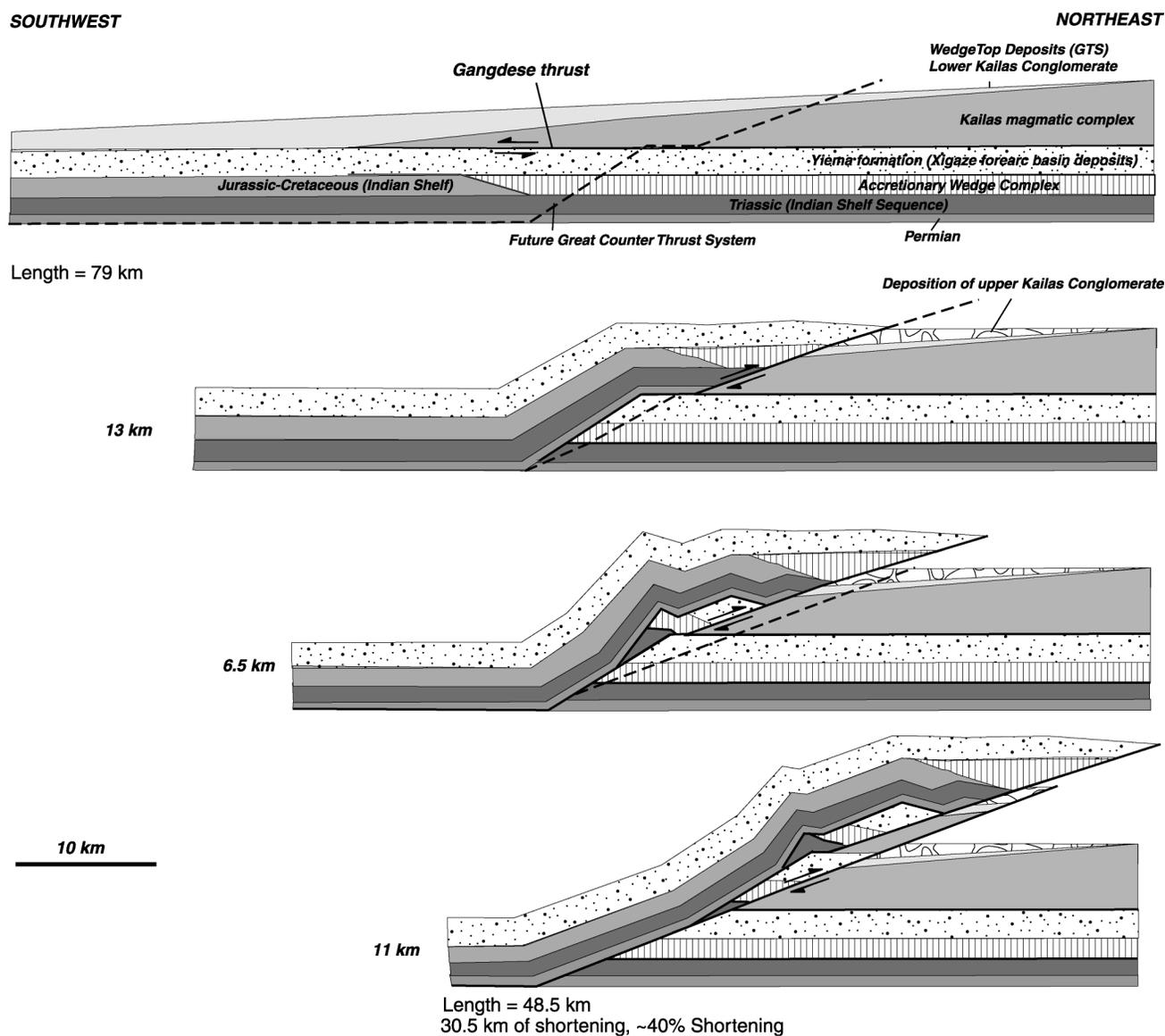
### Stage B (Late Cretaceous to Paleocene)

We interpret the earliest thrusting event to involve emplacement of the Kiogar-Jungbwa ophiolite thrust sheet onto the Tethyan Sedimentary Sequence (Fig. 5B). We estimate that 53 km of displacement (51 km horizontal

shortening) has occurred on the Kiogar-Jungbwa thrust. The magnitude of displacement is defined by the present surface exposure of the ophiolitic complex (~20 km) (Figs. 1A and 2) and the observation that Tethyan Sedimentary Sequence rocks that predate Permian rifting (Gaetani and Garzanti, 1991) of the Lhasa block from the northern margin of India are present north of the ultramafic rocks. As we show in Figure 5B, an out-of-sequence thrust may explain the presence of Tethyan Sedimentary Sequence rocks north of the Kiogar-Jungbwa ophiolitic thrust sheet. In stage B of our proposed sequence of events, the Kiogar-Jungbwa thrust sheet moved south over the passive continental margin; this scenario provides the necessary precondition for the inferred out-of-sequence thrust in the Tethyan Sedimentary Sequence. We view the 53 km as a minimum displacement because we chose the thrust sheet to have originated close to the continental borderland. Had the thrust originated farther north, within the oceanic lithosphere, there could be substantially more slip on the fault. The thrust that now juxtaposes the Kiogar-Jungbwa ophiolitic sequence against the Jurassic strata may well be a reactivated thrust, as seen by the lack of an metamorphic sole beneath the ophiolitic sequence. However, the initial stripping of the ophiolitic rocks from either transitional or oceanic lithosphere must have occurred prior to the collision, and prior to underthrusting of the Indian subcontinent. The mechanism for ophiolite obduction is uncertain. Studies by Aitchison et al. (2000) in southeast Tibet near Zedong (29°15' N, 91°45' E) suggest the presence of remnants of a south-facing (north-dipping) intraoceanic subduction system, south of the Indus-Yalu suture zone. Therefore, the ophiolite may have been obducted during the development of the subduction zone. The timing of its emplacement is likely slightly older than estimates for the timing of the initial collision between India and Asia. However, estimates for the onset of collision remain uncertain, varying between 70 Ma and 45 Ma, and probably reflecting the different

**Figure 5. Sequential cross-section restoration across the Tethyan Himalaya and Indus-Yalu suture zone. Cross sections are oriented N23°E. Reconstruction shows 60% horizontal shortening (176 km), corresponding to 112 km within Tethyan fold-thrust belt and 64 km within the Indus-Yalu suture zone faults (Great Counter Thrust and Gangdese thrust system) (see text for details). (A) Initial configuration prior to significant underthrusting of the Indian subcontinent (initial length 290 km). (B) Emplacement of the Kiogar-Jungbwa ophiolite thrust sheet over the Tethyan Sedimentary Sequence. C, D, and E: Propagation of the Tethyan fold-thrust belt toward the foreland. The largest of the thrusts juxtaposes Ordovician strata over Jurassic strata. (F) South-directed thrusting on the Gangdese thrust system (GTS) resulting in burial of the Xigaze forearc and accretionary-wedge complex and deposition of the lower section of the Kailas conglomerate as wedge-top deposits on the Kailas magmatic complex. (G) North-directed thrusting on the Great Counter Thrust system resulting in significant shortening of the Permian–Triassic strata, the accretionary-wedge complex, and the Yiema Formation (Xigaze forearc deposits) (see Fig. 6 for a detailed reconstruction of the Great Counter Thrust system).**





**Figure 6.** Development of the Great Counter Thrust system in southwest Tibet. Cross section is oriented N33° E and shows a total of 30.5 km (~40%) of horizontal shortening accommodated by three north-directed thrusts, which were initiated in the footwall of the preceding thrust. Configuration of the Indus-Yalu suture zone prior to slip on the Great Counter Thrust approximates that shown in stage F of Figure 5, in which the Kailas magmatic complex, in the hanging wall of the Gangdese thrust system (GTS), has been juxtaposed over the Yiema Formation (forearc deposits), in the thrust's footwall.

types of data used (Yin and Harrison, 2000). Examination of magnetic seafloor anomalies and fracture zones in the Atlantic and India Oceans indicates that India's northward motion slowed dramatically at ca. 45 Ma (Dewey et al., 1989; Le Pichon et al., 1992). Stratigraphic (Rowley, 1996) and metamorphic constraints (de Sigoyer et al., 2000) suggest initiation of collision in the northwest Himalaya at 55–50 Ma. These estimates are an upper bound for the timing of collision. Collision may have been earlier as sediments may have been subducted, and metamorphism due to burial by thrusting must have occurred ear-

lier than growth of peak metamorphic assemblages, depending on the regional thermal regime (e.g., England and Thompson, 1984). As mentioned earlier, the maximum age limit on slip of the Kiogar-Jungbwa ophiolite thrust sheet is Cretaceous, on the basis of the age of flysch-type rocks within the thrust zone (Heim and Gansser, 1939). The minimum age limit is poorly determined in southwest Tibet, but must predate the Gurla Mandhata detachment system because related structures cut the thrust sheet (Fig. 2). Elsewhere in the Tethyan Himalaya, the timing of ophiolite obduction was between Late Cretaceous and Paleocene

(see Burg et al. [1987] and Makovsky et al. [1999] for south-central Tibet and Searle [1996a] and Searle et al. [1997] for the northwest Himalaya), suggesting that the emplacement age for ophiolites along the Indian margin may be similar along strike.

#### Stage C (Eocene to Early Oligocene)

Development of two south-directed thrusts and one north-directed normal fault resulted in ~31 km of horizontal shortening. As just discussed, we interpret the existence of an out-of-sequence thrust to explain the presence of

Tethyan Sedimentary Sequence rocks to the north of the Kiogar-Jungbwa thrust sheet. This thrusting event may also explain the exposure of Precambrian–Cambrian rocks east of Mapam Yum Co immediately north of the Kiogar-Jungbwa ophiolitic complex (Fig. 1A). A similar kinematic interpretation was conceived by Searle (1986) to explain the position of the Spontang ophiolite. We infer the existence of a top-to-the-north normal fault in order to explain Permian strata juxtaposed against Ordovician strata. An unconformity may also explain this relationship. However, because an unconformity at these stratigraphic levels was not recognized in other parts of the study area, its aerial extent would necessarily need to be restricted to the northern parts of the Tethyan Sedimentary Sequence. Although we interpret the normal fault to be active at this stage, it is also possible that it slipped later and may be related to slip on the South Tibetan Detachment System (Figs. 1A and 1B). Alternatively, it may have formed during the initial development of the passive margin during the Permian.

#### Stage D (Eocene to Early Oligocene)

The thrust active during stage D shows the largest magnitude of slip, ~40 km of southward movement, resulting in ~30 km of horizontal shortening. Moreover, this thrust has the greatest observed stratigraphic throw along the profile and, as interpreted at depth, doubles the thickness of the Tethyan Sedimentary Sequence in the immediate area.

#### Stage E (Eocene to Early Oligocene)

The development of a south-directed thrust and two north-directed normal faults result in <1 km of total horizontal shortening across the profile compared to that shown in stage D (Fig. 5E). The south-directed thrust was not observed in the field, but it is inferred to account for the large antiform in the hanging wall of the inferred thrust where we show it to have developed as a fault-bend fold. The relationship between the normal faults, including the one shown in stage C, and thrust faults is uncertain. Either the normal faults are related to development of the thrust belt in a simple shear zone (Yin and Kelty, 1991) or are part of the South Tibetan Detachment System (Burchfiel et al., 1992). If the latter is true, then they probably were active later than what the reconstruction shows.

#### Stage F (Late Oligocene to Early Miocene)

South-directed thrusting on the Gangdese thrust system resulted in overthrusting of the

Yiema Formation (correlated to the Xigaze forearc basin deposits) and deposition of the Gangdese foreland basin system (Fig. 5F). Yin et al. (1999) interpreted the lower part of the Kailas conglomerate as wedge-top deposits related to slip on a thrust equivalent to the Gangdese thrust recognized in southeastern Tibet near Zedong (Yin et al., 1994). If correct, their interpretation would predict accumulation of the rest of the foreland basin system (foredeep, forebulge, back-bulge) (DeCelles and Giles, 1996) south of Mount Kailas. The ramp-flat geometry of the Gangdese thrust is suggested by the  $^{40}\text{Ar}/^{39}\text{Ar}$ -derived thermal history from a sample of granite (95-6-11-3) presented in Yin et al. (1999) and the erosional pattern of the Gangdese batholith in this region. The volcanic cover is eroded away in the south, but preserved to the north of Mount Kailas (Fig. 1A). Yin et al. (1999) showed that the granite was emplaced at an ambient temperature of ~400 °C and rapidly cooled from 30 to 25 Ma. A assumed geothermal gradient of 35°C/km puts this rock's intrusion level at a depth of 11.5 km. Harrison et al. (2000) estimated 50 km of displacement on the Gangdese thrust in southeast Tibet (Zedong window). To explain the increased denudation of the Kailas magmatic complex southward and overlying volcanic rocks to the south (K-Tv in Fig. 1A), we have drawn the Gangdese thrust to have a 30-km-long ramp dipping 30° to the north and a nearly horizontal, 44-km-long flat. Although we expect that the forearc basin is significantly shortened as its bedding is isoclinally folded and locally transposed in the study area, no attempt was made to define its magnitude owing to limited exposure in the study area.

#### Stage G (Early Miocene to Middle Miocene)

North-directed thrusting on the Great Counter Thrust system resulted in (1) stacking of the Cretaceous Xigaze forearc basin deposits, accretionary-wedge materials, and Triassic strata, (2) burial of the Gangdese thrust system, and (3) deposition of the upper Kailas conglomerate (Fig. 5G). Figure 6 shows a separate reconstruction of the Great Counter Thrust in which its development is modeled as a imbricate thrust system propagating toward the foreland. Approximately 20 km of shortening is shown to have been accommodated along a basal thrust lying along the Permian/Carboniferous contact. This position was chosen to explain the widespread occurrence of imbricated Triassic strata along the Indus-Yalu suture zone in southern Tibet (Liu, 1988). The rest of the displacement is accom-

modated along a later north-dipping thrust that extends to deeper structural levels. We have chosen not to root this thrust into the basal décollement between the Greater Himalayan Crystalline Sequence and the Tethyan Sedimentary Sequence, but instead, project it into the Greater Himalayan Crystalline Sequence. This choice is motivated by the potential link between the Great Counter Thrust and the South Tibetan Detachment System that is based on their compatible slip direction and coeval fault movement (Yin et al., 1999; Lee et al., 2000). The dip-slip component of faults related to the Gurla Mandhata detachment system and the Karakoram fault system have also been restored (Murphy et al., 2002).

Because the Karakoram fault system intersects the cross section, the assumption in our restoration that no out-of-the-plane motion has occurred is not valid. However, because dextral strike-slip faults that are part of the Karakoram fault system intersect the cross section at angles between 85° and 90°, <5 km of apparent shortening along the cross section is expected to have resulted from slip on these faults.

## DISCUSSION

Our reconstruction shows that the locus of Cenozoic crustal shortening (112 km) occurred significantly south of the Indus-Yalu suture zone during the early stages of the India-Asia collision. Although highly dependent upon the assumptions we made in our reconstruction, the geometry shown in our reconstruction results in preserving a >60-m-wide piece of oceanic lithosphere between the Tethyan fold-thrust belt and the Kailas magmatic complex until activation of the Gangdese thrust system in the Oligocene. Major and trace element contents and geochronologic data of the Kailas magmatic complex presented in Miller et al. (2000) indicate that high-K, calc-alkaline magmatism did not end until 40 Ma. Further consideration of the age and chemistry of younger volcanic rocks in the Mount Kailas area extends the arc-type igneous activity to the Miocene (Miller et al., 1999). A similar time-span for arc-type magmatism has been reported in Ladakh (Honegger et al., 1982) and southeastern Tibet (Harrison et al., 2000). These data indicate that fluid and thermal conditions remained appropriate for arc-type magmatism well after the onset of collision between India and Asia, regardless of which data set is used (Yin and Harrison, 2000). Rather than calling upon a complex mechanism to explain fluid influx and elevated temperatures, our reconstruction is consistent with melting due to active sub-

duction of oceanic lithosphere and the presence of an asthenospheric wedge beneath the Kailas magmatic complex until the late Oligocene or early Miocene.

In light of this conclusion, it is necessary to account for the amount of underthrusting of the Indian plate's lower crust beneath Asia in southwest Tibet. In Figure 1B we have combined our cross section with the balanced cross section by DeCelles et al. (1998) and the profile by Heim and Gansser (1939). We have attempted to line up all three cross sections by projecting the Jahla normal fault and Vaikrita thrust, which are equated with the South Tibetan Detachment System (and Zaskar normal fault [Herren, 1987; Burchfiel et al., 1992]) and the Main Central Thrust, respectively. DeCelles et al. (1998) calculated ~228 km of horizontal shortening of the Subhimalaya and Lesser Himalaya and later refined this estimate with more detailed mapping along the Seti River corridor to 460 km (DeCelles et al., 2001) (Fig. 1B). A minimum-shortening estimate for the Dadeldhura thrust and Main Central Thrust is 117 km (DeCelles et al., 2001). Along the Seti River and Karnali River corridors, considerably more shortening is required if both thrusts reached as far south as the Dadeldhura synform (DeCelles et al., 2001; Upreti and Le Fort, 1999). DeCelles et al. (2001) emphasized that the shortening estimate for the Main Central Thrust is a minimum estimate because internal deformation within its hanging wall is not accounted for. Srivastava and Mitra (1994) estimated between ~193 and 260 km on the Main Central Thrust and Almora thrust (equivalent to the Dadeldhura thrust) in northern India. Combining the shortening estimates for (1) the Subhimalaya and Lesser Himalaya along the Dadeldhura-Baitadadi road transect (DeCelles et al., 1998) (Fig. 1A), (2) the Main Central Thrust and Almora thrust (Srivastava and Mitra, 1994), and (3) the Tethyan fold-thrust belt and Indus-Yalu suture zone (this study) yields a total horizontal shortening estimate across the central Himalaya of 597–664 km. Alternatively, combining the shortening estimates along the Seti River corridor (DeCelles et al., 2001) with those in the Tethyan fold-thrust belt and Indus-Yalu suture zone yields a total shortening estimate of 763 km, which is clearly a minimum estimate because internal deformation within the hanging wall of the Main Central Thrust is not accounted for. If we assume that (1) all the southward displacement was accommodated along the Main Central Thrust, (2) thrusts south of the Main Central Thrust root into a thrust equivalent to the Main Himalayan Thrust (Zhao et al., 1993; Brown et al., 1996; Nelson et al., 1996), as

suggested by microseismic activity in far-western Nepal (Pandey et al., 1999) (Fig. 1B), (3) a shallow subduction angle for the Indian lithosphere, and (4) the configuration of the Greater Himalayan Crystalline Sequence, Lesser Himalayan Sequence, and the Indian plate's lower crust and lithospheric mantle that is shown in Figure 2, our reconstruction indicates that the northern edge of the Indian plate's lithosphere has been underthrust between 421 and 587 km north of the present position of the Indus-Yalu suture zone. If the shortening in the Himalaya was completely accommodated by flat subduction, then it would imply that the northern edge of the Indian continent has already reached the Jinsha suture separating the Qiangtang terrane from the Songpan Ganzi terrane (Yin and Harrison, 2000) (Fig. 1A). This possibility may be tested by geophysical observations of the lithospheric structure beneath the western part of the Tibetan plateau. In fact, preliminary results from seismic tomography, using the P1200 global data set (Zhou, 1996), appear to support this interpretation (H.-W. Zhou, 2001, personal commun.). However, our assumption that Indian lithosphere is inserted horizontally beneath Tibet appears to be inconsistent with the depth estimates for Indian coesite-bearing rocks in the Greater Himalayan Crystalline Sequence (O'Brien et al., 2001) and helium isotopic studies in southern Tibet by Hoke et al. (2000), who defined the southern limit of mantle-derived geothermal helium in southwest Tibet to coincide with the surface trace of the Karakoram fault (Fig. 1A). Because metamorphism of coesite-bearing rocks in the western Himalaya is estimated to have occurred in the Eocene (O'Brien et al., 2001), it is possible that the flat subduction of India was initiated later in the Oligocene with the arrival of less dense lithosphere (Indian continental lithosphere) as implied by our reconstruction. Regarding the observations made by Hoke et al. (2000), we note that their samples came from exclusively the active rifts or pull-apart basins in Tibet. As pointed out by Yin (2000), these rifts most likely involve thinning of both the Tibetan and Indian mantle lithosphere in southern Tibet, which may have also induced upwelling of the asthenospheric flow. Such upwelling would permit flat subduction of the Indian lithosphere beneath Tibet, as shown in our reconstruction.

The timing of underthrusting can be determined from the temporal estimates of displacements on individual thrusts shown in Figure 1B. The Main Central Thrust (Vaikrita thrust) in the Garhwal Himalaya was active at ca. 20 Ma (Metcalf, 1993). Farther east, in central Nepal, the Main Central Thrust is also

known to have been active in the early Miocene (Hubbard and Harrison, 1989; Hodges et al., 1996; Harrison et al., 1998), but was also reactivated in the Pliocene (Harrison et al., 1995, 1998; Catlos, 2000). DeCelles et al. (1998) interpreted offset on the Dadeldhura thrust to have begun at ca. 15–14 Ma, the oldest age of the Siwalik Group. Sediment-accumulation rates and magnetostratigraphic data from northern India suggest that offset on the the Main Boundary Thrust was initiated at ca. 11 Ma (Meigs et al., 1995; Burbank et al., 1996). DeCelles et al. (1998) interpreted the thrust to have formed somewhat later in the central Himalaya. The Main Frontal Thrust is active today (Nakata, 1989; Lavé and Avouac, 1999) and is interpreted to have been initiated coevally with the Pliocene upper Siwalik Group (DeCelles et al., 1998). These timing constraints indicate that underthrusting of the Indian Shield in southwest Tibet did not begin until the early Miocene and underthrusting rates have been on the order of ~21.3 mm/yr. By using this slip-rate estimate, the leading edge of the subducted part of the Indian Shield would have reached the Indus-Yalu suture zone around the early Miocene, thereby allowing arc-type magmatism to continue until that time.

## CONCLUSIONS

Cross-section restoration of a 111-km-long traverse from the India-Nepal-China border to Mount Kailas in southwest Tibet is used to estimate a minimum of 176 km of north-south Cenozoic horizontal shortening, which was partitioned between the Tethyan fold-thrust belt, including the Kiogar-Jungbwa ophiolite thrust sheet (112 km) and contractional structures along the Indus-Yalu suture zone (64 km). Sequential reconstruction of the cross section shows that the locus of Cenozoic shortening due to the India-Asia collision since the late Oligocene occurred significantly south (>60 km) of the Indus-Yalu suture zone within the Tethyan fold-thrust belt. Moreover, oceanic lithosphere was present south of the Indus-Yalu suture zone to the north and the Tethyan fold-thrust belt to the south until the late Oligocene when movement on the Gangdese thrust system was initiated in southwest Tibet. An implication of this reconstruction is that postcollision high-K, calc-alkaline magmatism in southwestern Tibet may be explained by melting due to active subduction of a remnant oceanic lithosphere beneath the Kailas magmatic complex until the Miocene. A regional profile across the Tibet-Himalaya orogen from the Subhimalaya to the Gangdese Shan (Transhimalaya), together with previous-

ly reported shortening estimates in the central Himalaya, yields a total shortening estimate across the orogen of 593–763 km. Timing constraints for thrusts south of and including the Main Central Thrust indicate that the underthrusting northern edge of the Indian Shield along the Main Himalayan Thrust did not reach the Indus-Yalu suture zone until the early Miocene, thereby allowing arc-type magmatism to persist north of the suture until that time.

#### ACKNOWLEDGMENTS

We gratefully acknowledge support in the field from Paul Kapp (University of Arizona), Ding Lin, and Guo Jinghui (Chinese Academy of Sciences–Institute of Geology and Geophysics) and funding from U.S. National Science Foundation grant EAR-9628178 (to An Yin and T.M. Harrison). Jean-Pierre Burg, Richard Law, and Lothar Ratschbacher provided careful reviews and many useful suggestions.

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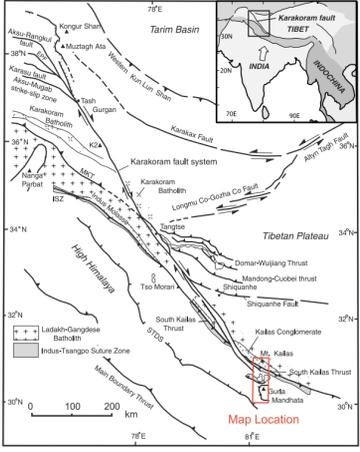
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MANUSCRIPT RECEIVED BY THE SOCIETY 23 APRIL 2001  
REVISED MANUSCRIPT RECEIVED 7 NOVEMBER 2001  
MANUSCRIPT ACCEPTED 2 MARCH 2002

Printed in the USA

# Geologic Map of the Mt. Kailas-Gurla Mandhata Area, southwest Tibet



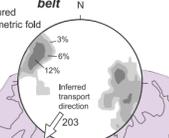
Quaternary units		Gurla Mandhata footwall	
Qbc	Landslide deposits	agn	Mylonitic augen gneiss
Qg	Glacial deposits - coarse clastic deposits, poorly sorted containing boulder-size clasts	mbt	Mylonitic marble
Qaf	Alluvial fan deposits - cobble-pebble gravel, sand, silt, and clay	bs	Mylonitic biotite schist, marble, leucogranite dikes and sills
Qal	Alluvial deposits - cobble-pebble gravel, sand, silt, and clay	gn	Mylonitic gneiss, leucogranite dikes and sills
Qtr2	River terrace deposits - cobble-pebble gravel, sand, silt, and clay	mig	Migmatite
Qtr1	Older river terrace deposits - cobble-pebble gravel, sand, silt, and clay	mg	Mylonitic leucogranite
Qc	Colluvial deposits - boulder-cobble-pebble gravel and sand	tb	Leucogranite
Pulian basin strata		Mapam Yum Co area	
Tcg3	Upper conglomerate unit - boulder-cobble-pebble gravel conglomerate	vc	Volcanic center?
Tcg2	Middle conglomerate unit - cobble-pebble-gravel conglomerate, sandstone & shale	ta	Agglomerate interlayered with vesiculated volcanic flows
Tcg1	Lower conglomerate unit - pebble-gravel conglomerate, sandstone and shale	ta	Agglomerate, siltstone, sandstone
Tethyan Metasedimentary Sequence		Mt. Kailas Area	
Kc	Cretaceous - shale and limestone	K-Tg	Kailas magmatic complex, Cretaceous-Tertiary granitoids
Js	Jurassic shale - contains ammonites	Tcg	Tertiary Kailas conglomerate
Tu	Undifferentiated Tertiary siltstone, sandstone, and siltstone	Kc	Cretaceous Vienna formation, conglomerate and sandstone
Pl	Permian limestone	Lm	Cretaceous limestone
Dqs	Devonian quartzite	bs	sandstone unit of unknown age
Sl	Silurian phyllite with minor quartzite	sch	schist of unknown age
Op2	Ordovician limestone, quartzite, tan phyllite	AWC	serpenitized ultramafic rocks, interpreted as accretionary wedge complex
Op1	Ordovician phyllite - reddish purple crinoid bearing		
Z-Cqs	Precambrian-Cambrian quartzite		
Z-Ccs	Precambrian-Cambrian calc-silicate rocks		

## Geologic Symbols

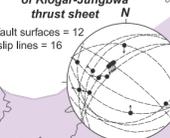
Lithologic contact: dashed where approximately located or inferred, dotted where concealed or inferred.  
 Faults: dashed where approximately located or inferred, dotted where concealed or inferred. Arrows indicate dip of the fault and orientation of lineations. Where two arrows exist, the greater number indicates the dip.  
 Strike-slip fault: opposing arrows indicate the sense of horizontal motion along the fault.  
 Thrust fault: barbs on hanging wall.  
 Normal fault: bar and ball on hanging wall.  
 small-scale ductile normal fault.  
 Detachment fault: (low-angle normal fault) box on hanging wall - open box on older detachment (GMDF 1), closed box on younger detachment (GMDF 2).

Folds: Arrows indicate the dip direction of the fold limbs. Arrow oriented parallel to the trace of the fold axis indicates the plunge direction. Dashed where approximately located and dotted where concealed.  
 Overturned anticline, Syncline, Anticline.  
 Strike and dip of beds: horizontal, inclined, overturned.  
 Strike and dip of foliation: transposed bedding, mylonitic foliation, younger, older.  
 Cleavage.

## Tethyan fold-thrust belt



## Fault-slip data from base of Kioagar-Jungbwa thrust sheet



## southern most strand of the Karakoram fault

contour interval 200m

## Kioagar-Jungbwa ophiolite thrust sheet

contoured asymmetric fold axes N=33

inferred transport direction

fault surfaces = 12, slip lines = 16

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