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Crustal deformation of the Lhasa terrane, Tibet plateau from Project INDEPTH deep seismic reflection profiles

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Abstract. International Deep Profiling of Tibet and the Himalaya (INDEPTH) deep reflection data in the Yangbajain-Damxung graben of southern Tibet yield evidence of magmatism and deformation beneath the southern Lhasa terrane and Yarlung-Zangbo suture. Shallow reflections and low-velocity first arrivals indicate a thin, Quaternary graben fill of generally less than a few hundred meters thickness. Underlying stratified reflections, extending to a maximum of about 11.5 km depth, likely originate from deformed Paleozoic-Cenozoic supracrustal strata of the Lhasa terrane. A prominent, undulatory band of reflections within the crystalline basement extends beneath the length of the Yangbajain-Damxung graben (depth ranges from ~12 km to ~18 km). This horizon has been interpreted to mark the top of a midcrustal partial-melt zone underlying southern Tibet. The undulatory character of this horizon additionally suggests that it may be tectonically deformed. A somewhat deeper, subhorizontal, wide-angle reflection extends southward beneath the outcrop of the Yarlung-Zangbo suture, indicating that the suture is cut off or superposed by a younger structure at depth. Three gently north dipping reflections at 19 km, 24 km, and 27 km depth beneath the Gangdese batholith are suggestive of a midcrustal duplex and may mark the northward (downdip) extension of the late Oligocene-early Miocene Gangdese thrust system. A prominent ~40° north dipping reflection imaged in the deep crust beneath the Gangdese batholith, between 40 and 60 km depth, might mark the downdip expression of the Yarlung-Zangbo suture or, alternatively, a younger reverse fault in the lower crust (or both). Viewed in aggregate, the reflection data are suggestive of moderate, postcollisional shortening of the upper crust of the Lhasa terrane, accompanied by melting of the middle crust. Although the data are permissive of wholesale underthrusting or fluid injection of Indian continental crust beneath the Lhasa terrane, they show no direct evidence for this having occurred.

1. Introduction

The ongoing collision between India and Asia is generally regarded as the type example of an active continent-continent collision [*Dewey et al.,* 1988]. The Himalaya and adjacent Tibetan plateau, which are the product of this collision, encompass the largest expanse of high topography and anomalously thick continental crust on Earth. The thickened crust and the existence of active thrust belts around the margins of the Tibetan plateau attest to the role of plate convergence in producing the plateau. How this convergence is accommodated within the crust and upper mantle underlying the Tibetan plateau, however, remains a central problem in the tectonics of the region and in the tectonics of mountain belts in general. The models that have been proposed to date can broadly be categorized in two "end-member" groups: (1) those in which Indian continental crust has been substantially underthrust beneath or injected into the crust of southern Asia [e.g., *Argand,* 1924; *Barazangi and Ni,* 1982; *Ni and Barazangi,* 1984; *Zhao and Morgan,* 1987; *Beghoul et al.,* 1993] and (2) those in which convergence has been accommodated largely by internal shortening of the preexisting Asian crust [e.g., *Dewey and Bird,* 1970; *Dewey and Burke,* 1973; *Houseman et al.,* 1981; *England and McKenzie,* 1982; *Dewey et al.,* 1988; *Molnar,* 1988]. The orientation of lithospheric subduction beneath the plateau and the extent to which the plateau's evolution can be viewed as a fluid dynamic process are also currently in debate [*Willett and Beaumont,* 1994; *England and Thompson,* 1986; *Houseman and England,* 1996; *Royden et al.,* 1997]. The existence of N-S trending graben systems and shallow earthquakes on the Tibetan plateau with first motions implying east-west extension indicate that the plateau crust is extending in an east-west direction, while convergence between India and Asia is ongoing [*Molnar and Chen,* 1983; *Armijo et al.,* 1986; *Molnar and Lyon-Caen,* 1988]. Models that have been proposed to explain this behavior include geometrically mediated radial spreading of the overriding (Himalayan) plate [*Seeber et al.,* 1981], eastward escape of the overthickened Tibetan crust [*Molnar and Tapponnier,* 1978; *Mercier et al.,* 1987], and extensional collapse of overthickened crust attendant upon mechanical thinning of the lithosphere [*England and Houseman, 1989*; *Molnar et al.,* 1993].

Each of these geodynamic models incorporates the assumption that the crust of the Tibetan plateau has been thickened as a result of the India-Asia collision. To date, however, geological evidence for collision-related shortening within the interior of the Tibetan plateau is sparse and geographically scattered [*Burg et al.,* 1983; *Coward et al.,* 1988]. Indeed, on the basis of a recent geological study in

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central Tibet, it has been argued that relatively little collision-related contractional deformation has occurred in the plateau crust [*Murphy et al.*, 1997]. Similarly, although evidence for Neogene-Quaternary east-west extension of the plateau is unassailable, constraints on the actual magnitude of east-west extension across the plateau and subsurface geometry of extensional structures have largely been lacking.

Recently, the International Deep Profiling of Tibet and the Himalaya (INDEPTH) project undertook geophysical and geological investigations in southern Tibet along a N-S transect at approximately 90° east longitude. INDEPTH is a collaborative geoscience project involving scientists of the Ministry of Geology and Mineral Resources of China and several North American and European institutions. The INDEPTH transect extends from the crest of the Himalaya to approximately the middle of the Lhasa terrane (Figure 1). It coincides largely with the Yadong-Gulu rift, which is one of the largest of the N-S trending graben systems crossing the Himalaya and southern Tibetan plateau. The valleys composing the rift provided a logistically feasible route for geophysical work in the otherwise mountainous terrain of southern Tibet. In this paper, we describe and interpret the multichannel seismic reflection data acquired within the rift north of the Yarlung-Zangbo suture zone. These northerly profiles lie within the Lhasa terrane, which composed the southern, active continental margin of Asia prior to the beginning of collision between India and Asia about 50 million years ago [*Searle et al.*, 1997]. A preliminary report of the entire INDEPTH reflection data set is given by *Brown et al.* [1996] and *Nelson et al.* [1996]. A detailed presentation of the reflection data acquired south of the Yarlung-Zangbo suture is given by *Hauck et al.* [this issue] and an analysis of the shallow structure of the Yadong-Gulu rift is given by *Cogan et al.* [1998].

2. Lhasa Terrane

The Tibetan plateau is composed of a series of terranes progressively sutured to Asia during Paleozoic and Mesozoic time [*Dewey et al.*, 1988]. The Lhasa terrane is the southernmost of these, whose accretion predated the arrival of India. The terrane is generally thought to have rifted from the southern hemisphere Gondwana supercontinent in Early Permian time and subsequently to have moved northward, colliding with the southern margin of Asia in Late Jurassic time [*Tapponnier et al.*, 1981; *Allegre et al.*, 1984; *Dewey et al.*, 1988]. This collision produced the Banggong suture which trends approximately E-W through the middle of the Tibetan plateau (Figure 1). After this collision, northward subduction of neo-Tethyan oceanic lithosphere initiated beneath the southern margin of the Lhasa terrane, resulting in the formation of the Gangdese batholith, which intrudes the southern half of the terrane [e.g., *Scharer et al.*, 1984; *Debon et al.*, 1986]. Initial contact with India along the Yarlung-Zangbo suture apparently occurred during Eocene time (~50 Ma), as manifest by a change from shallow water carbonate to north derived clastic sedimentation on the northern Indian margin, now preserved in the Tethyan Himalaya [*Tapponnier et al.*, 1981; *Burg and Chen*, 1984; *Searle et al.*, 1997]. Convergence between India and Asia has continued to the present in an intracontinental setting. Magmatism in the Gangdese arc also apparently continued for about 10 million years after the initiation of collision, as indicated by U-Pb crystallization ages in the Gangdese batholith that range to as young as ~40 Ma [*Scharer et al.*, 1984].

2.1. Stratigraphy

Bedrock of the Lhasa terrane exposed north of the Gangdese batholith consists of orthogneiss, generally regarded as the basement of the terrane, and an overlying supracrustal sequence of limestones, shales, and arenites of Paleozoic through Paleogene age [*Burg and Chen*, 1984; *Kidd et al.*, 1988]. Sedimentation appears to have occurred in a mostly shallow marine environment during Late Paleozoic and Mesozoic time, becoming more detrital during the Cretaceous [*Tapponnier et al.*, 1981]. The uppermost unit of the Paleozoic/Mesozoic sequence is the Takena Formation, a Cretaceous clastic unit that becomes continental upward. The Takena Formation is composed largely of silicic volcanic detritus [*Tapponnier et al.*, 1981; *Burg et al.*, 1983; *Kidd et al.*, 1988]. Cenozoic strata lie unconformably on the Takena Formation and older units. These include the calc-alkaline Linzizong Volcanics of Paleogene age, inferred to be the extrusive equivalent of the Paleogene part of the Gangdese batholith [*Allegre et al.*, 1984] and unconformably overlying Neogene/Quaternary clastic sediments composing the fill of the north trending graben and half graben that transect the Lhasa terrane. The basement gneisses and overlying supracrustal sequence are well exposed within and around the northeast trending Nyainqentanglha range, adjacent to the INDEPTH survey. On the basis of field mapping in the vicinity of Lhasa, *Burg et al.* [1983] suggested that the Paleozoic-Mesozoic section of the southern Lhasa terrane is about 5 km thick and that the overlying Linzizong Volcanics make up roughly an additional 2 km thickness. Scattered granitic plutons of Early Cretaceous age intrude the Paleozoic-Mesozoic supracrustals north of the main mass of the Gangdese batholith [*Chengfa et al.*, 1986]. It is presently unclear whether these are outliers of the Gangdese batholith or collisional granites associated with the Late Jurassic collision of the Lhasa terrane with southern Asia (Banggong suture).

2.2. Deformation

Geological evidence indicates that the southern Lhasa terrane in the vicinity of the INDEPTH survey was subject to north-south shortening in Late Cretaceous time prior to collision with India. Folds in the Takena Formation cropping out between Lhasa and Yangbajain are upright or verge slightly either to the north or south, and evidence 30 to 50% shortening [*Burg et al.*, 1983; *Coward et al.*, 1988]. The overlying, largely postinitial collision Linzizong Formation is also folded and locally faulted, but to a markedly lesser degree [*Burg et al.*, 1983; *Coward et al.*, 1988]. The regional extents of these fold phases are not well known; however, recent field mapping along a N-S transect in the Lhasa terrane, ~500 km west of the INDEPTH profiles, indicates that substantial N-S shortening also occurred there prior to collision with India, with substantially less shortening

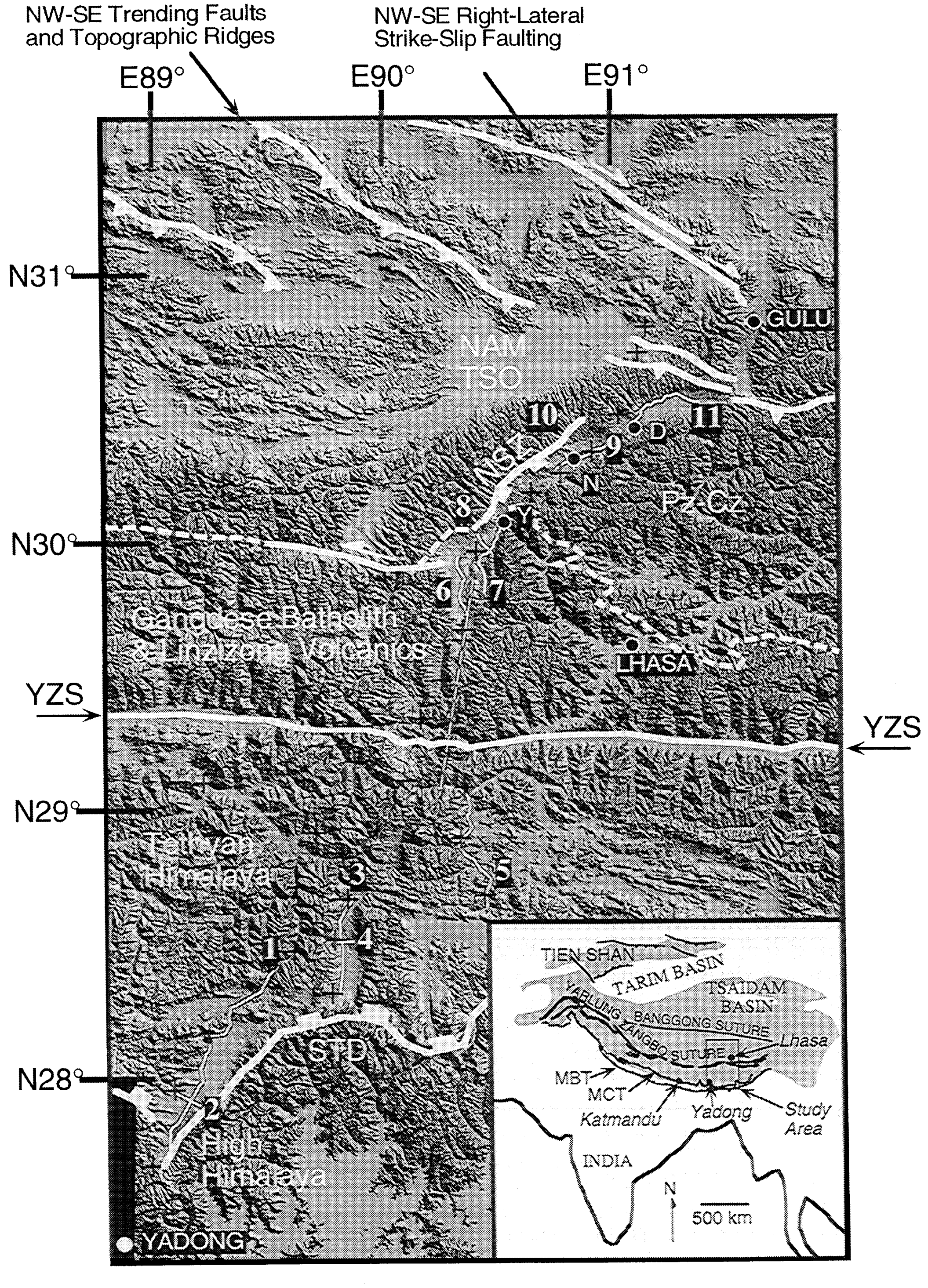


Figure 1. Topographic map showing the location of the International Deep Profiling of Tibet and the Himalaya (INDEPTH) Project seismic lines. The high topography of the Tibetan plateau and the Tien Shan is shaded in the location map. Major structural boundaries of the India-Tibet collision system include the Main Boundary Thrust (MBT), Main Central Thrust (MCT), South Tibetan Detachment (STD normal fault), and the Yarlung-Zangbo suture (YZS) [*Gansser,* 1983; *Burchfiel et al.,* 1992; *Kidd et al.,* 1988]. The Lhasa terrane is located north of the YZS. Generalized geologic units are also noted (Pz-Cz, Paleozoic-Cenozoic supracrustal section of the Lhasa terrane; Gangdese batholith and Linzizong volcanics are north of the YZS and mostly south of the ~EW trending dashed lined at ~N30°). Included are the following: NSZ is the Nyainqentanglha shear zone; ~N-S trending dashed line between Tib-5 and Tib-6 is the approximate location of the common midpoints (CMPs) for the wide angle section; strike-slip fault near Gulu is part of the Jiali shear zone of *Armijo et al.* [1989]; and Nam Tso is a large lake.

evidenced after the initiation of collision [*Murphy et al.*, 1997].

The Yarlung-Zangbo suture delineates the southern boundary of the Lhasa terrane. It is marked regionally by dismembered ophiolite fragments, melange, and late north vergent reverse faults [*Gansser*, 1964; *Burg and Chen*, 1984; *Ratschbacher et al.*, 1994]. Recent field geological and thermochronological observations indicate that the suture has been modified by two discrete phases of postinitial collision thrusting [*Yin et al.*, 1994; *Harrison et al.*, 1992]. During late Oligocene-early Miocene time, the Gangdese batholith was apparently thrust southward over its associated forearc basin (Xigaze Group) and the suture along a north dipping thrust fault termed by *Harrison et al.* [1992] the "Gangdese Thrust" system (GTS). The GTS crops out locally along the Yarlung river valley about 200 km east of the INDEPTH survey [*Yin et al.*, 1994]. *Yin et al.* [1994] have suggested that southward displacement and resulting throw on the GTS were substantially greater east of the Yadong-Gulu rift than to the west, based on thermochronologic data within the Gangdese batholith and the lack of preservation of both the Linzizong volcanic cover and the Xigaze forearc basin deposits east of the Yadong-Gulu rift as compared to the west. During Miocene time a system of "back thrusts" developed that transported Tethyan strata northward across the suture zone and southern margin of the Gangdese batholith in most areas truncating the GTS. The principal thrust in this system has been termed the "Renbu-Zedong Thrust" (RZT) by *Yin et al.* [1994].

Neogene/Quaternary E-W extension, manifest in the development of the Yadong-Gulu rift, is the latest deformational event recognized in the Lhasa terrane [*Armijo et al.*, 1986]. The northern Yadong-Gulu rift (north of the Yarlung River) is composed of several graben and half graben segments linked by strike-slip and oblique-slip fault zones. At its northern end, the rift is linked to a system of northwest trending strike-slip faults termed by *Armijo et al.* [1989] the "Jiali Fault system." *Coward et al.* [1988] and *Pan and Kidd* [1992] and have described a moderately southeast dipping, normal-sense ductile shear zone in the Nyainqentanglha range, bordering the northwest side of the northern Yadong-Gulu rift. *Pan and Kidd* [1992] termed this structure the Nyainqentanglha Shear Zone (NSZ) and suggested that the adjacent rift formed, in part, by slip on this low-angle detachment fault. *Harrison et al.* [1995], reporting thermochronological data derived from samples taken in the footwall of the NSZ, have subsequently argued that the NSZ initiated at about 7.5 Ma and that about 17 km of relative uplift of the footwall (Nyainqentanglha range) has occurred since that time. *Cogan et al.* [1998] combine these data with INDEPTH first-break (refraction) and shallow reflection observations and argue for a "rolling hinge-type" core complex model for the evolution of the Nyainqentanglha range and adjacent rift basin.

2.3. Existing Geophysical Observations

Seismic refraction data acquired in the early 1980s, as well as receiver function studies of INDEPTH broadband earthquake data, show that the crust beneath the southern Lhasa terrane is 70 to 80 km thick [*Hirn et al.*, 1984; *Kind et al.*, 1996]. Additionally, north-south wide-angle fan profiles collected by Sino-French investigators, recorded at near-critical distance for Moho reflections, show dipping arrivals in the deep crust of southern Tibet [*Hirn et al.*, 1984; *Shi et al.*, 1991]. These have been suggested by Sino-French investigators to mark reverse fault offsets of the Moho spaced several tens of kilometers apart in a N-S section and to have throws of 10 to 20 km [*Hirn et al.*, 1984; *Allegre et al.*, 1984]. This interpretation has been questioned by *Molnar* [1988], who noted that the dipping arrivals cannot unequivocally be shown to be Moho. One of *Hirn et al.*'s [1984] interpreted Moho offsets occurs beneath the Yarlung-Zangbo suture approximately 100 km west of the INDEPTH survey. The spacing of the more recent broadband earthquake observations is too coarse to unequivocally test the existence of these interpreted Moho offsets.

Earthquake seismological observations indicate that the uppermost mantle beneath southern Tibet is a fast and efficient propagator of seismic waves. There is no obvious change in the seismological properties of the upper mantle across the Yarlung-Zangbo suture [*Ni and Barazangi*, 1984; *Beghoul et al.*, 1993; *McNamara et al.*, 1994, 1995]. Similarly, shear wave azimuthal anisotropy is low beneath both the Tethyan Himalaya and southern Lhasa terrane. These observations have led a number of recent investigators to conclude that the Indian mantle lid extends northward in contact with the overlying crust to approximately the middle of the Tibetan plateau [e.g., *Beghoul et al.*, 1993; *Nelson et al.*, 1996; *Owens and Zandt*, 1997]. North of that position, the properties of the upper mantle change substantially [e.g., *McNamara et al.*, 1994, 1995].

3. INDEPTH Seismic Reflection Data

The INDEPTH seismic reflection profiles acquired north of the Yarlung-Zangbo suture consist of four main lines recorded within and roughly parallel to the northern Yadong-Gulu rift (Tib-6, Tib-7, Tib-9, and Tib-11 with an average length of ~23 km) and two crosslines (Tib-8 and Tib-10 with an average length of ~7 km) (Plates 1 and 2). The northern Yadong-Gulu rift is composed of a series of north to northeasterly trending subvalleys separated by relative topographic highs. The INDEPTH profiles lie within the Yangbajain (Tib-6, Tib-7, and Tib-8), Nyinzhong (Tib-9 and Tib-10), and Damxung (Tib-11) subvalleys (Plate 2), which collectively we refer to as the Yangbajain-Damxung graben. The lines were recorded with a 6-km-long, 240-channel telemetry recording system (25-m channel spacing and 200-m near offset) and explosive sources (Table 1). Drilling conditions within the northern Yadong-Gulu rift did not permit continuous profiling. A 37-km skip occurs between Tib-7 and Tib-9, and a 16-km skip occurs between Tib-9 and Tib-11. Additionally, there is a substantial skip in the CMP coverage across the Yarlung River valley and southern Gangdese batholith (between Tib-5 and Tib-6). Where profiling was possible, the choice of routes was limited by available roads and by the presence of rivers and wetlands; hence the lines are crooked and vary in distance from the valley edges. The profiles were recorded during the morning when wind noise was low. Processing of the seismic data included elevation and residual static and normal move-out corrections and signal-to-noise improvement filtering. A detailed description of the processing is provided by *Alsdorf et*

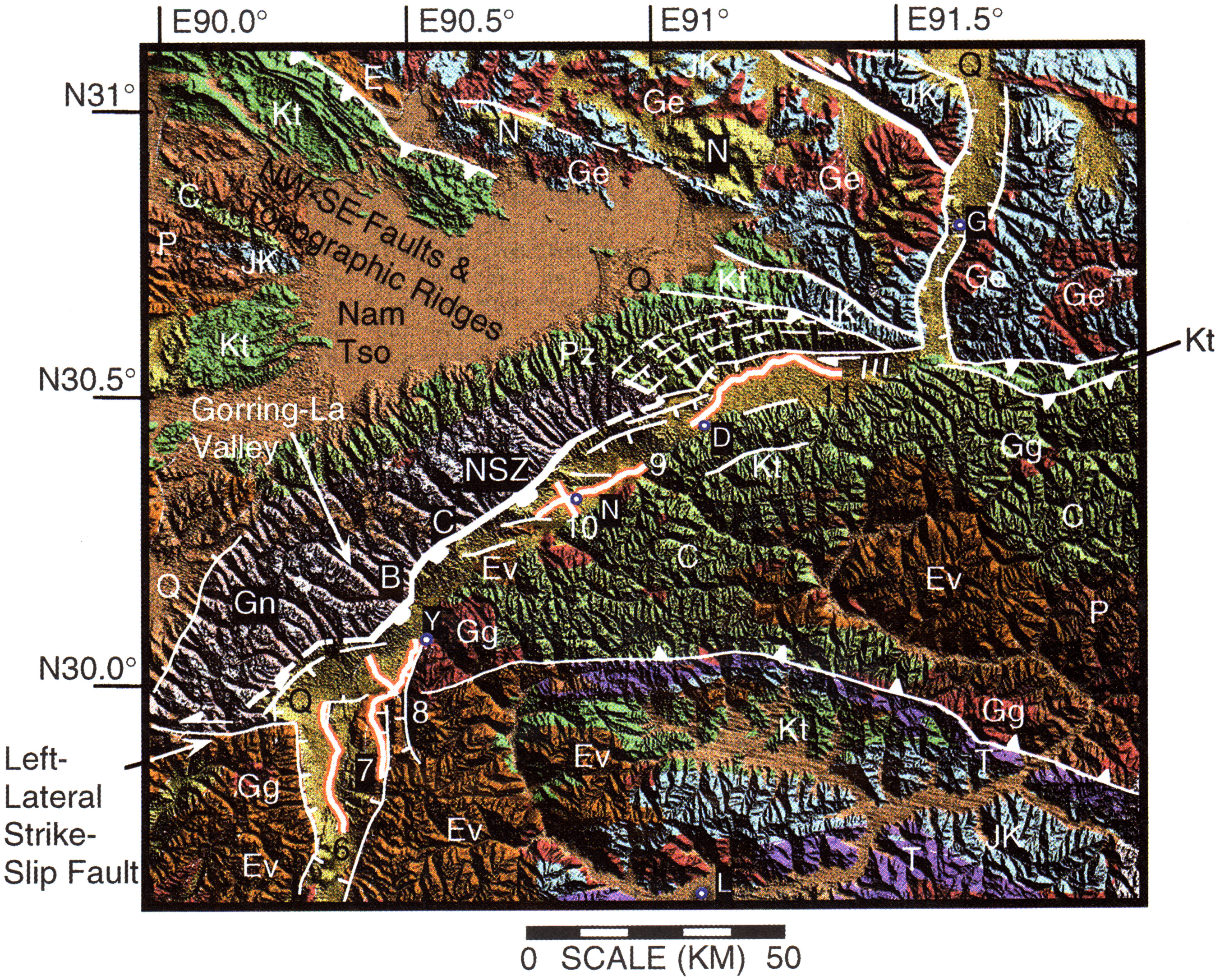


Plate 2. Geologic map of Yangbajain-Damxung graben [*Kidd et al.*, 1988] overlain on topography. Seismic lines Tib-6, Tib-7, Tib-8, Tib-9, Tib-10 and Tib-11 are white-on-red lines. Units include Gg, Gangdese batholith; Gn, Nyainqentanglha gneiss; Ge, north Lhasa terrane granitoids; C, carboniferous portion of the Lhasa terrane supracrustal sequence; P, Permian limestones and shales; T, Triassic limestones and shales; JK, Jurassic-Cretaceous arenites and shales; Kt, Takena Formation; Ev, Linzizong Volcanics; N, Neogene basin fill; and Q, Quaternary graben fill. Faults are bold white lines including the Nyainqentanglha shear zone (NSZ) of *Pan and Kidd* [1992]. The NSZ is mapped north of Tib-8 (locations "B" and "C" of *Pan and Kidd* [1992]; and Gorring-La valley of *Harrison et al.* [1995]; northwest of Tib-10 [*Clark* , 1996]), whereas its southwest extent is based on the exposed Nyainqentanglha orthogneiss. Its northward extent is unknown; here we suggest that it may follow the dashed white line. Right-lateral strike-slip fault near Gulu (i.e., part of the Jiali shear zone) connects with the Beng Co pull-apart basin to the NW [e.g., *Armijo et al.,* 1989]. Towns are marked by white on blue dots and include L, Lhasa; Y, Yangbajain; N, Nyinzhong; D, Damxung; and G, Gulu.

al. [1996] and *Alsdorf* [1997b]. For presentation purposes, the rift parallel lines north and south of the Yarlung-Zangbo suture were migrated using the constant-velocity method described by *Alsdorf* [1997a] and then merged into one profile (Plate 1). The gap in the CMP acquisition across the suture (between Tib-5 and Tib-6) is filled in with wide-angle reflection data acquired with portable seismographs (Y. Makovsky, S. L. Klemperer, L. Ratschbacher, and D. Alsdorf, Mid-crustal reflector truncating the India-Asia suture from INDEPTH wide-angle profiling in southern Tibet, submitted to *Tectonics*, 1998, hereinafter referred to as Makovsky et al., submitted manuscript, 1998). These data provide low-fold information on the middle and lower crust, but because of relatively large source-receiver offsets, they do not effectively image the upper crust (above approximately 18 km depth).

In the following sections, we describe the geometry and physical attributes of the prominent reflections observed in the common midpoint (CMP) data within the Lhasa terrane.

Table 1. Details of the Acquisition and Source Parameters for Tib-6 Through Tib-11

Recording Parameter	Value	
Recording system	Wave-3	
Number of channels	240	
Geophones	10 Hz	
Receiver group spacing	25 m	
Number geophones/group	27	
Receiver array	25 m, uniform linear	
Record length	50 s	
Sample interval	4 ms	
Near offset (normal)	200 m	
Far offset (normal)	6200 m	
Near offset (large shots)	3000 m	
Far offset (large shots)	9000 m	
Explosive Seismic Source	Normal	Optional
Shot size	50 kg	200 kg
Shot depth	50 m	50 m
Shot spacing	200 m	6000 m
Shot pattern	Single Hole	Four Holes
Profile Name	Length, Km	
Tib-6	22	
Tib-7	28	
Tib-8	9	
Tib-9	20	
Tib-10	5	
Tib-11	31	

Shallow holes were used when drilling conditions prevented charge placement at target depth of 50 m. Shot depth averaged ~25 m for the survey.

The descriptions reference the composite profile shown in Plate 1 and the close-up views of the reflection profiles shown in Figures 2 and 3.

3.1. Paleozoic-Paleogene Supracrustal Sequence of the Lhasa Terrane

Reference to Figures 2 and 3 shows that the upper few kilometers to approximately 11.5 km of the crust beneath the Yangbajain-Damxung graben is characterized by variably dipping stratified reflections ("1" in Figures 2 and 3). These appear to originate from the Paleozoic-Paleogene supracrustal sequence of the Lhasa terrane. Beneath Yangbajain valley, southwest dipping reflections composing this package imaged on Tib-7B extend to 11.5 km depth and tie with northwest dipping reflections on Tib-8 yielding a locally determined true strike and dip of 357°, 31°W. To the north, beneath Nyinzhong valley, the base of this reflection package varies between about 3 and 8 km depth, and the reflections have an apparent dip to the northeast (Tib-9, Figure 3). Farther north, beneath Damxung valley, the reflection package thins to just a few kilometers thickness and exhibits variable internal dip. In general, the thickness and variable dip of this reflection package is consistent with the mapped ~7 km thickness and folded character of the Paleozoic-Paleogene supracrustal sequence exposed in the vicinity of the INDEPTH lines [*Burg et al.,* 1983]. Additionally, the reflections composing this package beneath Yangbajain valley project upward to the supracrustal strata exposed in the mountains to the southeast. We therefore interpret the stratified reflections ranging from a few kilometers to 11.5 km depth beneath the Yangbajain-Damxung graben to mark the supracrustal sequence of the Lhasa terrane, and we interpret the immediately underlying unreflective section to mark the crystalline basement. Because the deformation associated with the Takena and older formations is principally Late Cretaceous in age [*Burg et al.,* 1983], the correlation also suggests that the geometry of the supracrustal reflections is largely a consequence of precollisional deformation.

In general, the Neogene-Quaternary sedimentary fill of the Yangbajain-Damxung graben appears to be less than a few hundred meters deep along most of the graben system. For the most part, it is too shallow to be imaged effectively on the CMP profiles. The first arrivals (i.e., refracted arrivals) on the INDEPTH shot gathers typically exhibit a near-source leg with apparent velocities between 2.0 and 3.0 km/s, whereas subsequent legs exhibit apparent velocities in excess of 4.5 km/s. The slower velocities are appropriate for weakly consolidated sands and gravels, and the faster velocities are typical of lithified sedimentary or crystalline rock. The low-velocity "surficial layer" likely represents the poorly consolidated Neogene-Quaternary fill of the graben system. *Cogan et al.* [1998] have analyzed the refracted arrivals on the INDEPTH crosslines and have shown that the base of the low-velocity fill generally dips gently to the southeast beneath the crosslines and reaches a maximum thickness of only about 800 m beneath the southeast end of Tib-8. We have also analyzed the refracted arrivals on the rift parallel lines. In general, the low-velocity surficial layer averages only about 260 m along these lines (apparent velocity ranges from 1550 to 3700 m/s, and thickness ranges from 80 to 846 m). Locally, at the southern end of Yangbajain valley (Tib-6, "2" in Figure 2) and at the northern end of Damxung valley (Tib-11, "2" in Figure 3), shallow reflections with appropriately low stacking velocities are observed from the graben fill (Tib 6A, locally to ~1100 m depth and Tib 11C locally to ~ 2800 m depth).

3.2. Nyainqentanglha Shear Zone

One of the more prominent shallow reflections on the INDEPTH profiles projects updip to the low-angle NSZ exposed along the NW side of Nyinzhong valley. Mylonites defining the NSZ adjacent to Tib-7 and Tib-9 (Plate 2, location C of *Pan and Kidd* [1992]) strike ~N40°E and exhibit C surfaces dipping 24°-26° southeast. INDEPTH field observations also show that the NSZ crops out just west of Tib-10 [*Clark,* 1996]. A shallow reflection on Tib-10, with an apparent southeast dip of 25°, ties with a prominent reflection on Tib-9, with an apparent northeast dip of 9° ("3", labeled NSZ in Figures 3 and 4). The true attitude (046°, 26°SE) and depth (3.8 km) at the tie point of this reflection are such that it projects upward to the outcrop of the NSZ.

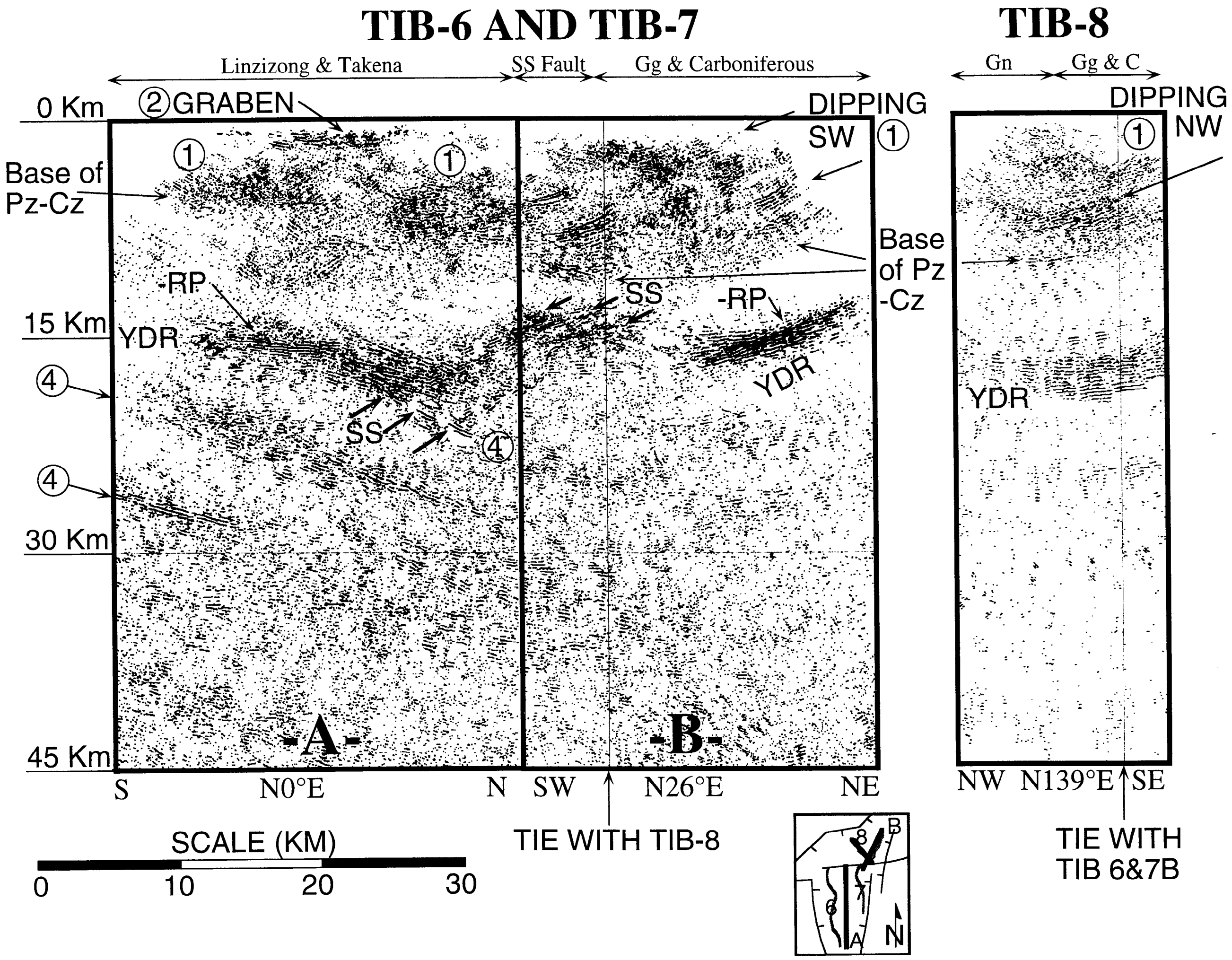


Figure 2. Migrated CMP reflection profiles Tib-6, Tib-7, and Tib-8. Small map denotes the general position and orientation of each line segment (detail locations are given in Plate 2). As discussed in text and Figure 5, portions of Tib-6 and Tib-7 have been added together where they overlap to form segment -A-. SS denotes likely sideswipe reflections of the graben-bounding faults; thus they are not associated with deep structures (see Figure 5). These SS events are not interpreted as part of the Yamdrok-Damxung reflection sequence, that is the YDR. Numbers with circles follow from Plate 1. Several reflections have negative reflection polarity (-RP) [*Brown et al.,* 1996]. Surface geology noted across the top is based on Plate 2.

To the southwest beneath Yangbajain valley (Tib-6, Tib-7, and Tib-8, Figure 2), there is no similarly prominent reflection that can be attributed to the NSZ. However, the observation that the Nyainqentanglha orthogneiss is exposed in the footwall of the NSZ suggests that the NSZ likely lies at or beneath the supracrustal-basement contact on the lines in the Yangbajain valley. Thus, if the previous interpretation of the supracrustals is correct, the NSZ is likely to be at least 11.5 km deep on Tib-6, Tib-7, and Tib-8. This minimum depth is compatible with the 10+ km emplacement depth of the Nyainqentanglha orthogneiss based on its metamorphic assemblage [*Harris et al.,* 1988] and with the ~15 km of tectonic denudation of the range inferred from $^{40}Ar/^{39}Ar$ cooling histories of samples collected in the footwall of the NSZ [*Harrison et al.,* 1995].

Identification of the NSZ to the northeast of Nyinzhong valley is hindered by discontinuities in the reflection and by the skip in acquisition between Tib-9 and Tib-11. The projection of the NSZ reflection from the tie point on Tib-9 and Tib-10 to the northeast is close to the four prominent reflections labeled NSZ? on Tib-9 and Tib-11 in Figure 3. One of these four reflections locally exhibits negative reflection polarity (-RP) [*Brown et al.,* 1996] (Figure 3). Projection of these reflections updip (reflection attitude of 050°, 35° SE) suggests that the NSZ should surface within the Paleozoic section exposed in the northern Nyainqentanglha range (Plate 2). This is consistent with the geologic interpretation of *Cogan et al.* [1998], who have suggested that the NSZ beneath the Damxung graben splays upward into a series of oblique-slip normal faults cutting the Paleozoic section exposed in the

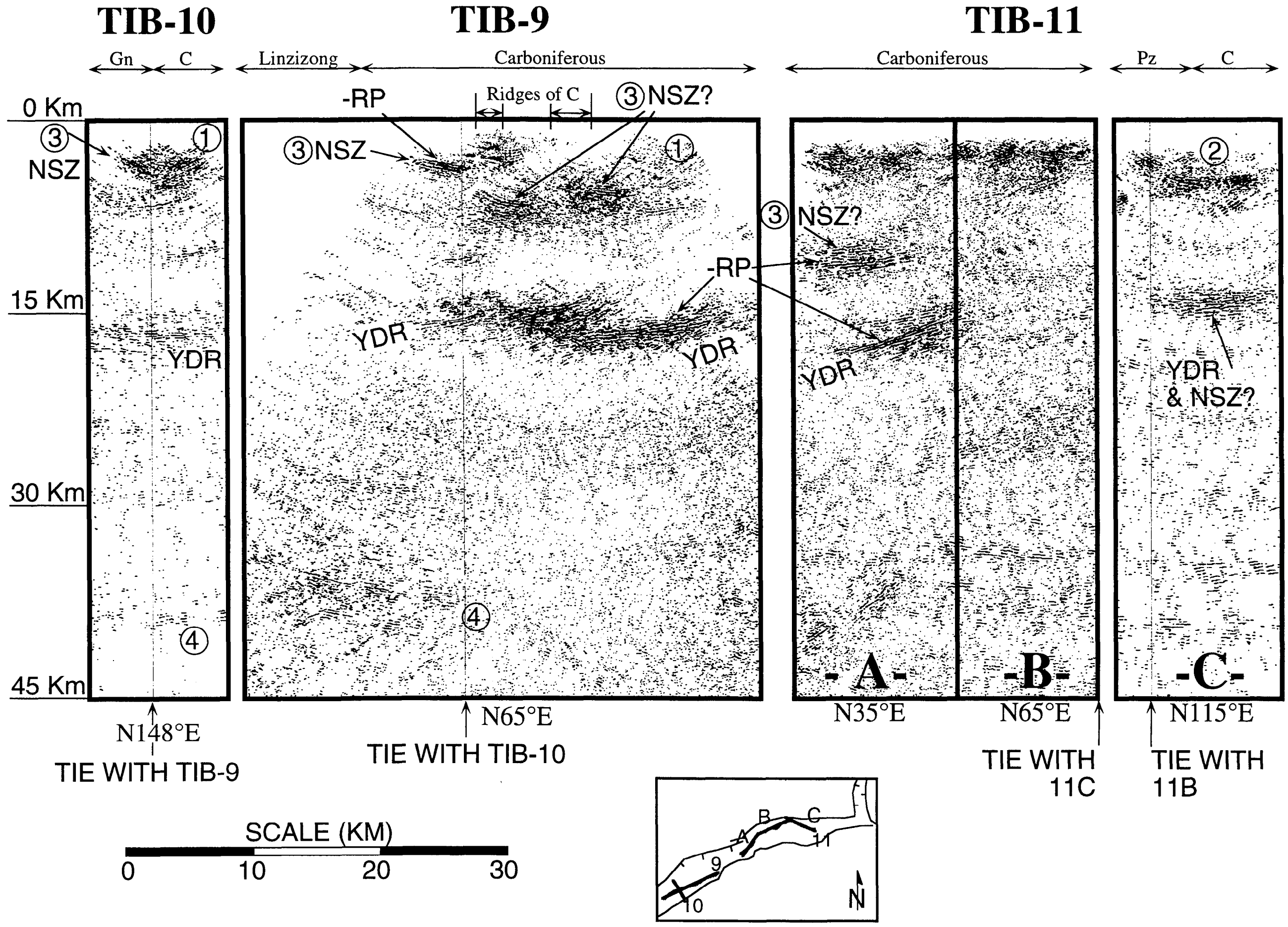


Figure 3. Migrated CMP reflection profiles Tib-9, Tib-10, and Tib-11. Numbers with circles follow from Plate 1. Small map denotes the general position and orientation of each line segment (detail locations are given in Plate 2). Several reflections have negative reflection polarity (-RP) [*Brown et al.*, 1996]. Surface geology noted across the top is based on Plate 2. NSZ denotes the reflections interpreted as the Nyainqentanglha shear zone whereas NSZ? events possibly mark the shear zone.

northern part of the Nyainqentanglha range. INDEPTH magnetotelluric (MT) data also indicate the existence of a gently southeast dipping, electrically conductive horizon within the crust at approximately the position of the NSZ? reflections on Tib-11 (feature "4" in Figure 2 of *Chen et al.* [1996]). This sharply defined anomaly occurs at about 10 km depth beneath the Damxung graben and projects to the surface approximately 25 km northwest of the village of Damxung (i.e., near Nam Tso). The apparent coincidence of the NSZ? reflections, locally exhibiting negative reflection polarity, with a highly conductive horizon is suggestive of the existence of hydrothermal fluids along the NSZ (or similar low-angle structure).

3.3. Yamdrok-Damxung Reflection Band

The most prominent reflections recorded within the Lhasa terrane compose a subhorizontal, midcrustal reflection band extending beneath the length of the Yangbajain-Damxung graben (Plate 1) ("YDR" of *Brown et al.* [1996]). In detail, this band consists of individual segments having varying dips and lying between 12 km and 18 km depth (Figures 2 and 3). The segments typically are multicyclic and extend up to 1.0 s in two-way travel time (e.g., a thickness of ~3 km). The reflections composing the YDR on Tib-7B (Figure 2) and Tib-9 (Figure 3) dip to the southwest and tie with flat-lying reflections on the crosslines Tib-8 and Tib-10. The true strike and dip of the reflections at the tie points are 319°, 25°SW and 328°, 10°SW, respectively. Farther north, the reflections composing the YDR occur about 17 km deep on Tib-11A (Figure 3) and also have an apparent southwest dip. To the south, parallel segments of the YDR, imaged at a depth of about 19 km on Tib-6 and Tib-7, apparently strike east-west and dip about 31°N (Figures 2 and 5).

As described by *Brown et al.* [1996], the YDR band locally exhibits extreme amplitude and negative reflection polarity (reflections labeled "-RP" in Figures 2 and 3). INDEPTH three-component recording has additionally shown that the reflectors at these locations produce large *P*-to-*S* phase conversions [*Makovsky et al.*, 1996]. Large amplitude,

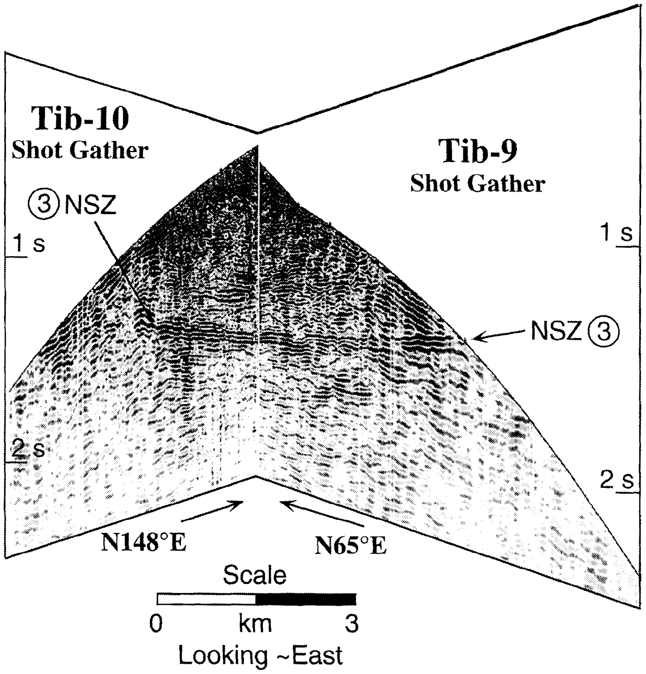


Figure 4. Two shot gathers, one from Tib-9 and one from Tib-10, that show the tie of the NSZ reflections across the two lines. A normal move-out velocity correction of 4.5 km/s has been applied to the first 2.5 s.

negative polarity, and large *P*-to-*S* conversion are characteristic of seismic "bright spots" [*Sheriff*, 1989] and are suggestive of at least the local occurrence of a solid over fluid interface coincident with the YDR reflection band [*Brown et al.*, 1996; *Makovsky et al.*, 1996]. Additionally, receiver function analyses of INDEPTH broadband earthquake data have shown that the YDR corresponds grossly with the top of a midcrustal, shear wave, low-velocity zone [*Kind et al.*, 1996]. Similarly, INDEPTH magnetotelluric profiling has shown that the electrical conductivity of the crust increases markedly with depth beneath the survey and that the depth at the top of this electrically conductive zone corresponds, within resolution, with the YDR [*Chen et al.*, 1996]. These observations, together with evidence for high heat flow in southern Tibet [*Francheteau et al.*, 1984; *Shen*, 1993], led *Nelson et al.* [1996] to propose that the YDR marks the top of a regionally developed midcrustal partial melt layer underlying the region and that the bright spots mark local accumulations of granitic magma and/or brine ponded at the top of the partial melt layer. They further suggest that partial melting of the middle crust in southern Tibet most likely resulted from collisional shortening (thickening) of the crust combined with internal heat production.

Allowing this hypothesis, the discontinuous, locally folded appearance of the YDR might simply reflect an irregular ("corrugated") upper surface of the partial melt zone and/or irregularly shaped intrusive bodies emplaced along it (Figure 6A). Setting aside the partial melt hypothesis, it is alternatively arguable that the YDR might mark a preexisting structural or lithological boundary within the Lhasa terrane that has been tectonically deformed (Figure 6B). It seems unlikely to us that the YDR could be a precollisional horizon, because any regionally developed precollisional horizon within the middle crust of the southern Lhasa terrane would presumably have been substantially obliterated by Gangdese plutonism. A hybrid possibility is that the YDR is a Neogene/Quaternary magmatic or hydrothermal boundary, which has also been tectonically deformed as a consequence of postinitial collision shortening of the Lhasa terrane (Figure 6C).

3.4. Yarlung-Zangbo Reflection

There is an approximately 70-km-wide gap in the INDEPTH CMP coverage across the southern Gangdese mountains and Yarlung River gorge (Figure 1). To fill this gap, wide-angle reflection data were acquired with portable seismographs deployed on either side of and within the gap. These instruments recorded the CMP shots detonated along Tib-5 south of the gap and Tib-6 and Tib-7 to the north. Midpoint sections produced from these data show a subhorizontal reflection band occurring at about 25 km depth beneath the southern Gangdese belt and surface trace of the Yarlung-Zangbo suture [*Makovsky et al.*, 1995] (Plate 1). This reflection band, termed the "Yarlung Suture Reflection" by *Makovsky et al.* [1995], is one of the most intriguing features discovered in the INDEPTH work to date. Here we refer to it as the Yarlung-Zangbo Reflection (YZR) in recognition of the fact that it appears to extend beneath the Yarlung River but may not actually mark the suture (discussed below). Wide-angle data recorded with portable seismographs deployed in a fan configuration to the west of the main INDEPTH survey also show a subhorizontal reflection beneath the Yarlung-Zangbo suture. The reflection is imaged ~30 to ~40 km west of the main line at a depth of about 20 km [*Mechie et al.*, 1995; *Zhao et al.*, 1997]. Taken together, these two sets of wide-angle observations suggest that the YZR marks a laterally extensive, subhorizontal structure underlying the surface expression of the Yarlung-Zangbo suture.

Viewed in detail, the YZR appears somewhat deeper than the YDR imaged in the CMP profiles to the north and somewhat deeper than a bright subhorizontal reflection occurring at a similar depth to the YDR on Tib-5 immediately to the south (Plate 1 and Figure 7). Presently, it is not clear whether the YZR is, in fact, a geometrically distinct deeper horizon or, alternatively, is continuous with one or both of the nearby reflections imaged on the CMP sections. This ambiguity arises from difficulties inherent in merging the wide-angle profile with the narrow-angle CMP profiles. Because the normal-move-out (NMO) correction is a function of both offset and depth, the NMO-corrected reflection times of features imaged on the wide-angle section may not correspond precisely to the NMO-corrected reflection times of equivalent features on the narrow-angle CMP sections. Also, because of the first-break mutes required to produce the wide-angle section, horizons shallower than 18-20 km are not imaged in these data. Thus it cannot presently be determined whether or not a shallower equivalent to the YDR exists above the YZR. Additional analyses of the overlapping wide-angle receiver and CMP shot gathers near the ends of the wide-angle profile may resolve these ambiguities. Regardless of these ambiguities, the existence of the YZR suggests that the

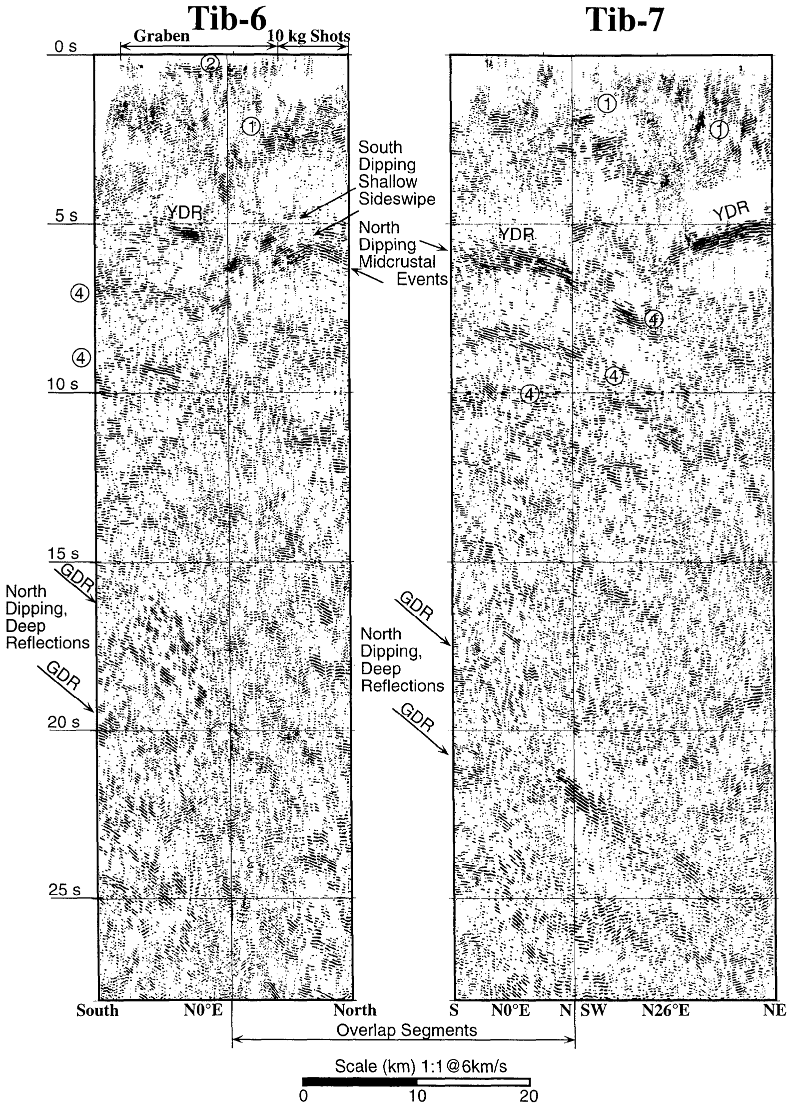
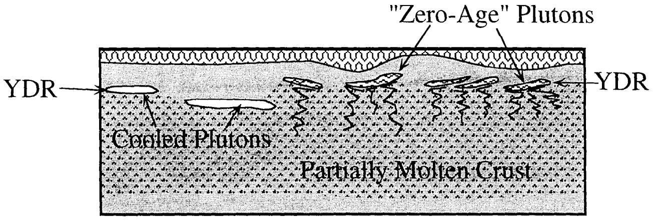


Figure 5. Unmigrated CMP reflection lines Tib-6 and Tib-7. The profiles are separated by ~9.5 km in the east-west direction (Plate 2), and their unmigrated CMP reflection points overlap by 10.6 km in the north-south direction. South dipping reflections from ~5 s to ~7 s were imaged on the overlap section of Tib-6 but not on Tib-7, whereas north dipping events were imaged on both overlapping segments at similar travel times. Most of Tib-6 was recorded within graben fill, yet the overlap section of Tib-7 was recorded over mostly volcanic rocks. Using appropriate graben fill velocities, the south dipping reflections could result from *P* wave sideswipe of the graben-bounding faults to the east and west of Tib-6. Hence the south dipping reflections are believed to result from sideswipe (SS in Figure 2), whereas the north dipping events likely image structures at midcrustal depths. Prior to migration, the overlapping sections were added together, forming one continuous line. North dipping reflections at great travel times (e.g., 16 s-23 s) are generally inline, suggesting that they are not related to shallow sideswipe. Note that 10-kg shots were used for the northern half of Tib-6 because of difficult drilling conditions. Other nomenclature follows from Plate 1.

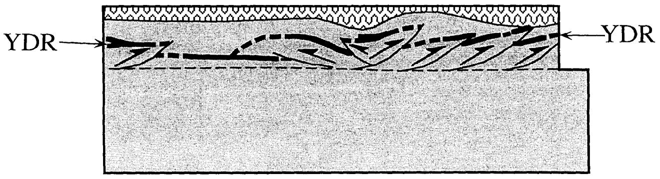
Yarlung-Zangbo suture is cut off or superposed by a younger structure in the middle crust. The principal "classes" of geologic interpretation that are possible are (1) the YZR marks (directly or indirectly) a low-angle fault, which cuts and displaces the suture, or (2) it marks a magmatic, metamorphic or hydrothermal boundary that is superimposed across the suture.

3.5. Deep Crustal Reflections Within the Lhasa Terrane

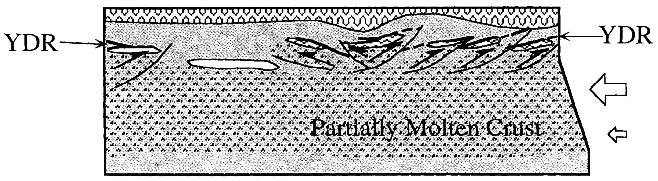
There are a number of distinct reflections visible beneath the YDR on the INDEPTH CMP profiles. In general, however, the crust beneath this horizon appears relatively less reflective than the crust to the south at comparable depths



(A) YDR=Magma Accumulations, No Shortening



(B) YDR=Deformed Pre-Existing Horizon



(C) YDR= Shortened Horizon with Magma Accumulations

Figure 6. Schematic showing three possible interpretations of the YDR. (A) The YDR marks the random arrangement of plutons at the top of a midcrustal partial melt zone; (B) the YDR is a previously existing horizon, subsequently deformed by discrete structures resulting in shortening of the uppermost crust (bold lines represent the reflections and dashed lines are inferred reflections); or (C) the YDR marks the top of a midcrustal partial melt, and it is deformed by faults which "sole" into the melt.

(Plate 1, compare Tib-1 and Tib-3 with Tib-5 through Tib-11). Qualitatively, there appears to be a northward "fade out" of middle and deep crustal reflectivity on the INDEPTH profiles that begins approximately at the latitude of the North Himalayan anticlinorium (~28°40'N, Plate 1). It presently does not appear that this northward decrease in deep reflectivity is an artifact of changing near-surface conditions. The geometry and depth of the rift valleys in which the INDEPTH profiles were acquired do not change dramatically along the survey [*Cogan et al.*, 1998], nor is there any obvious regional south-to-north variation in the character of the rift fill sediments. Analysis of the amplitude decay exhibited in shot records additionally suggests that source and receiver coupling was essentially similar along the length of the INDEPTH survey and, if anything, was somewhat better in the northern part of the survey as compared to the south. It therefore appears that the northward decrease in deep reflectivity evident on the INDEPTH transect manifests either a northward decrease in the number of reflectors in the middle and deep crust or a northward increase in crustal attenuation (or both). Both possibilities are consistent with the evidence cited above for distributed partial melt within the middle crust underlying the YDR. Sub-YDR reflections that are visible within the Lhasa terrane are as follows:

1. There are a set of three north dipping reflections visible in the middle crust beneath the Yangbajain valley ("4," Tib-6 and Tib-7A, Figure 2). A deeper north dipping reflection occurs along their approximate northward projection beneath the Nyinzhong valley ("4," Figure 3). The three reflections beneath Yangbajain valley occur at depths of approximately 19, 24, and 27 km, respectively, with the deeper reflections exhibiting successively decreasing northward apparent dip (31°, 23°, and 16°, respectively). The uppermost of these dipping reflections appears to merge with the YDR reflection band (Figure 2). The lowermost appears to merge with the YZR (Figure 7).

2. An approximately 40° north dipping reflection is visible between 40 and 60 km depth beneath the Gangdese batholith and is termed here the "Gangdese Deep Reflection" (GDR) (Plate 1 and Figures 5 and 7). The GDR was recorded on subparallel segments of Tib-6 and Tib-7, which are approximately 9.5 km apart. Although there is ambiguity in phase correlation between the two lines, the reflection band occurs at similar travel times and with similar dip on both profiles (Figure 5), implying that it lies approximately within the plane of the two sections. The GDR is particularly intriguing because it projects updip approximately to the outcrop of the Yarlung-Zangbo suture. It also coincides with the position, in cross section, where *Hirn et al.* [1984] have interpreted an offset of the Moho from wide-angle fan observations approximately 100 km along strike to the west of the INDEPTH profiles.

3. Relatively weak subhorizontal reflections occur beneath the Damxung valley in the depth range of 35-40 km (Tib-11, Figure 3). A steep, apparently southwest dipping reflection in the same depth range is superimposed on the deep subhorizontal reflections beneath the southern end of the valley (Tib-11A, Figure 3). Lacking crossline control, the true dip and position of the dipping reflections are undetermined. Weaker isolated reflection segments occur at similar depths on Tib-7 and Tib-9.

4. Discussion

4.1. Gangdese Thrust System

Harrison et al. [1992] and *Yin et al.* [1994] have suggested that the Gangdese batholith was transported southward relative to the Yarlung-Zangbo suture on a north dipping thrust in late Oligocene-early Miocene time (GTS). The evidence cited for the existence of the GTS includes the rapid differential cooling of the Gangdese batholith during late Oligocene/early Miocene time, the relative narrowness of the Xigaze Group forearc basin sequence (entirely cut out at the longitude of the INDEPTH survey), and the observation in the Zedong region of a north dipping thrust fault carrying the Gangdese batholith in the hanging wall [*Yin et al.*, 1994]. Thermochronological studies have additionally shown that this fault was active during the period from ~27 Ma to ~22 Ma [*Yin et al.*, 1994; *Copeland et al.*, 1987, 1995].

The INDEPTH CMP coverage within the Lhasa terrane does not extend southward to the suture, and thus the existence of

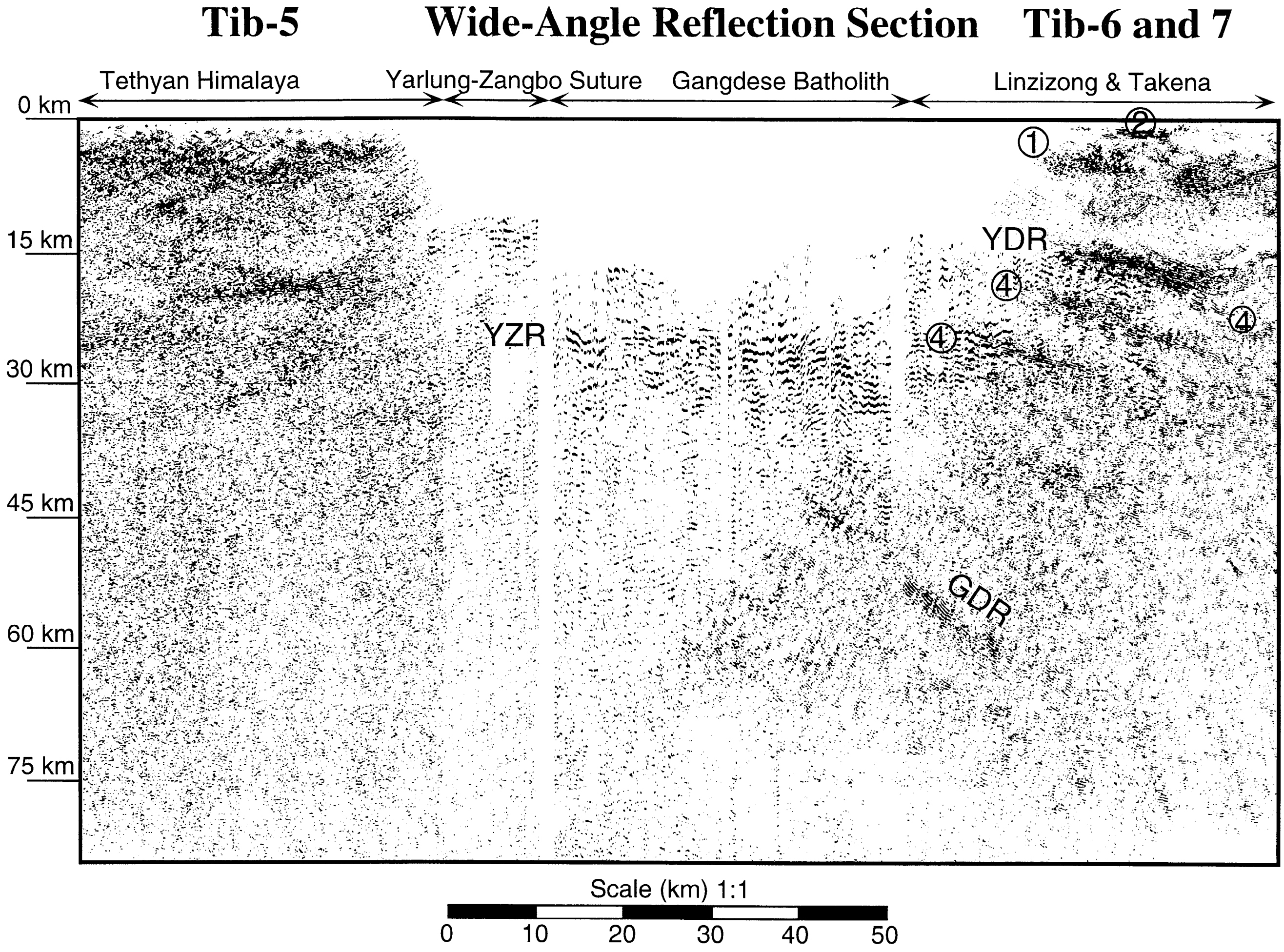


Figure 7. Portions of migrated CMP reflection profiles Tib-5, Tib-6, and Tib-7 and depth converted wide-angle suture section. Because of acquisition geometry, the wide-angle section is much lower resolution than the near-vertical incidence profiles. Numbers with circles follow from Plate 1. The steeply, northward dipping reflection (GDR) may mark the Yarlung-Zangbo suture or a Moho fault. If the GDR is the suture, then very little Indian crust has underthrust the Lhasa terrane, and the thickening of the Tibetan plateau crust could not have occurred by underthrusting of India's crust.

the GTS cannot be unequivocally demonstrated in the seismic data. The three north dipping reflections observed in the middle crust on Tib-6 and Tib-7 ("4," Figure 2), however, are suggestive of south vergent thrusting and are in an appropriate position to represent the downdip continuation of the GTS. The occurrence of these north dipping reflections, together with the observation that deeper reflections exhibit successively less dip, is further suggestive of a duplex structure. In this interpretation, the north dipping reflections would originate from the back (north dipping) limbs of the duplex horses. The front limbs of the duplex were arguably not imaged because they lie off the south end of Tib-6.

On the basis of the differential cooling observed across the Gangdese batholith, *Yin et al.* [1994] suggested that the GTS ramps downward from the surface to a "flat" at about 15 km depth (assumed brittle-ductile transition). Allowing this interpretation, the three north dipping reflections visible on Tib-6 and Tib-7 ("4," Figure 2) would then presumably mark the location where *Yin et al.*'s [1994] interpreted flat, in turn, ramps downward to a deeper level within the crust or, alternatively, merges downward into a zone of distributed deformation. The simplified model of the GTS shown in Figure 8 illustrates this geometry. The reconstruction yields a minimum estimate of about 40 km N-S shortening across the GTS. This estimate is comparable to the minimum of 46±9-km slip estimated by *Yin et al.* [1994] from the surface dip of the GTS and denudation of the upper plate evidenced from thermochronological data. The upper limit of shortening on the GTS is unconstrained. In principle, the development of the duplex illustrated in Figure 8 could also have contributed to the relative uplift and denudation of the Gangdese belt (~14 km as drawn).

4.2. Shortening of the YDR Horizon?

As summarized above, a variety of observations lead to the inference that the YDR is a relatively young feature of the crust and that it broadly coincides with the top of a midcrustal partial melt layer underlying, minimally, the Yangbajain-

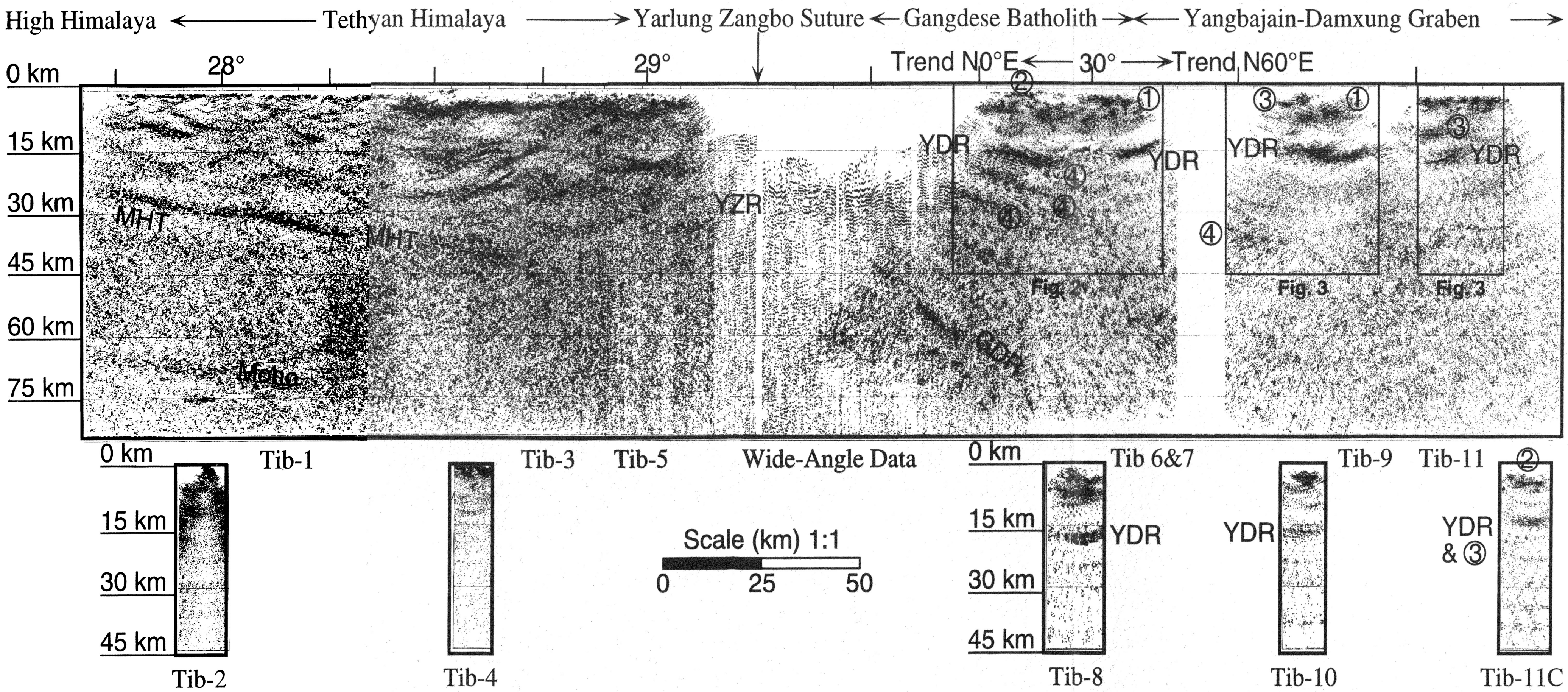


Plate 1. Multichannel CMP reflection profiles migrated by the method of *Alsdorf* [1997a] and depth converted wide-angle suture section. Tib-1, Tib-3, and Tib-5 trend ~N-S and have been projected into a true N-S orientation, however no projection is used for Tib-9 and Tib-11 which generally trend ~N60°E. Crosslines are plotted near their tie points across the bottom. Prominent reflections include: MHT, Main Himalayan Thrust [*Zhao et al.,* 1993]; GDR, Gangdese Deep Reflection; YDR, Yamdrok-Damxung Reflector; and YZR, Yarlung-Zangbo Reflection. Circled numbers refer to 1, supracrustal sequence; 2, graben fill; 3, Nyainqentanglha shear zone; and 4, possibly the Gangdese thrust system.

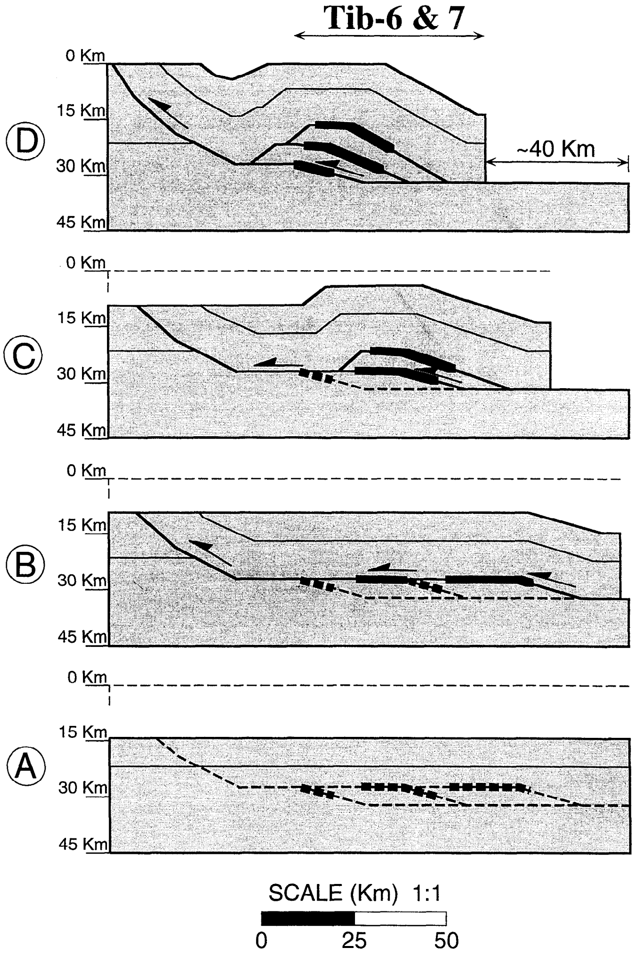


Figure 8. Schematic evolution of the proposed GTS duplex beneath the Gangdese batholith. Bold lines are observed reflections (Figure 2); thinner, solid lines are not observed. Arrows show motion along active faults, solid lines without arrows indicate inactive faults, thin solid line is an assumed horizon boundary, and dashed lines indicate faults that will occur (oldest time is A and youngest time is D). Shortening is minimally estimated at ~40 km and thickening at ~14 km. However, the hanging wall ramps may extend much farther south (not shown), possibly to the Yarlung-Zangbo suture where the GTS out crops, thus significantly increasing the shortening estimate.

Damxung graben. The precise origin of the reflections that compose the YDR band, however, remains unknown. It is also not clear whether the corrugated geometry of the YDR is a primary feature, for example, reflecting the irregular shape of intrusive bodies or hydrothermal fracture systems or, alternatively, the result of tectonic deformation, or both (Figure 6). The observation that the Linzizong Formation, cropping out within the southern Lhasa terrane, has suffered moderate postcollisional shortening suggests that tectonic deformation probably has played a role. If it is allowed that the middle crust beneath the Lhasa terrane is partially molten, then, qualitatively, one would expect postcollisional shortening of the upper crust of the terrane to have been accommodated at depth by distributed flow in the weak, partially molten middle crust (Figure 6C). If so, the geometry of the of the YDR, whatever its precise origin, might be expected to reflect a complex interplay between progressive shortening (folding and possibly faulting) of the horizon and magmatic, or related healing of it, that is presently ongoing. Suggestive evidence for a tectonic component to the geometry of the YDR is afforded by the observation that the strike of the YDR corrugations, where they are constrained by crossing lines, appears to be consistently northwest (Tib-7 and Tib-8, Tib-9 and Tib-10). This is subparallel to the strike of Tertiary contractional structures outcropping NW of the Nyainqentanglha range (Plate 2).

4.3. Yarlung-Zangbo Suture

The Yarlung-Zangbo suture is the principal paleogeographic boundary within the Himalayan orogen and is arguably the archetypal collisional suture. The crustal structure beneath the surface expression of the suture is therefore of considerable interest, both as it relates to the evolution of the Himalayan orogen and because of its possible role as a "benchmark" for interpreting the subsurface geometry of other older suture zones.

In Figure 9, we show two alternative crustal-scale interpretations of the INDEPTH reflection data centered on the outcrop of the Yarlung-Zangbo suture. These serve as a vehicle for discussing the principal classes of interpretation of the geologic structure beneath the suture zone that are permitted by the presently available data. The two cross sections are necessarily simplified, and other permutations are possible. Both cross sections depict the same crustal structure south of the North Himalayan anticlinorium, which is simplified from that described by *Hauck et al.* [this issue]. Both show a midcrustal partial melt layer extending southward in the subsurface to approximately the north limb of the North Himalayan anticlinorium, as suggested by the combined INDEPTH results [*Nelson et al.*, 1996]. In both interpretations, the top of the partial melt layer is drawn approximately coincident with the YDR and YZR reflection horizons. In reality, the thickness of the inferred partial melt zone is not well constrained, nor is the percentage or distribution of melt within the zone well understood. Following *Yin et al.* [1994], both interpretations also depict a north dipping GTS merging downward into the north dipping midcrustal reflections imaged beneath the Gangdese belt, and a younger south dipping RZT that cuts downward into the North Himalayan anticlinorium [see *Hauck et al.,* this issue].

The fundamental difference between the two cross sections in Figure 9 is in the specific interpretations given to the YZR and the GDR reflections. In Figure 9A, we illustrate the possibility that the GDR might mark the downdip continuation of the Yarlung-Zangbo suture in the deep crust. This interpretation requires that the YZR postdate the suture and be superimposed across it at depth. As described above, possibilities for the YZR that would meet this criterion include a magmatic, metamorphic, or hydrothermal boundary of Neogene/Quaternary age. In this class of interpretation, the YZR and YDR can have the same origin (e.g., both mark the top of a partial melt or hydrothermal zone), but this is not

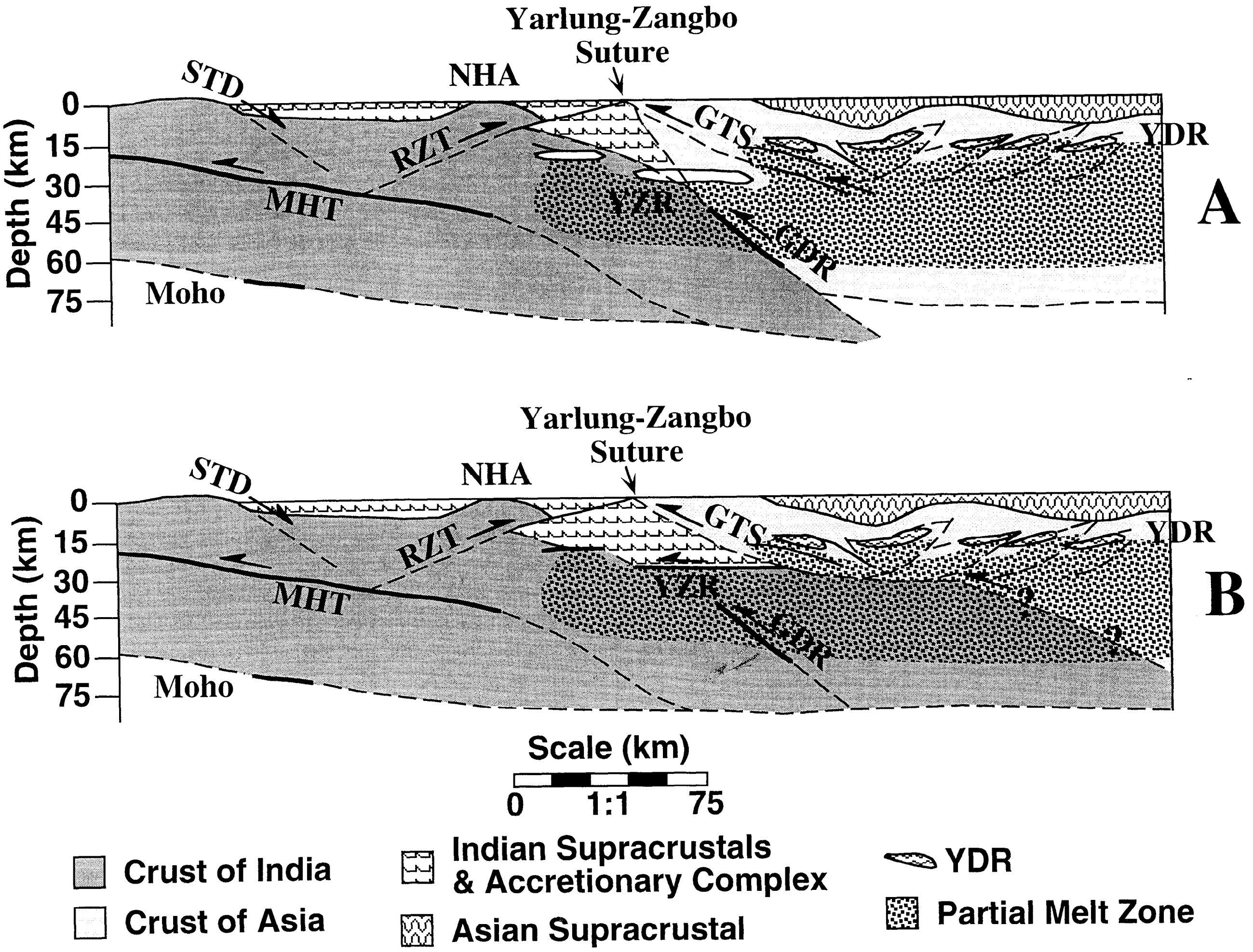


Figure 9. Two end-member block diagram interpretations of the INDEPTH survey. Solid lines denote reflections imaged on the seismic data or taken from the geologic map, whereas dashed lines are inferred. STD is the South Tibetan Detachment, NHA is the North Himalayan Anticlinorium, and RZT is the Renbu Zedong Thrust. Both diagrams incorporate the YDR, Figure 6C interpretation and a duplex along the GTS. The primary difference lies with the roles of the GDR and YZR. In (A) the GDR is the Yarlung-Zangbo suture at depth, and the YZR is a younger feature superimposed on the suture, for example a magmatic horizon like the YDR. In (B) the GDR only coincidentally projects to a surface location near the suture and is, instead, a lower crustal horizon, for example a reverse fault similar to those interpreted in the Sino-French wide-angle data [*Hirn et al.,* 1984]. Also in (B), the YZR is interpreted to mark a low-angle fault which cuts and displaces the suture.

required. In the alternative cross section shown in Figure 9B, the YZR is interpreted to mark a low-angle fault that cuts and displaces the suture. In this "class" of interpretation, the actual YZR reflection could arise directly from the fault (as depicted) or from some lithologic contrast in its hanging wall. In either case, in this class of interpretation the GDR marks a structure of unknown origin in the deep crust, which only coincidentally projects updip to the outcrop of the Yarlung-Zangbo suture. It could, in this class of interpretation, mark a postcollisional thrust in the deep crust of the sort interpreted by *Hirn et al.* [1984]. If so, the thrust would have to "sole out" updip below the YZR because the YZR does not appear to be cut.

While other permutations can be drawn, the contrasting interpretations shown in Figure 9 illustrate the fundamental ambiguity that exists in our current knowledge of the geologic structure beneath the outcrop of the Yarlung-Zangbo suture. In the interpretation shown in Figure 9A, precollisional Indian continental crust is constrained to lie entirely south of a steeply dipping Yarlung-Zangbo suture marked by the GDR. This is essentially the interpretation depicted by *Nelson et al.* [1996] and, with slight modification, by *Hauck et al.* [this issue]. At the scale of the Tibetan plateau, this interpretation is compatible with the *Dewey and Burke* [1973] view that thickening of the plateau crust was largely a consequence of internal shortening of the crust north of the suture. In the alternative interpretation shown in Figure 9B, there is effectively no constraint on the northern extent of Indian continental crust in the subsurface. This is essentially the configuration proposed by *Harrison et al.* [1992] and *Yin et al.* [1994], which at the plateau scale is compatible with the "Argandian" view that crustal thickening north of the suture was accomplished substantially by underthrusting Indian crust beneath Tibet (though it does not require this). Both classes of interpretation are allowable given the present surface geological and seismic reflection constraints. Several of the INDEPTH researchers believe that the Figure 9A class of interpretation is more likely because (1) it provides a simple explanation for the set of prominent midcrustal reflections seen on the INDEPTH survey (GDR, YDR, and YZR), (2) it explains the apparent coincidence between the GDR and Yarlung-Zangbo suture, and (3) it is consistent with INDEPTH MT observations which indicate that the top of the electrically conductive midcrustal "layer" tracks the YDR and YZR [*Chen et al.,* 1996; J. Booker, personal communication, 1997]. Others within the INDEPTH team prefer the Figure 9B class of interpretation, arguing that the YZR does not exhibit the seismic bright spot characteristics exhibited by the YDR (locally negative reflection polarity and large *P*-to-*S* conversion [Makovsky et al., submitted manuscript, 1998; Y. Makosky and S. Klemperer, Measuring the seismic properties of Tibetan bright spots: Evidence for free aqueous fluids in the Tibetan middle crust, submitted to *Journal of Geophysical Research,* 1997]).

5. Conclusions

The INDEPTH CMP data recorded within the southern Lhasa terrane show a variable thickness stratified assemblage extending from the near surface to a maximum of about 11.5 km depth. Correlation with surface geology suggests that these reflections originate from the Paleozoic-Paleogene supracrustal sequence of the Lhasa terrane. The correlation also suggests that the folding and tilting of these strata, evident on the seismic sections, largely reflects precollisional deformation of the Lhasa terrane. For the most part, the Neogene-Quaternary fill of the northern Yadong-Gulu rift is too shallow to be effectively imaged on the seismic sections. The southern Lhasa terrane is underlain at 15 to 18 km depth by a bright, corrugated reflection horizon, which complementary data suggest coincides broadly with the top of a midcrustal partial melt zone. It is presently unclear whether the corrugated appearance of this horizon is a primary feature or the result of tectonic deformation. The observation that Paleogene volcanic strata in the region are mildly deformed and that the corrugations appear to strike parallel to surface structures is suggestive of at least some tectonic deformation. Additional evidence for postcollisional contractional deformation within the southern Lhasa terrane is afforded by a set of north dipping midcrustal reflections beneath the Gangdese belt that are appropriately positioned to represent the downdip extension of the Gangdese thrust system. The geologic structure beneath the Yarlung-Zangbo suture zone is fundamentally ambiguous. The existence of a subhorizontal, wide-angle reflection at 20-30 km depth, extending beneath the outcrop of the suture, implies that the suture is cut off or superposed at depth by a younger geologic structure. A deeper, steeply north-dipping reflection also exists that projects upward toward the outcrop of the suture. Two "classes" of interpretation are permissible. (1) The deep, north dipping reflection marks the downdip extension of the suture, and the shallower, subhorizontal wide-angle reflection marks a horizon that has been superposed across the suture, for example, an intrusive or hydrothermal boundary. (2) The subhorizontal wide-angle reflection marks a low-angle fault that cuts and displaces the suture, and the deeper north dipping reflector marks an unknown lower crustal structure that only coincidentally projects toward the outcrop of the suture. Viewed in aggregate, the INDEPTH reflection data are permissive of large-magnitude underthrusting and/or fluid injection of Indian crust beneath the Lhasa terrane but do not provide compelling evidence that this has occurred.

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References

Allegre, C.J., et al., Structure and evolution of the Himalaya-Tibet orogenic belt, *Nature, 307,* 17-22, 1984.

Alsdorf, D., A simple method for migrating narrow aperture, noisy seismic reflection data and application to Project INDEPTH deep seismic profiles, *J. Geophys. Res., 102,* 17807-17811, 1997a.

Alsdorf, D., Noise reduction in seismic data using Fourier correlation coefficient filtering, *Geophysics, 62,* 1617-1627, 1997b.

Alsdorf, D., L. Brown, and D. Nelson, Possible upper mantle reflection fabric on seismic profiles from the Tethyan Himalaya: Identification and tectonic interpretation, *J. Geophys. Res., 101,* 25305-25320, 1996.

Argand, E., La tectonique de l'Asie, *Int. Geol. Cong. Rep. Sess., 13(1),* 170-372, 1924.

Armijo, R., P. Tapponnier, J.L. Mercier, and H. Tong-Lin, Quaternary extension in southern Tibet: Field observations and tectonic implications, *J. Geophys. Res., 91,* 13803-13872, 1986.

Armijo, R., P. Tapponnier, and H. Tonglin, Late Cenozoic right-lateral strike-slip faulting in southern Tibet, *J. Geophys. Res., 94,* 2787-2838, 1989.

Barazangi, M., and J. Ni, Velocities and propagation characteristics of *Pn* and *Sn* beneath the Himalayan arc and Tibetan plateau: Possible evidence for underthrusting of Indian continental lithosphere beneath Tibet, *Geology, 10,* 179-185, 1982.

Beghoul, N., M. Barazangi, and B.L. Isacks, Lithospheric structure of Tibet and western North America: Mechanisms of uplift and a comparative study, *J. Geophys. Res., 98,* 1997-2016, 1993.

Brown, L.D., W. Zhao, K.D. Nelson, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, M. Clark, X. Liu, And J. Che, Bright spots, structure, and magmatism in southern Tibet from INDEPTH seismic reflection profiling, *Science, 274,* 1688-1690, 1996.

Burchfiel, B.C., C. Zhiliang, K.V. Hodges, L. Yuping, L.H. Royden, D. Changrong, and X. Jiene, The south Tibetan detachment system, Himalayan Orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt, *Spec. Pap. Geol. Soc. Am., 269,* 41 pp., 1992.

Burg, J.-P., and G.M. Chen, Tectonics and structural zonation of southern Tibet, China, *Nature, 311,* 219-223, 1984.

Burg, J.-P., F. Proust, P. Tapponnier, and C.G. Ming, Deformation phases and tectonic evolution of the Lhasa block (southern Tibet, China), *Eclogae Geol. Helv., 76/3,* 643-665, 1983.

Chen, L., J.R. Booker, A.G. Jones, N. Wu, M.J. Unsworth, W. Wei, and H. Tan, Electrically conductive crust in southern Tibet from INDEPTH magnetotelluric surveying, *Science, 274,* 1694-1696, 1996.

Chengfa, C., et al., Preliminary conclusions of the Royal Society and Academia Sinica 1985 geotraverse of Tibet, *Nature, 323,* 501-507, 1986.

Clark, M., The Nyainqentanglha shear zone at depth: detachment faulting in southern Tibet, senior thesis, Dep. of Geol. Sci., Cornell Univ., Ithaca, N.Y., 1996.

Cogan, M.J., K.D. Nelson, W.S.F. Kidd, and W. Changde, Shallow structure of the Yadong-Gulu rift, southern Tibet, from refraction analysis of Project INDEPTH common midpoint data, *Tectonics, 17,* 46-61, 1998.

Copeland, P., T.M. Harrison, W.S.F. Kidd, X. Ronghua, and Z. Yuquan, Rapid early Miocene acceleration of uplift in the Gangdese belt, Xizang (southern Tibet), and its bearing on accommodation mechanisms of the India-Asia collision, *Earth Planet. Sci. Let., 86,* 240-252, 1987.

Copeland, P., T.M. Harrison, P. Yun, W.S.F. Kidd, M. Roden, and Z. Yuquan, Thermal evolution of the Gangdese batholith, southern Tibet: A history of episodic unroofing, *Tectonics, 14,* 223-236, 1995.

Coward, M.P., W.S.F. Kidd, P. Yun, R.M. Shackleton, and Z. Hu, The structure of the 1985 Tibet geotraverse, Lhasa to Golmud, *Philos. Trans. R. Soc. London Ser. A., 327,* 307-336, 1988.

Debon, F., P. LeFort, S.M.F. Sheppard, and J. Sonet, The four plutonic belts of the Transhimalaya-Himalaya: A chemical, mineralogical, isotopic, and chronological synthesis along a Tibet-Nepal section, *J. Petrol., 27,* 219-250, 1986.

Dewey, J.F., and J.M. Bird, Mountain belts and the new global tectonics, *J. Geophys. Res., 75,* 2625-2647, 1970.

Dewey, J.F., and K.C.A. Burke, Tibetan, Variscan, and Precambrian basement reactivation: Products of continental collision, *J. Geol., 81,* 683-692, 1973.

Dewey, J.F., R.M. Shackleton, C. Chengfa, and S. Yiyin, The tectonic evolution of the Tibetan plateau, *Philos. Trans. R. Soc. London, Ser. A, 327,* 379-413, 1988.

England, P., and G. Houseman, Extension during continental convergence, with application to the Tibetan plateau, *J. Geophys. Res., 94,* 17561-17579, 1989.

England, P., and D. Mckenzie, A thin viscous sheet model for continental deformation, *Geophys. J. R. Astron. Soc., 70,* 295-321, 1982.

England, P.C., and A. Thompson, Some thermal and tectonic models for crustal melting in continental collision zones, in *Collision Tectonics*, edited by M.P. Coward and A.C. Ries, *Geol. Soc. Spec. Publ. 19,* 83-94, 1986.

Francheteau, J., C. Jaupart, S.X. Jie, K. Wen-Hua, L. De-Lu, B. Jia-Chi, W. Hung-Pin, and D. Hsia-Yeu, High heat flow in southern Tibet, *Nature, 307,* 32-36, 1984.

Gansser, A., *Geology of the Himalayas,* 289 pp., Wiley-Interscience, New York, 1964.

Gansser, A., Geology of the Bhutan Himalaya, *Denkschriften der Schweizerischen Naturforschenden Gesellschaft, Mem. Soc. Helv. Sci. Nat., 96,* 1983.

Harris, N.B.W., T.J.B. Holland, and A.G. Tindle, Metamorphic rocks of the 1985 Tibet geotraverse, Lhasa to Golmud, *Philos. Trans. R. Soc. London Ser. A, 327,* 203-213, 1988.

Harrison, T.M., P. Copeland, W.S.F. Kidd, and A. Yin, Raising Tibet, *Science, 255,* 1663-1670, 1992.

Harrison, T.M., P. Copeland, W.S.F. Kidd, and O.M. Lovera, Activation of the Nyainqentanglha shear zone: Implications for uplift of the southern Tibetan plateau, *Tectonics, 14,* 658-676, 1995.

Hauck, M., K.D. Nelson, L.D. Brown, C. Wu, and A. Ross, Crustal structure of the Central Himalayas: INDEPTH reflection profiles in Southern Tibet, *Tectonics,* this issue.

Hirn, A., A. Nercessian, M. Sapin, G. Jobert, X.Z. Xin, G.E. Yuan, L.D. Yuan, and T.J. Wen, Lhasa block and bordering sutures - A continuation of a 500-km Moho traverse through Tibet, *Nature, 307,* 25-27, 1984.

Houseman, G., and P. England, A lithospheric-thickening model for the Indo-Asian collision, in *The Tectonic Evolution of Asia,* edited by A. Yin and T.M. Harrison, pp. 1-17, Cambridge Univ. Press, New York, 1996.

Houseman, G.A., D.P. Mckenzie, and P. Molnar, Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts, *J. Geophys. Res., 86,* 6115-6132, 1981.

Kidd, W.S.F., P. Yusheng, C. Chengfa, M.P. Coward, J.F. Dewey, A. Gansser, P. Molnar, R. M. Shackleton and S. Yiyin, Geological mapping of the 1985 Chinese-British Tibetan (Xizang-Qinghai) Plateau geotraverse route, *Philos. Trans. R. Soc. London Ser. A, 327,* 287-305, 1988.

Kind, R., J. Ni, W. Zhao, J. Wu, X. Yuan, L. Zhao, E. Sandvol, C. Reese, J. Nabelek, and T. Hearn, Evidence from earthquake data for a partially molten crustal layer in southern Tibet, *Science, 274,* 1692-1694, 1996.

Makovsky, Y., S.L. Klemperer, and L. Ratschbacher, India-Asia suture observed on wide-angle seismic data of Project INDEPTH (abstract), *Eos, 76 (46),* Fall Meet. Suppl., F566, 1995.

Makovsky, Y., S.L. Klemperer, L. Ratschbacher, L.D. Brown, M. Li, W. Zhao, and F. Meng, INDEPTH wide-angle reflection observation of *P*-wave-to-*S*-wave conversion from crustal bright spots in Tibet, *Science, 274,* 1690-1691, 1996.

McNamara, D.E., T.J. Owens, P.G. Silver, and F.T. Wu, Shear wave anisotropy beneath the Tibetan plateau, *J. Geophys. Res., 99,* 13655-13665, 1994.

McNamara, D.E., T.J. Owens, and W.R. Walter, Observations of regional phase propagation across the Tibetan Plateau, *J. Geophys. Res., 100,* 22215-22229, 1995.

Mechie, J., F. Wenzel, R. Meissner, H. Steentoft, S. Husen, W. Frisch, L. Ratschbacher, W. Zhao, J. Guo, and D. Jiang, A deep crustal seismic section beneath the Indus-Yarlung suture, Tibet from wide-angle seismic data (abstract), *Eos, 76(46),* Fall Meet. Suppl., F566, 1995.

Mercier, J.-L., R. Armijo, P. Tapponnier, E. Carey-Gailhardis, and H.-T. Lin, Change from late Tertiary compression to Quaternary extension in southern Tibet during the India-Asia collision, *Tectonics, 6,* 275-304, 1987.

Molnar, P., A review of the geophysical constraints on the deep structure of the Tibetan Plateau, the Himalaya and the Karakoram, and their tectonic implications, *Philos. Trans. R. Soc. London Ser. A., 326,* 33-88, 1988.

Molnar, P. and W.-P. Chen, Focal depths and fault plane solutions of earthquakes under the Tibetan plateau, *J. Geophys. Res., 88,* 1180-1196, 1983.

Molnar, P., and H. Lyon-Caen, Some simple physical aspects of the support, structure, and evolution of mountain belts, *Spec. Pap. Geol. Soc. Am. 218,* 179-207, 1988.

Molnar, P., and P. Tapponnier, Active tectonics of Tibet, *J. Geophys. Res., 83,* 5361-5375, 1978.

Molnar, P., P. England, and J. Martinod, Mantle dynamics, uplift of the Tibetan plateau, and the Indian monsoon, *Rev. Geophys., 31,* 357-396, 1993.

Murphy, M.A., A. Yin, T.M. Harrison, S.B. Durr, Z. Chen, F.J. Ryerson, W.S.F. Kidd, X. Wang., and X. Zhou, Did the Indo-Asian collision alone create the Tibetan plateau?, *Geology, 25,* 719-722, 1997.

Nelson, K.D., et al., Partially molten middle crust beneath southern Tibet: Synthesis of Project INDEPTH results, *Science, 274,* 1684-1688, 1996.

Ni, J., and M. Barazangi, Seismotectonics of the Himalayan collision zone: Geometry of the underthrusting Indian plate beneath the Himalaya, *J. Geophys. Res., 89,* 1147-1163, 1984.

Owens, T.J., and G. Zandt, Implications of crustal property variations for models of Tibetan plateau evolution, *Nature, 387,* 37-43, 1997.

Pan, Y., and W.S.F. Kidd, Nyainqentanglha shear zone: A late Miocene extensional detachment in the southern Tibetan plateau, *Geology, 20,* 775-778, 1992.

Ratschbacher, L., W. Frisch, G. Liu, and C. Chen, Distributed deformation in southern and western Tibet during and after the India-Asia collision, *J. Geophys. Res., 99,* 19917-19945, 1994.

Royden, L.H., B.C. Burchfiel, R.W. King, E. Wang, Z. Chen, F. Shen, and Y. Liu, Surface deformation and lower crustal flow in eastern Tibet, *Science, 276,* 788-790, 1997.

Scharer, U., R.-H. Xu, and C.J. Allegre, U-Pb geochronology of Gangdese (Transhimalaya) plutonism in the Lhasa-Xigaze region, Tibet, *Earth Planet. Sci. Let., 69,* 311-320, 1984.

Searle, M.P., R.I. Corfield, B. Stephenson, and J. McCarron, Structure of the north Indian continental margin in the Ladakh-Zanskar Himalayas: Implications for the timing of obduction of the Spontang ophiolite, India-Asia collision and deformation events in the Himalaya, *Geol. Mag., 134,* 297-316, 1997.

Seeber, L., J. Armbruster, and R. Quittmeyer, Seismicity and continental collision in the Himalayan arc, in *Zagros, Hindu-Kush, Himalaya-Geodynamic Evolution, Geodyn. Ser., vol. 3,* edited by H. K. Gupta and F. M. Delany, pp. 215-242, AGU, Washington, D. C., 1981

Shen, X., Kinematics and tectonothermal modeling - Interpretation of heat flow observed on the Tibetan Plateau, *Tectonophysics, 225,* 91-106, 1993.

Sheriff, R.E., *Geophysical Methods,* pp. 605, Prentice-Hall, Englewood Cliffs, N.J., 1989.

Shi, W., L. Deyuan, H. Liyan, L. Xiaopeng, and A. Hirn, Crustal structure and velocity distribution characteristics of the Xizang (Tibet) Plateau in N-S direction, in *Geology of the Himalayas, Pap. Geophys., vol. 1,* edited by L. Guangcen, Y. Xuecheng, and A. Hirn, pp. 53-64, Geol. Publ. House, Beijing, 1991.

Tapponnier, P., et al., The Tibetan side of the India-Eurasia collision, *Nature, 294,* 405-410, 1981.

Willett, S.D., and C. Beaumont, Subduction of Asian lithospheric mantle beneath Tibet inferred from models of continental collision, *Nature, 369,* 642-645, 1994.

Yin, A., T.M. Harrison, F.J. Ryerson, C. Wenji, W.S.F. Kidd, and P. Copeland, Tertiary structural evolution of the Gangdese thrust system, southeastern Tibet, *J. Geophys. Res., 99,* 18175-18201, 1994.

Zhao, W., K.D. Nelson, and the Project INDEPTH Team, Deep seismic reflection evidence for continental underthrusting beneath southern Tibet, *Nature, 366,* 557-559, 1993.

Zhao, W., et al., Seismic mapping of crustal structures beneath the Indus-Yarlung suture, Tibet, *Terra Nova, 9,* 42-46, 1997.

Zhao, W.-L. and W.J. Morgan, Injection of Indian crust into Tibetan lower crust: A two-dimensional finite element model study, *Tectonics, 6,* 489-504, 1987.

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