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Midcrustal reflector on INDEPTH wide-angle profiles: An ophiolitic slab beneath the India-Asia suture in southern Tibet?

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Abstract. The wide-angle seismic experiment of Project INDEPTH (International Deep Profiling of Tibet and the Himalayas) focused on the structure of the India-Asia continental collision suture (Yarlung Zangbo suture) in southern Tibet. Three-component portable seismographs recorded the explosive sources of the INDEPTH seismic reflection profile across the suture zone. We image a prominent subhorizontal reflector, the "Yarlung Zangbo reflector" (YZR), dipping ~4°N at ~20-km depth beneath the outcrop position of the Yarlung Zangbo suture, with a total area of at least 90 × 80 km. Possible geological interpretations for the YZR include fault/shear zones, fluids (magmatic, metamorphic, or hydrothermal), or lithotectonic contacts. High-amplitude reflections off the YZR out to postcritical offsets and refracted phases with a velocity of $\sim 7\ \mathrm{km\ s^{-1}}$ provide evidence that it is a solid-solid interface and the top of a mafic to ultramafic lithological unit. We suggest that the YZR is a Tethyan ophiolitic slab involving several kilometers of mafic-ultramafic rocks. We interpret the origin of the slab and its position in the midcrust in the context of the emplacement history of oceanic lithosphere and accreted material onto the northwestern and northern Indian passive margin and the tectonic history of the Yarlung Zangbo suture zone. The origin of the YZR body and its position in the midcrust are explained by the emplacement of an ophiolite nappe-accretionary wedge complex onto India's passive margin prior to continental collision, the subduction of this nappe complex beneath the forearc basin and the Asian (Gangdese) magmatic arc, and its further burial by the Gangdese arc from the north and the Indian passive margin sedimentary sequence from the south. Our model of the YZR constituting an ophiolitic sheet can explain several features of southern Tibetan tectonics, namely, the pre-collisional deformation within the northern Indian passive margin, the lack of strong deformation during collision, and the bivergent thrust belt along the suture zone and doming within central southern Tibet (e.g., Kangmar dome). Our interpretation implies that the Yarlung Zangbo suture is subhorizontal in the middle crust in southern Tibet.

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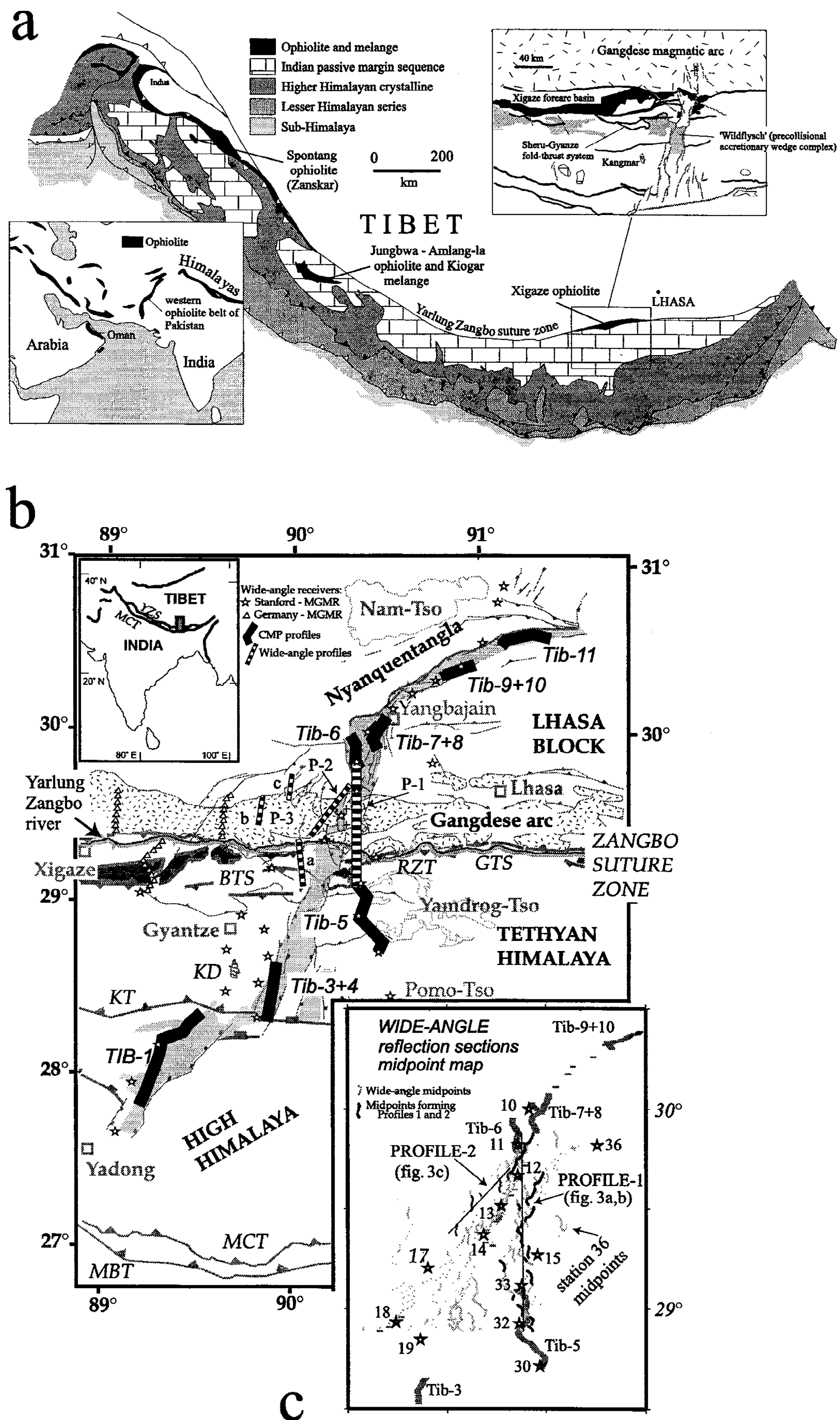
1. Introduction

The Yarlung Zangbo suture in southern Tibet, the focus of this paper, is the Tertiary suture between the Indian and Asian plates along the former Tethyan subduction zone. Continental collision along the Yarlung Zangbo suture thickened the crust of the Himalayas and Tibet to double the thickness of normal continental crust and induced the formation of the Tibetan plateau [e.g., *Allègre et al.*, 1984; *Molnar et al.*, 1993]. The presence of a high-velocity shield-like mantle lid suggests that Indian lithosphere underthrusts southern Tibet, possibly to the Banggong suture ~300 km north of the Yarlung Zangbo suture [*Owens and Zandt,* 1997]. A major reflector imaged on Project International Deep Profiling of Tibet and the Himalayas (INDEPTH) reflection profiles, dipping north beneath the Tethyan Himalaya to ~50 km south of the Yarlung Zangbo suture, is interpreted to be the detachment at the top of the underthrusting Indian crust (Main Himalayan thrust (MHT)) [*Zhao et al.*, 1993; *Nelson et al.*, 1996]. Field mapping and thermochronologic data demonstrate that crustal thickening across the Yarlung Zangbo suture involved postsuturing deformation partitioned into a bivergent fold-thrust structure including the south-vergent Gangdese thrust system and the north-vergent Backthrust system (which includes the Renbu-Zedong thrust) [e.g., *Girardeau et al.*, 1984; *Burg and Chen,* 1984; *Ratschbacher et al.*, 1992, 1994; *Yin et al.*, 1994; *Quidelleur et al.*, 1997]. Major still-unresolved questions include the projection of the suture through the lithosphere and the location of underthrusting Indian lithosphere (the MHT) beneath the Yarlung Zangbo suture.

In our study area (Figure 1) the Yarlung Zangbo suture, broadly coinciding at the surface with the Yarlung Zangbo (Zangbo is Tibetan for river), separates Asian Andean-type magmatic arc rocks of the Gangdese belt to the north from Indian (Tethyan) passive-margin rocks to the south [e.g., *Allègre et al.*, 1984]. The linear east-west trending outcrop of the Yarlung Zangbo suture and the often steeply dipping faults accompanying it [e.g., *Gansser,* 1964] led to the depiction of the Yarlung Zangbo suture in geological sections as a steeply dipping zone [e.g., *Shackleton,* 1981; *Burg and Chen,* 1984] and the postulation of major strike-slip offset along it [e.g., *Tapponnier et al.*, 1986]. The interpretation as a subvertical crustal feature is emphasized by steeply dipping seismic reflections projecting toward the outcrop of the Yarlung Zangbo suture, imaged at a depth of ~45-75 km beneath the Gangdese belt. These reflections have been interpreted as crustal imbrications which involve a possible extension of the Yarlung Zangbo suture to depth [e.g., *Hirn et al.*, 1984; *Alsdorf et al.*, 1996, 1998a]. In southern Tibet the suture is cut by a series of north trending rift systems along


a
Ophiolite and melange
Indian passive margin sequence
Higher Himalayan crystalline
Lesser Himalayan series
Sub-Himalaya
Spontang ophiolite (Zanskar)
0 200 km
TIBET
Jungbwa - Amlang-la ophiolite and Kiogar melange
Xigaze ophiolite
LHASA
Yarlung Zangbo suture zone
Gangdese magmatic arc
40 km
Xigaze forearc basin
'Wildflysch' (precollisional accretionary wedge complex)
Sheru-Gyanze fold-thrust system
Kangmar
Ophiolite
Himalayas
western ophiolite belt of Pakistan
Oman
Arabia
India
b
89° 90° 91°
31° 30° 29° 28° 27°
TIBET
INDIA
YZS
MCT
Wide-angle receivers:
Stanford - MGMR
Germany - MGMR
CMP profiles
Wide-angle profiles
Nam-Tso
Nyanquentangla
Tib-11
Tib-9+10
Yangbajain
LHASA BLOCK
Tib-6
Tib-7+8
P-2
P-1
P-3
Lhasa
Yarlung Zangbo river
Gangdese arc
ZANGBO SUTURE ZONE
Xigaze
BTS
RZT
GTS
Yamdrog-Tso
Gyantze
Tib-5
TETHYAN HIMALAYA
KD
KT
Tib-3+4
Pomo-Tso
TIB-1
HIGH HIMALAYA
Yadong
MCT
MBT
WIDE-ANGLE reflection sections midpoint map
Wide-angle midpoints
Midpoints forming Profiles 1 and 2
Tib-9+10
Tib-7+8
Tib-6
PROFILE-2 (fig. 3c)
PROFILE-1 (fig. 3a,b)
station 36 midpoints
Tib-5
Tib-3
c
90° 91°

which east-west extension has been taking place since circa 8 Ma [e.g., *Harrison et al.*, 1995]. The geophysical data discussed in this paper were acquired along the Yadong-Gulu rift, which is the most prominent of these rift systems. Here we use the wide-angle seismic data from Project INDEPTH to show that the surface exposure of the Yarlung Zangbo suture in southern Tibet is underlain by a midcrustal subhorizontal reflector of large lateral extent, the Yarlung Zangbo reflector (YZR).

Sutures are commonly recognized by the outcrop of remnants of oceanic lithosphere (ophiolites) in orogenic belts [e.g., *Nicolas*, 1989]. Ophiolites that crop out along the trace of the Yarlung Zangbo suture in southern Tibet all represent Tethyan lithosphere formed in Cretaceous time between the Lhasa block to the north and the Indian plate to the south, most notably the Xigaze ophiolite, which displays a complete ophiolite sequence from mantle peridotites to pillow lavas stratigraphically covered by deep-sea sediments (Figure 1) [*Nicolas et al.*, 1981; *Pozzi et al.*, 1984; *Girardeau et al.*, 1984]. Here we present geophysical evidence that the YZR marks the top of a lithologic unit with high seismic velocity suggestive of a mafic to partially serpentinized ultramafic composition and a persuasive, albeit nonunique, geological interpretation that the YZR represents an ophiolitic slab which outlines the Yarlung Zangbo suture as subhorizontal at midcrustal level. This paper augments previous brief discovery reports [e.g., *Makovsky et al.*, 1995] by detailing the evidence given by our seismic data for the existence, character, and extent of the YZR and by a discussion of our geological interpretation.

2. Project INDEPTH

Project INDEPTH is an ongoing multinational, multidisciplinary effort to provide a geophysical transect across the Tibetan plateau [*Nelson et al.*, 1996]. About 400 km of seismic common midpoint (CMP) reflection data were acquired from the High Himalaya in the south to well into the Tibetan plateau. These data were collected in the summers of 1992 and 1994 by seismic crews of the Ministry of Geology and Mineral Resources (MGMR) of the People's Republic of China. Because of rugged topography, CMP profiling was segmented into 11 lines, most notably leaving a 70-km data gap across the Yarlung Zangbo suture. Explosive sources, typically of 50-200 kg dynamite, were triggered every 200 m along the profile and recorded by a 6-km-long, 240-channel receiver spread (120 channels in 1992). The data were processed to produce 15-fold stack sections of the line segments [*Zhao et al.*, 1993; *Brown et al.*, 1996; *Hauck et al.*, 1998; *Alsdorf et al.*, 1998b]. The seismic reflection profiling was accompanied by our wide-angle profiling (discussed in section 3), a collocated broadband teleseismic array [*Kind et al.*, 1996], and localized surface geological mapping [e.g., *Edwards et al.*, 1996; *Wu et al.*, 1998], and the profiling was followed in 1995 by an approximately collocated magnetotelluric profile [*Chen et al.*, 1996]. Combined INDEPTH results suggest the presence of fluid concentrations in the Tibetan middle crust to the north of the Yarlung Zangbo suture, relatively low crustal S wave velocity and an approximately constant depth of 75-80 km to the Moho beneath the Yarlung Zangbo suture, and the underthrusting of Indian continental crust beneath the Tethyan Himalaya along the Main Himalayan thrust (MHT), at least to a point ~ 50 km south of the Yarlung Zangbo suture where the MHT reaches a depth of ~ 50 km [*Nelson et al.*, 1996], and possibly to ~ 20 km north of the Yarlung Zangbo (as discussed in section 6).

3. INDEPTH Wide-Angle Experiment

The wide-angle component of Project INDEPTH was designed to delineate, among other objectives, the deep structure of the Yarlung Zangbo suture in the regions where standard CMP profiling was technically not feasible. Sixty permanent stations equipped with REFTEK digital three-component seismographs were deployed for the 5-month duration of the CMP experiment. A Stanford University - MGMR team deployed 30 of these stations along and off the ends of the CMP profiles in a continuous 400-km-long array from Pagri and Pomo Tso (Tso is Tibetan for lake) in the south, across the Yarlung Zangbo suture, to the north edge of Nam Tso (Figure 1). An additional 30 stations were deployed by a German - MGMR team [*Mechie et al.*, 1996; *Zhao et al.*, 1997] across the Yarlung Zangbo suture in three north-south arrays, each ~ 50 km long, 70-130 km to the west of the CMP profiles (Figure 1). The INDEPTH explosive sources were recorded by these permanent stations out to maximum offsets of up to 350 km across the Yarlung Zangbo suture. Several short-term deployments were carried out in conjunction with extra shots to augment near-vertical data coverage in the gaps between

Figure 1. (a) Tectonic map of the Himalayas and southern Tibet detailing the major tectonic units and ophiolite occurrences discussed in the text. Lower left inset shows location of the Oman ophiolite and of the western ophiolite belt of Pakistan within the Alpine-Himalayan orogenic belt. Top right inset depicts simplified geologic and tectonic map of eastern south Tibet with the geologic and tectonic units discussed in the text. Maps are modified from *Gansser* [1964] and *Burg* [1983]. (b) Location map of Project International Deep Profiling of Tibet and the Himalayas (INDEPTH) seismic experiment, including the wide-angle reflection sections across the Yarlung Zangbo suture, overlain on the simplified geological map of southern Tibet. P1, P2, and P3 are wide-angle reflection sections across the Yarlung Zangbo suture (YZS). For P-1, see Figures 3a and 3b, and Plate 2a; for P-2, see Figure 3c; and for P-3a, P-3b and P-3c, see *Mechie et al.* [1996] and *Zhao et al.* [1997]. Geological map is modified from *Burg* [1983]. Light shading indicates the extent of the Yadong-Gulu rift system; dark shading indicates Xigaze ophiolite outcrops; and random stipple indicates Gangdese magmatic arc plutons. Major structural elements (solid lines) include the following: MBT, Main Boundary thrust; MCT, Main Central thrust; KT, Kangmar thrust; KD, Kangmar dome (striped pattern); BTS, Backthrust System; RZT, Renbu-Zedong thrust; and GTS, Gangdese thrust system. MGMR, Ministry of Geology and Mineral Resources. (c) Location map of wide-angle reflection midpoints in the gap in common midpoint (CMP) profiling across the Yarlung Zangbo suture.

CMP profile segments, in particular across the Yarlung Zangbo suture. This paper focuses on the Stanford-MGMR data and the analysis done at Stanford. These data were reduced into receiver (station) gathers (Figure 2) as summarized by *Makovsky and Klemperer* [1996] and are freely available from the Incorporated Research Institutions for Seismology - Program for Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL) Data Management Center (http://www.iris.washington.edu/).

4. Description of the Midcrustal Reflection Sequence

The main feature observed on the wide-angle data recorded across the Yarlung Zangbo suture (Figure 1) is a high-amplitude midcrustal P wave reflectivity band [*Makovsky et al.,* 1995]. This band is clear even on minimally processed single-fold true-amplitude displays of the data (Figure 2), and

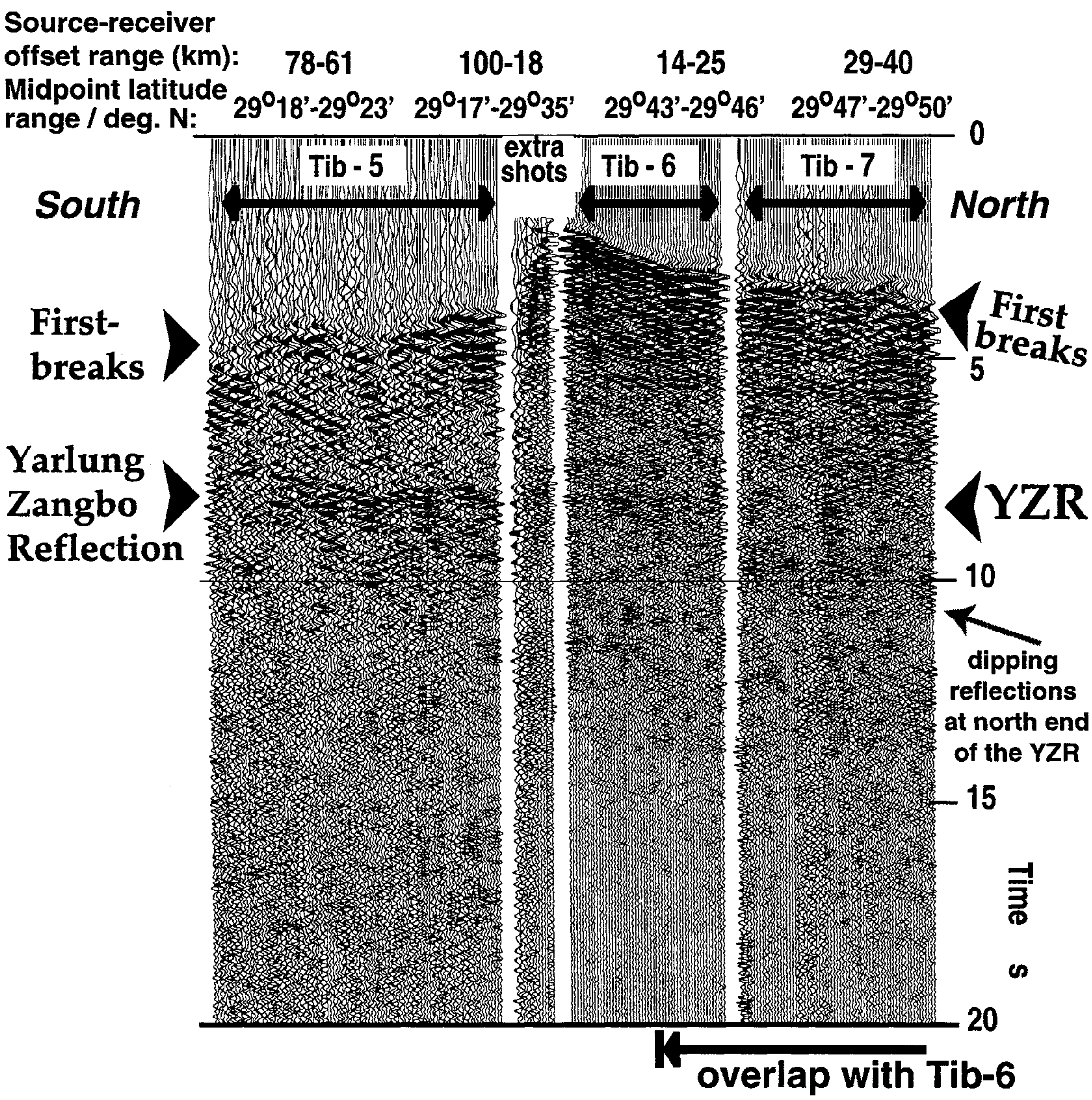


Figure 2. Data recorded on wide-angle station-12 from shots triggered along CMP profiles Tib-5 to-Tib-7 (left to right, respectively) and from extra shots triggered in the gap across the Yarlung Zangbo suture. Data are normal move-out (NMO) corrected for a velocity of 5.75 km s^{-1}, and plotted trace sequentially with true amplitude. The Yarlung Zangbo reflector (YZR) reflection appears on data from Tib-5 and Tib-6 shots as a horizontal phase at ~ 8-11 s two-way time (twt), clearly delayed from the first breaks (crustal direct arrivals) which arrive at times changing with the offset. Note the apparent change in frequency content caused by the different NMO stretch in each panel.

the band is delayed with respect to, and clearly discernible from, the first arrivals at source-receiver offsets of ~ 0-140 km (Figure 3). The correlation of wide-angle reflections recorded at different widely spaced stations is not always immediately obvious. We correlated the wide-angle reflections recorded by our different stations by making single-fold (Figure 3) and low fold stacked sections using different subsets of the data and different normal move-out (NMO) corrections. We put special emphasis on correlating the character of reflections between segments of continuous midpoint coverage recorded on different receivers (compare methodology of *Klemperer et al.* [1986]). A uniform NMO correction with a constant 5.75 km s^{-1} velocity projects the reflection band, recorded at very different travel times by different receivers at different offsets, to a single reflective band with aligned phases (Figures 2 and 3). Using an NMO correction with velocities greater or less than 5.75±0.1 km s^{-1} causes the reflective band recorded on different receivers, at the same midpoint ranges but at different offsets, to have inconsistent times. We therefore conclude that the observed midcrustal reflectivity corresponds to a single reflection sequence, which we name the Yarlung Zangbo reflection (YZR), at ~8-s zero-offset two-way reflection time (twt). The phase correlation and zero-offset twt of the YZR as imaged on large-offset data alone would be highly sensitive to the velocity used in the NMO correction. However, the same 8-s twt high-amplitude reflection sequence is observed also on our sparse near-offset data, obtained using extra shots detonated within the gap in CMP profiling (Figures 1 and 2). The reflection twt on the near-offset data does not depend on the velocity used for NMO correction and therefore gives independent confirmation of the 8-s zero-offset twt. The uncertainty in NMO velocity and uncorrected static delays (near-surface corrections) suggest an uncertainty of ±0.5 s in the YZR twt (approximately ±1.5-km depth) on our sections.

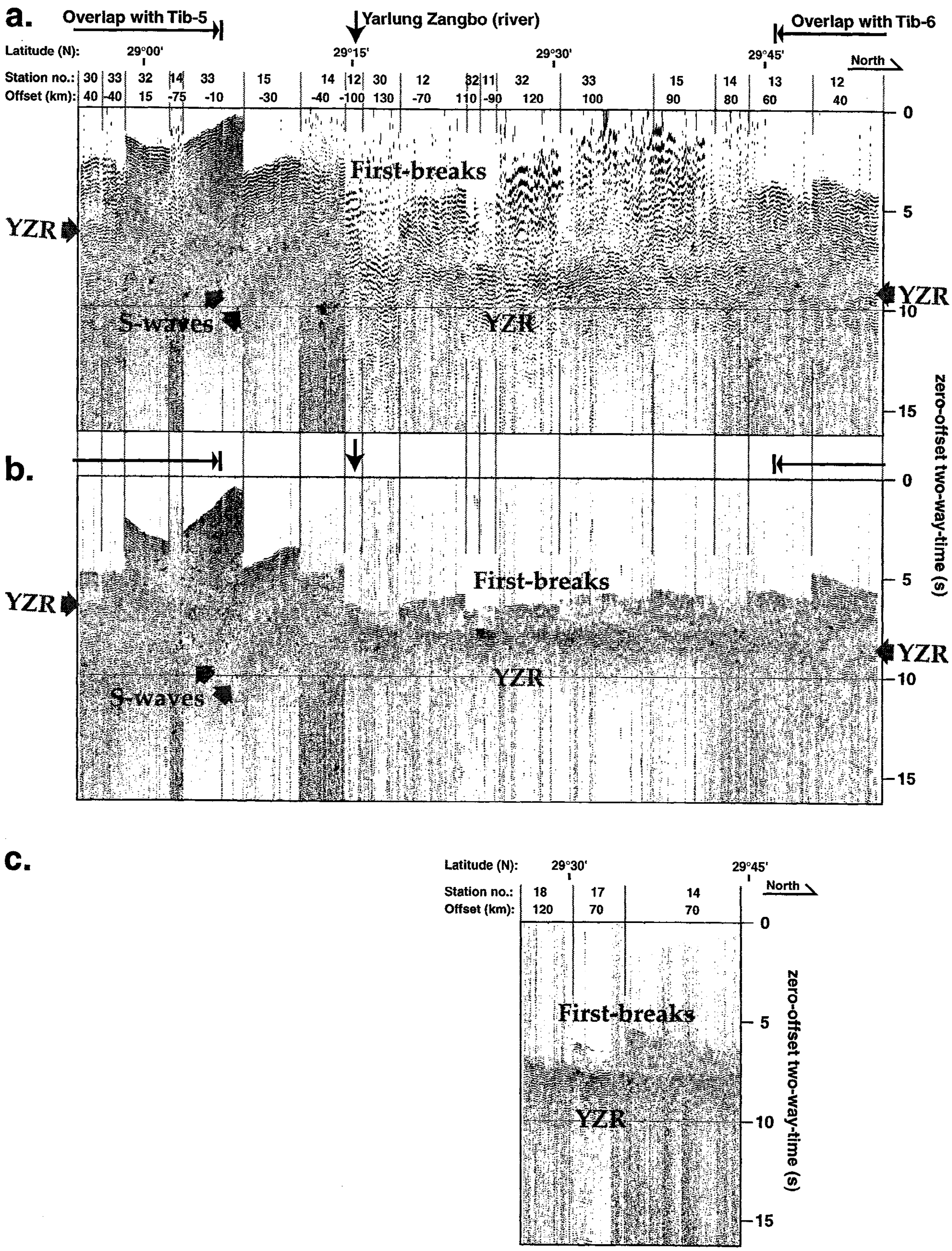
5. Reflection Sections Across the Yarlung Zangbo Suture

We filled the gap in CMP profiling with a CMP-like single-fold north-south reflection section crossing the Yarlung Zangbo suture. This section (Figure 3a) was produced by concatenating continuous panels of NMO-corrected single-receiver data, with offsets less than 140 km, at successive midpoint latitude ranges. This section follows approximately longitude 90.4°E between latitudes 28.8° and 29.9°N and connects across the gap between the CMP profile segments Tib-5 and Tib-6, south and north of the Yarlung Zangbo suture, respectively (Figure 1). To avoid combining data across a large lateral (east-west) extent, we limited our profile (Figure 3a) to data with midpoints in a 20-km-wide swath along this profile (profile 1, Figure 1). For each latitude range we selected the best data available within the swath of midpoints, usually preferring the data with shorter offsets. The main feature observed on our section is the YZR, a consistent high-amplitude band of reflections, with its onset ~6-7 s twt at the south part of the section and ~8 s at the northern part of the section (Figure 3a). The consistency of the YZR reflection sequence is demonstrated by the match between successive section panels, in particular those that were recorded at similar offset range but in opposite directions (shots received from the north show first arrivals dipping south (to the left); shots received from the south show first arrivals dipping north).

The NMO correction, the conventional method to correct for reflection travel time with offset (Figures 2 and 3a), stretches the data [*Sheriff,* 1991] and moves the onset of each reflected phase to its correct zero-offset time. However, the NMO stretch (up to 300% in Figures 2 and 3a) causes the band of reflections to appear with significantly lower frequency and with longer duration on long-offset data than on short-offset data. The apparent discrepancies of frequency content and of time extent of the reflective band between adjacent panels in Figure 3a are therefore artifacts of NMO stretch enhanced by our juxtaposition of NMO-corrected wide-angle data from very different offset ranges. To evaluate the continuity in the character of the YZR across the Yarlung Zangbo suture, it is helpful to produce a section in which the YZR reflections are projected to zero-offset time without being stretched (Figure 3b). This is done by advancing every trace by a constant time shift equivalent to the move-out of a 8-s zero-offset twt reflection. The steeply dipping events masking the YZR in the southern part of the section are not reflections but are direct *S* wave phases (arrowed in Figures 3a and 3b). These *S* wave phases are prominent south of the Yarlung Zangbo suture and largely diminished to the north of it [*Makovsky et al.,* 1996a]. This section (Figure 3b) shows that the YZR is a 1-2-s thick continuous reflective band of approximately uniform character along the entire section, across the Yarlung Zangbo suture. The continuity of the YZR may be explained, as in the case of all subhorizontal seismic reflectors, by a fortuitous alignment of two or more different reflectors separated by vertical boundaries. The connection of the YZR north and south of the surface trace of the Yarlung Zangbo suture, across poorer data from 29°10' to 29°15'N, is not unequivocal on the wide-angle data. However, the simplest explanation, and our preferred interpretation based on the uniformity of the reflection character, is that the YZR marks a continuous reflector and a single subsurface structure from 28°55' to 29°55'N. The time extent of the YZR remains similar even after deconvolution to correct for the reverberatory source signature (estimated from the first-break waveform). This result suggests that the YZR possesses internal structure over a thickness of ~ 5 km.

6. Wide-Angle Seismic Character of the YZR

The YZR appears on normal-incidence reflection section Tib-5 (Plate 2) to be very similar to the band of bright-spot reflections that are observed beneath the north Yadong-Gulu rift at ~ 5-s twt (~ 15-km depth) on Tib-6 and Tib-7, and that are interpreted to be midcrustal fluid concentrations (Yamdrok-Damxung Reflection of *Brown et al.* [1996]). However, the wide-angle reflection character of the bright-spot reflections [*Makovsky et al.,* 1996a; *Makovsky and Klemperer,* 1999] is in clear contrast with that of the YZR. A quantitative analysis of the YZR reflection amplitude is not possible, but qualitatively, the YZR is characterized on the wide-angle data by (1) strong *P* wave reflections throughout the wide range of offsets (to ~ 140 km) at which they were recorded (Figures 2 and 3a); (2) particularly strong reflections at offsets between ~ 100 and 140 km (Plate 1), which we interpret to be critical-angle reflections thereby requiring a velocity increase across the YZR; and (3) *P*-to-*S* wave converted reflections, recorded on our three-component seismometers, that are much weaker than the corresponding *P* wave reflections (see south (left) part of Figure 2 by *Makovsky et al.* [1996a]). None of these three observations is true of the "bright spots," which show no critical-angle reflections but instead show diminished *P* wave reflection amplitudes and strong *P*-to-*S* wave conversions at offsets from 30 to 50 km [*Makovsky et al.,* 1996a]. The bright spots' reflection


a.
Overlap with Tib-5
Yarlung Zangbo (river)
Overlap with Tib-6
Latitude (N):
29°00'
29°15'
29°30'
29°45'
North
Station no.: 30 33 32 14 33 15 14 12 30 12 32 11 32 33 15 14 13 12
Offset (km): 40 -40 15 -75 -10 -30 -40 -100 130 -70 110 -90 120 100 90 80 60 40
First-breaks
YZR
S-waves
zero-offset two-way-time (s)
0
5
10
15
b.
c.
Latitude (N):
29°30'
29°45'
Station no.: 18 17 14
Offset (km): 120 70 70

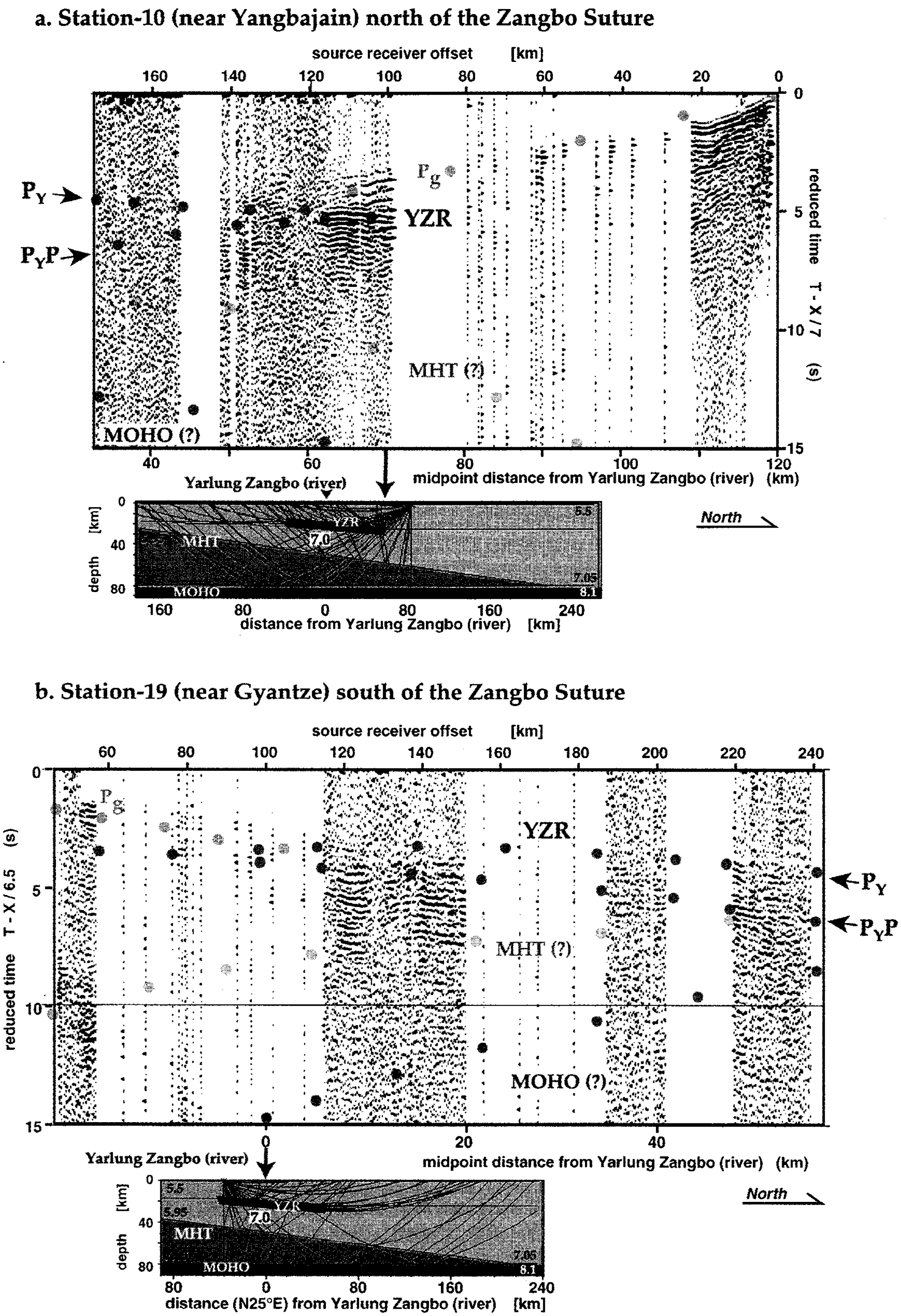
characteristics, in contrast to the YZR's characteristics, suggest a reduction of the seismic velocities and hence the presence of fluids (water or magma) in the middle crust [*Makovsky et al.*, 1996a; *Makovsky and Klemperer,* 1999]. Taken together the YZR wide-angle reflection characteristics (characteristics 1 to 3 above) are a strong (albeit qualitative) indication [*Ostrander,* 1984] that the YZR marks a positive impedance contrast (velocity increasing with depth to > 5.75 km s^{-1}), the top of a crustal high-velocity layer.

Refractions through the YZR can be identified with confidence only on data from two of our stations: receiver 10 north of the YZR and receiver 19 south of the YZR (Plate 1). These refractions show apparent velocities of ~7.2 and 6.5 km s^{-1}, respectively. The retrograde dip (earlier times at larger offsets) of P_Y in Plate 1a (displayed with reduction velocity 7 km s^{-1}) requires the apparent velocity to be greater than 7 km s^{-1}; the almost horizontal P_Y phase in Plate 1b (displayed with reduction velocity 6.5 km s^{-1}) requires the apparent velocity to be ~6.5 km s^{-1}. The observation of different apparent velocities for opposed shooting directions very strongly suggests, and is most simply modeled by, a body of velocity intermediate between the two apparent velocities and dipping toward the receiver of the receiver gather which shows the higher apparent velocity. Together, receivers 10 and 19 provide reversed refraction coverage of the YZR and strongly suggest that the YZR has a velocity ~7 km s^{-1} and dips ~4°N. This is illustrated (Plate 1) by the match of the refracted travel times, on data recorded by both stations, with the results of ray tracing [*Luetgert,* 1992] through a simplified seismic velocity model for southern Tibet. Previous studies have demonstrated that the southern Tibetan crust has a relatively low average seismic velocity, down to the 75-to-80-km-deep Moho, of 5.9–6.5 km s^{-1} [e.g., *Sapin and Hirn,* 1997; *Rodgers and Schwartz,* 1997]. To fit these results our midcrustal high-velocity unit at ~20-km depth (the YZR) can only have very limited thickness. Our simplified ray-tracing model (insets to Plate 1) depicts the YZR as a 5-km-thick slab with velocity increasing from 7.0 km s^{-1} at its top to 7.1 km s^{-1} at its base, embedded at ~20 km depth in a laterally uniform crust of constant 80-km thickness with a constant velocity gradient from 5.5 km s^{-1} at the surface to 7.05 km s^{-1} above the Moho (and 8.1 km s^{-1} below the Moho), giving a model average velocity down to the YZR of 5.75 km s^{-1} Note that features depicted deeper than 30 km do not affect our results with respect to the YZR. The MHT in our simplistic model has no velocity change across it and is depicted as having a constant north dip until it intersects with the Moho. We note, however, that the northernmost midpoints of observed wide-angle reflections from the MHT are only ~20 km north of the Yarlung Zangbo suture (Plate 1b), at source-receiver offsets of 115-150 km, in which range they show a reflection character very similar to the MHT reflections reported by *Makovsky et al.* [1996b, Figure 2c]. The model used for station-19 is oriented 25° east of north (see Figure 1b), and the dips are adjusted accordingly. This highly simplified model is chosen to illustrate the essential features required by our data and is not calculated to be the best possible fit regardless of model complexity. This simplest model that approximately matches our data therefore demonstrates the need for a midcrustal, high-velocity, north dipping YZR (Plates 1a and 1b) and suggests that the MHT reflector continues with a constant dip to at least 20 km north of the Yarlung Zangbo (Plate 1b).

7. Extent of the YZR

Plotting our NMO-corrected one-fold section along profile-1 (Figure 3a) together with the INDEPTH CMP-stacked sections [*Brown et al.*, 1996; *Alsdorf et al.*, 1998b], by projecting the midpoint latitude onto a south-north line, provides a continuous reflection section across the Yarlung Zangbo suture (Plate 2). The YZR imaged on this section is a 95-km-long sub-horizontal reflector underlying the Yarlung Zangbo suture outcrop in the middle crust. The northern part of the YZR is a continuous band of reflections at 8-to-11-s twt (~23-to-32-km depth), from the Yarlung Zangbo suture to ~55 km to the north. The YZR appears to terminate in the north against a set of ~25° north dipping reflections, imaged both on CMP profile Tib-6 [*Alsdorf et al.*, 1998b] and on our wide-angle data (Figure 2). The discontinuous band of "bright-spot" reflections [*Brown et al.*, 1996; *Makovsky et al.*, 1996a], imaged on the CMP profiles at 6-s twt beneath the northern Yadong-Gulu rift system, is not observed south of the northern end of the YZR, ~50 km north of the suture (Plate 2a). The southern part of the YZR (to ~29°07'N, Figures 3a, and 3b) is convincingly corroborated by a 6-s twt (~17.5 km) near-vertical reflection imaged on CMP profile Tib-5, which terminates ~40 km south of the Yarlung Zangbo suture (Plate 2a).

Figure 3. (a) Wide-angle single-fold reflection section P-1 (Figure 1b), shown as receiver gathers plotted trace-sequentially and concatenated to provide complete coverage of midpoint latitude ranges from 28°55' to 29°55'N. Bounds of each receiver gather are marked by vertical lines at the top and bottom of section. Receiver number and typical source-receiver offset are noted above each gather (offset is negative for shots fired south of a receiver). Data are true-amplitude-corrected for a decay of (time)$^{-1}$ laterally equalized, and NMO-corrected at 5.75 km s^{-1}. Note YZR as a band of reflectivity with onset at ~7 s (south end) to ~8 s (north end), clearly distinct from the first breaks (annotated). First breaks are not muted in order to demonstrate this distinction. Note the match of the YZR reflection between successive receiver gathers recorded from shots at similar offset but opposite direction (e.g., receivers 12, 30, 12, 32, 11, and 32 in middle of section) and the change of NMO stretch with offset. Dipping phases obscuring the YZR in the south part of the section are crustal direct *S* waves (arrows). (b) Same data and processing as those in Figure 3a except data are not NMO corrected; instead, every trace is advanced by a time shift equivalent to the moveout of a 8-s zero-offset twt reflection with a move-out velocity of 5.75 km s^{-1} (applies the correct NMO to the 8-s twt reflector without stretch, but reflections with other twt are not properly corrected). Note consistent character of YZR along entire section. (c) Section P-2 (Figure 1b) constructed as in Figure 3b above but using a different subset of our wide-angle data. Although composed mostly of different data, this section is similar to the section in Figure 3b.


a. Station-10 (near Yangbajain) north of the Zangbo Suture
source receiver offset [km]
160 140 120 100 80 60 40 20 0
P_Y
P_YP
P_g
YZR
MHT (?)
MOHO (?)
reduced time T - X / 7 (s)
0 5 10 15
40 60 80 100 120
Yarlung Zangbo (river)
midpoint distance from Yarlung Zangbo (river) (km)
depth [km]
0 40 80
YZR
MHT
7.0
5.5
7.05
8.1
MOHO
160 80 0 80 160 240
distance from Yarlung Zangbo (river) [km]
North
b. Station-19 (near Gyantze) south of the Zangbo Suture
source receiver offset [km]
60 80 100 120 140 160 180 200 220 240
P_g
YZR
MHT (?)
MOHO (?)
P_Y
P_YP
reduced time T - X / 6.5 (s)
0 5 10 15
0 20 40
Yarlung Zangbo (river)
midpoint distance from Yarlung Zangbo (river) (km)
depth [km]
0 40 80
5.5
5.95
YZR
7.0
MHT
MOHO
7.05
8.1
80 0 80 160 240
distance (N25°E) from Yarlung Zangbo (river) [km]
North

Additional subsets of INDEPTH wide-angle seismic data that were recorded across the Yarlung Zangbo suture provide constraints on the lateral extent of, and a test for the existence of, the YZR. We constructed an additional section (Figure 3c) with the methodology described above along a southwesterly trending 20-km swath, between longitudes 90.0° and 90.2°E (profile 2, Figure 1b), in the area where most extra shots (discussed above) were recorded at short offsets. Again, we observe the YZR on profile 2 (Figure 3c) at the same twt and with the same reflection character as those on profile 1 (Figures 3a and 3b). *Mechie et al.* [1996] used INDEPTH broadside data (fan data) to produce, independently of our work, an additional set of reflection sections across the Yarlung Zangbo suture (Profiles 3a, 3b and 3c, Figure 1). Their sections show a subhorizontal reflected phase at ~8 s beneath and north of the surface trace of the Yarlung Zangbo suture, which presumably corresponds to our YZR. Taken with our eastern profile 1 and our western profile 2 (Figure 3), Mechie et al.'s broadside sections and our station 36 data (not shown) with midpoints ~20 km to the east of our eastern profile (Figure 1) outline the YZR as an approximately planar reflection with areal extent ~95 km north-south and at least 80 km east-west, dipping approximately 4°N from ~6-s twt (~17.5-km depth) in the south to ~8-s twt (~24-km depth) in the north.

8. Geologic Nature of the YZR

From our geophysical analysis we conclude that the YZR constitutes a single reflection sequence representing the top of a solid lithologic unit with large lateral extent 17-24 km beneath the surface outcrop of the Yarlung Zangbo suture. Our data broadly constrain the seismic velocities of the YZR unit to ~7 km s^{-1} and the crust around it to ~5.75 km s^{-1}. These velocities suggest that the YZR is a mafic [*Christensen and Mooney,* 1995] to partially serpentinized ultramafic [*Horen et al.,* 1996] unit embedded in the generally felsic southern Tibetan middle crust [*Sapin and Hirn,* 1997; *Rodgers and Schwartz,* 1997]. A significant compositional difference, such as felsic-mafic, is also suggested by the strong reflection amplitudes of the YZR.

Several alternative models for the nature of the YZR have been suggested [*Mechie et al.,* 1996; *Nelson et al.,* 1996; *Zhao et al.,* 1997; *Alsdorf et al.,* 1998a] on the basis of preliminary descriptions of the YZR that lacked the velocity and amplitude information discussed above. None of these previous models explains the full seismic character of the YZR. These models are detailed elsewhere and are only briefly mentioned here:

1. A fault or shear zone [*Mechie et al.,* 1996; *Zhao et al.,* 1997; *Alsdorf et al.,* 1998a] could not by itself explain the high velocities observed on the YZR. These high velocities require the presence of a distinct high-velocity lithologic unit, and an interpretation for the nature of the YZR must explain the origin of such a lithological unit, as well as its placement at midcrustal depth in the Yarlung Zangbo suture zone. In the scenario suggested by *Zhao et al.* [1997] and *Alsdorf et al.* [1998a] the YZR traces the basal décollement of the Gangdese thrust system, and the surface expression of the Gangdese thrust, as mapped in eastern southern Tibet, is a splay with the sole thrust continuing southwards either ending as a blind thrust or ramping up as a south-vergent thrust within the northern Indian passive margin rocks. However, no south verging deformation zone of the appropriate Oligocene age in the Indian passive margin rocks has yet been described, and no high-velocity lithological units outcrop within the exposed Indian basement and passive margin sediments. On the basis of the amount of Gangdese belt exhumation, *Yin et al.* [1994] suggested that the Gangdese thrust system ramps downward from the surface to a subhorizontal sole thrust at ~15-km depth, possibly following the brittle-ductile transition. The YZR, however, is as much as 10 km deeper than the proposed sole thrust.

2. An original in situ lower crustal unit of the Mesozoic Gangdese arc would not extend far to the south of the Gangdese belt as the YZR does.

3. A late Miocene to Recent east-west extensional feature related to rifting in southern Tibet (e.g., the Yadong-Gulu rift) would probably be limited in its east-west extent to the width of the rift; however, the YZR extends well west and east of the Yadong-Gulu rift. An exception could be a low-angle detachment, but such a detachment would not explain by itself the seismic character of the YZR (see discussion about shear zone in paragraph 1).

4. Autochthonous intrusions, either fluid bearing (e.g., partially molten) or solidified, and possibly a continuation or fossil equivalent of the band of "bright spots" observed beneath the northern Yadong Gulu rift [*Mechie et al.,* 1996; *Nelson et al.,* 1996; *Zhao et al.,* 1997; *Alsdorf et al.,* 1998a] are inconsistent with geophysical and geological observations. Fluid concentrations in the southern Tibetan crust (the bright spots) form zones of low seismic velocities with distinctive reflection characteristics [*Makovsky and Klemperer,* 1999; *Ross et al.,* in press], which are clearly different (as discussed in section 6) from the velocity and

Plate 1. Data from two receivers showing critical-angle reflections and refractions from the YZR: (a) station-10 near Yangbajain north of the YZR; (b) station-19 near Gyantze south of the YZR (Figure 1). Data are plotted with reduced time (station-10 by 7 km s^{-1} and station-19 by 6.5 km s^{-1}) against offset, stacked in 300-m bins (single to low fold). Each trace is internally true amplitude (no time-variant scaling) but laterally scaled (all traces scaled to same average value). The recording offset is annotated above each plot, and the distance of the trace midpoint from the Yarlung Zangbo (river) is annotated below each plot. The two receivers provide similar midpoint coverage with reversed ray paths constraining the YZR 10-30 km north of the Yarlung Zangbo. Beneath each data plot is a simplified ray-tracing model for southern Tibet. The paths of rays traced through the models are drawn as black lines, and travel times predicted by the model are marked on the data with the color coding of the corresponding model blocks. The modeling demonstrates that high-amplitude phases on both stations represent critical-angle reflections off the YZR (at the meeting of the P_Y and P_YP phases), whereas weak first arrivals at 120 to 200-km offset, with apparent velocities of ~7.2 and ~6.5 km s^{-1} for stations 10 and 19, respectively, match the predicted reversed refractions from the same area of the YZR body. Weak reflections probably correspond to the Main Himalayan thrust (MHT) and Moho as shown but are too weak to deserve careful modeling.

reflection characteristics of the YZR. Any intrusions represented by the YZR must therefore be solidified, presumably older than the currently fluid-bearing "bright spots", and have a mafic composition. Late Miocene to Recent mafic intrusions on the scale of the YZR would require mantle melts, which is hard to reconcile with the underthrusting of southern Tibet as far as 32°N by a high seismic velocity, supposedly cold, Indian lithosphere [*Owens and Zandt,* 1997] and with the lack of volcanism at the surface since late Miocene [*Zhang et al.,* 1997].

Our preferred interpretation (schematic cross section of Plate 2b) is that the YZR represents a distinct pre-collisional to syncollisional lithologic unit emplaced by thrusting into the middle crust beneath the Yarlung Zangbo suture zone. Near-vertical and wide-angle reflection sequences with characteristics similar to the YZR have been imaged beneath sutures along the western margin of North America [*Fuis and Clowes,* 1993; *Fuis,* 1998], including the buried suture beneath the Great Valley forearc basin of California [*Godfrey et al.,* 1997; *Godfrey and Klemperer,* 1998]. These reflection sequences have been interpreted, on the basis of their geological setting, outcrop patterns, and seismic velocity, to represent ophiolitic complexes. We therefore next consider in the context of the Himalayan–Tibetan geological setting the possibility that the YZR represents an ophiolitic complex.

9. Geological Evidence: Oceanic Lithosphere and Accreted Material in Southern Tibet

A geological model for the YZR as an ophiolitic complex, i.e., lithotectonic unit, must explain its origin, so we next discuss the distribution and emplacement of oceanic lithosphere and accreted material onto the Indian passive margin. In order ultimately to justify our tectonic model for the development of southern Tibet, we review the evidence that distinct groups of ophiolite and accreted rocks exist in southern Tibet and that an ophiolite nappe was emplaced onto the western and presumably also onto the northern margin of India at about the Cretaceous-Tertiary boundary, i.e., before continental collision. The evidence suggests that ophiolites were emplaced at about the same time all along the Indian margin; that these ophiolites were of substantial thickness, including a mantle section; and that the lithotectonic units associated with the ophiolite nappes can be correlated along the length of the orogen.

Ophiolites and associated sedimentary rocks along the Yarlung Zangbo suture in Tibet are all of Tethyan origin. From an evolutionary perspective, however, they may be attributed to three groups distinct by their lithostratigraphy, tectonic position, and origin, here called "Asian," "Tethyan," and "Indian" (Figure 4):

(1) The Xigaze ophiolite [e.g., *Nicolas et al.,* 1981; *Girardeau et al.,* 1985], exposed over ~ 800 km^2 and with a 7-to-12-km-thick complete crustal and mantle section, represents the Asian affinity. It is transgressively overlain by the Cretaceous Xigaze forearc basin sediments, which in the north are associated with late Aptian-Albian Asian passive margin limestones and which in the south form the sedimentary cover of late Albian-lower Cenomanian radiolarites and pillow

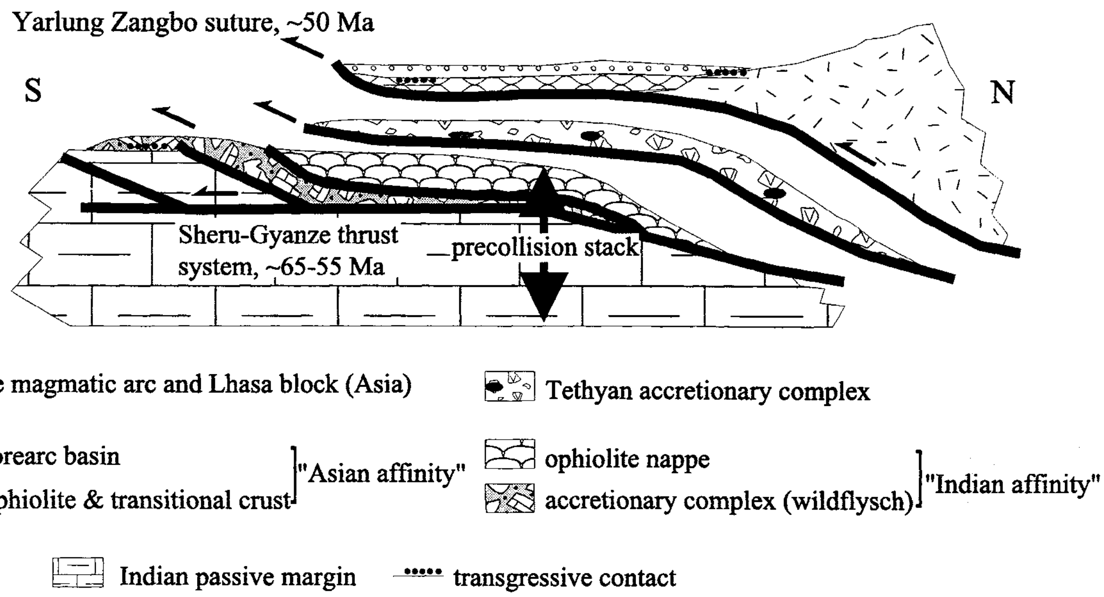


Figure 4. Schematic sketch of the lithotectonic pile underthrusting Asia at ~ 50 Ma. India consists of (from top to bottom) the ophiolite nappe, the wildflysch complex, and the distal passive margin; Asia comprises the Xigaze forearc basin, transgressively overlying the Xigaze ophiolite and associated with the Gangdese magmatic arc, and the arc, resting on the southern edge of the Lhasa block. The Tethyan accretionary wedge, marking the Tethyan subduction zone, is in between. See text for discussion.

basalts of the Xigaze ophiolite (Figure 4). This ophiolite formed attached to Asian continental crust along the northern margin of the Tethys, and the Tethyan subduction zone developed south of it [e.g., *Burg et al.*, 1983; *Girardeau et al.*, 1984; *Pozzi et al.*, 1984].

(2) Thrust slices of late Jurassic-Early Cretaceous radiolarite [*Bally et al.*, 1980], siliceous schist, quartzite, ophicalcite, and ophiolite breccia south of the Xigaze ophiolite constitute the accretionary complex related to subduction of ~ 6000 km of Tethyan oceanic lithosphere, here called the accretionary wedge of Tethyan affinity [*Burg et al.*, 1987; *Ratschbacher et al.*, 1994].

(3) A series of ophiolitic klippen, for example, the Spontang klippe and the Jungbwa-Amlang la ophiolite complex in Zanskar and western Tibet, mostly comprising partly serpentinized peridotite, attests to one or several ophiolitic nappes, here called the ophiolite of Indian affinity, emplaced onto the Indian passive margin at about the Cretaceous-Tertiary boundary prior to continent collision [e.g., *Searle et al.*, 1997]. Structurally below the "Indian" ophiolite nappe and above the Indian passive margin rocks is a flysch-wildflysch unit in part as young as Maastrichtian to lowermost Paleocene. Intense south-vergent deformation of this wildflysch complex accompanied ophiolite nappe emplacement. (We use the term "wildflysch" to follow the terminology of the original workers [e.g., *Burg et al.*, 1985] and to avoid a genetic connotation. We only use the term "accretionary complex" when we explicitly wish to imply that specific genetic interpretation of a lithotectonic unit.)

An ophiolitic nappe of "Indian" affinity is not exposed in southern Tibet, but a similar wildflysch unit has been mapped partly in transgressive contact with imbricated and isoclinally folded Indian passive margin rocks (Figure 4) [*Burg et al.*, 1987, and references therein]. This wildflysch unit consists, as in Zanskar and western Tibet, more than 800 km to the west, of exotic blocks of Permian to Late Cretaceous-early Paleocene age and has a matrix whose youngest members are Maastrichtian-lowermost Paleocene [*Burg et al.*, 1985]. The presence of this wildflysch unit in southern Tibet justifies our belief that an analogous "Indian" ophiolitic nappe also exists in southern Tibet.

The existence of the "Indian" ophiolite nappe - wildflysch complex in southern Tibet can be understood in the framework of ophiolite emplacement and trench-strata accretion history that is common to the western and northwestern continental margin of India and the eastern ophiolite belt of Oman [e.g., *Gnos et al.*, 1997, 1998; *Beck et al.*, 1995, 1996; *Searle et al.*, 1997]. Emplacement of the "Indian" ophiolites culminated at about the Cretaceous-Tertiary boundary, well before the early Eocene India-Asia continent collision. Convergence between Eurasia and the India-Seychelles continent in the Late Cretaceous was accommodated along at least two subduction zones, one along the southern margin of Asia (south of the Xigaze ophiolite; see above) and the other intra-oceanic, short-lived, and close to the margin of India. Along the latter, ophiolite emplacement and accretion of melange complexes onto the continental margin of India took place prior to the India-Asia collision. Cretaceous-Tertiary ophiolite emplacement and accretion, similar to the history postulated here for southern Tibet, have been studied in Oman, Pakistan, Ladakh, and western Tibet.

9.1. Eastern Ophiolite Belt of Oman

Preemplacement sedimentation on the eastern ophiolite belt of Oman (e.g., Masirah, Ra's Madrekah) terminated in the uppermost Maastrichtian. The ophiolites were emplaced together with accretionary wedge deposits onto the Arabian continental margin [see *Gnos et al.*, 1997 and references therein].

9.2. Western Ophiolite Belt of Pakistan

The last preemplacement sediments underneath western ophiolite belt of Pakistan (e.g., Muslim Bagh, Bela) are Maastrichtian [see *Gnos et al.*, 1997, 1998]. The ophiolite formed at 70 Ma, and the emplacement-related metamorphic sole cooled at 70-65 Ma. The first postemplacement sediments straddle the Paleocene-Eocene boundary. The ophiolitic sequence is underlain by an accretionary wedge that includes Indian shelf sediments and may have comprised one large and thin thrust sheet (Bela ophiolite: <4.5 km thick, >10,000 km^2) that was dismembered after emplacement during the India-Asia collision. In northwest Pakistan [*Beck et al.*, 1995] the Kahi accretionary prism-trench complex, which contains the Waziristan-Khost ophiolite, includes strata as young as latest Maastrichtian. Late Paleocene Indian shelf sediments depositionally overlap the Kahi complex, dating thrusting of the accretionary prism onto the Indian slope at 66-55 Ma. The eroded accretionary complex and the late Paleocene strata were overlapped by late early Eocene limestone, which is continuous with the Indian shelf sequence and dates continent-continent suturing at 55-50 Ma [see *Beck et al.*, 1995].

9.3. Ladakh region of the western Himalayas

Ophiolite emplacement in the Ladakh region of the western Himalayas is dated at 75-60 Ma, and continent collision was completed at 54 Ma [*Searle et al.*, 1997, and references therein]. Marls and turbidites along the northernmost Indian shelf reach locally up into the Maastrichtian and are overlain by an olistolithic melange with a matrix as young as Campanian-Maastrichtian and by the Spontang ophiolite nappe (~ 400 km^2). Shallow marine rocks transgressed after a stratigraphic gap lasting most of the Paleocene. The end of marine sedimentation in the early Eocene indicates final suturing.

9.4. Western Tibet

Near the Raskas and Manasarowar lakes the 3500 km^2 and ≥0.5 km thick, mostly eroded Jungbwa ophiolite nappe overlies the Kiogar ophilitic melange, which reaches into the uppermost Cretaceious [*Gansser*, 1974].

10. Geological Evidence: Structural Setting of the Yarlung Zangbo Suture Zone in Southern Tibet

A geological model for the YZR as an ophiolitic unit, i.e., a lithotectonic unit, must explain its placement at midcrustal depth underneath the Yarlung Zangbo suture zone. Therefore we next emphasize the tectonic shaping of the Yarlung Zangbo suture zone in southern Tibet. We suggest that this encompasses the emplacement of an ophiolite nappe - accretionary wedge complex onto the passive margin prior to collision, its subduction beneath the forearc basin and arc, and its further burial by the Gangdese arc from the north and the Indian passive margin series from the south.

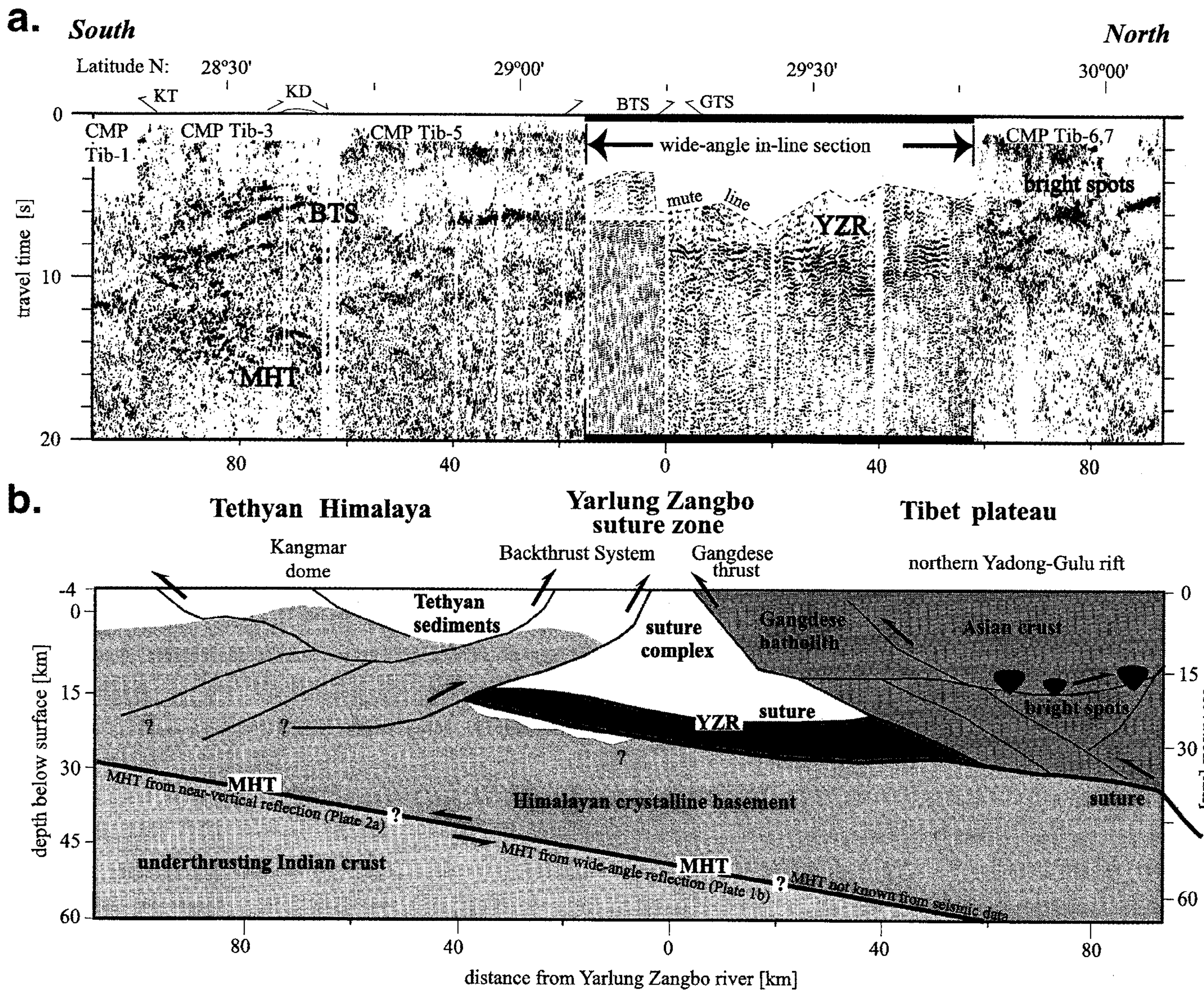


Plate 2. (a) A continuous, 200-km-long, north-south reflection section across the Yarlung Zangbo suture plotted at true vertical scale for a velocity of 6 km s^{-1}. The section is a composite of the unmigrated sections of CMP profiles Tib-3, Tib-5, Tib-6, and Tib-7 [*Alsdorf et al.*, 1998b] and our wide-angle NMO-corrected section (Figure 3a) along profile 1. The different sections were projected to a north-south profile and concatenated by successive midpoint latitude ranges (annotated above plot). Note that this projection positions the imaged reflections in their correct relative north-south location but may superimpose laterally distant reflections and results in a significant reduction of the image quality in comparison to Figure 3a and the work of *Alsdorf et al.* [1998b]. In the CMP sections we plot absolute value of the data. In the wide-angle section, first breaks are muted. NMO stretch causes the apparent low frequency and variable character of the YZR reflections. Data from the Yarlung Zangbo to 15 km south of it below 6 s (outlined by a dashed line) were processed differently to emphasize the continuity of the YZR across the Yarlung Zangbo suture. Yellow shading emphasizes reflections that we consider to be reliable. Main geological features, crossed by the profile, are schematically annotated above the section. Abbreviations are as in Figure 1. (b) Cartoon section for the structure of the Yarlung Zangbo suture as observed on the seismic section in Plate 2a. The major structural boundaries follow the yellow lines in Plate 2a (after appropriate migration of Plate 2a) and connect to the surface exposure of the major fault arrays in central southern Tibet. The Asian part of the section is modified from *Alsdorf et al.* [1998a]. The Yarlung Zangbo reflector (YZR) is the top of the ophiolite nappe-accretionary wedge complex (green). The suture complex may comprise the following (from top): the Xigaze forearc basin and Asian passive margin sedimentary rocks, both underlain by transitional and continental Asian crust in the north and the (Asian) Xigaze ophiolite in the south, and the Tethyan accretionary wedge, possibly multiply imbricated. See text for discussion.

In southern Tibet, three major events govern the formation and reactivation of the Yarlung Zangbo suture zone and taken together can explain the placement of an ophiolitic complex to midcrustal depth beneath the suture outcrop. The poorly studied Sheru-Gyanze fold-thrust system along India's northern passive margin section (Figure 4) [*Ratschbacher et al.*, 1994] is here interpreted to comprise the presuturing deformation during the emplacement of the Indian affinity ophiolite nappe because it predates and is coeval with wildflysch deposition. Deformation in the Indian passive-margin rocks underneath the wildflysch complex is characterized by large, recumbent, south verging folds which die out southward away from the Yarlung Zangbo suture; synkinematic, lower greenschist grade metamorphism has locally been dated at 50 Ma (K/Ar dates of fine-grained white mica) [*Ratschbacher et al.*, 1994; *Burg et al.*, 1987]. Both the wildflysch and the Indian passive-margin series were subsequently refolded (Backthrust event; see below). The Gangdese thrust system [*Yin et al.*, 1994] in eastern southern Tibet juxtaposed Gangdese arc-Lhasa block rocks over fragments of the Xigaze ophiolite, overthrusting the forearc basin. Equivalent thrusts probably underlie the forearc rocks farther to the west. Slip of 46±9 km in eastern southern Tibet has been dated at ≥27-24 Ma [*Yin et al.*, 1994]. The Backthrust system [e.g., *Girardeau et al.*, 1984; *Ratschbacher et al.*, 1992, 1994; *Yin et al.*, 1994; *Quidelleur et al.*, 1997] straddles the entire Yarlung Zangbo suture zone in central southern Tibet. It is concentrated along the northern margin of the Xigaze forearc basin and particularly south of the Xigaze ophiolite where it comprises thick tectonic breccia. Triassic and Jurassic turbidites of the Indian passive margin and/or wildflysch overthrust some or all northern units of the suture zone. In eastern southern Tibet, backthrusting deformation is concentrated along the Renbu-Zedong thrust, which places upper greenschist facies, Tethyan sedimentary rocks locally in contact with Gangdese arc rocks and which involves ≥30 km of displacement assuming a ~30° dipping fault zone. Synkinematic minerals and K-feldspar thermochronology date thrusting at circa 18-9 Ma [*Quidelleur et al.*, 1997; *Ratschbacher et al.*, 1994].

11. A tectonic Evolutionary Model for Southern Tibet

We interpret (schematic cross section of Plate 2b) the YZR to represent a distinct pre-collisional lithotectonic unit positioned by thrusting into the midcrust beneath the Yarlung Zangbo suture. Our model suggests that in southern Tibet an ophiolite nappe - wildflysch complex was emplaced onto the northern Indian passive margin at about the Cretaceous-Tertiary boundary, i.e., prior to the India-Asia continental collision, just as occurred on India's (north)western margin. In contrast to India's (north)western margin, the major part of the ophiolite nappe - wildflysch complex in southern Tibet is buried as a subhorizontal unit beneath the present exposure of the Yarlung Zangbo suture and constitutes the YZR. Synemplacement deformation has been little studied in southern Tibet (D1 phase of *Ratschbacher et al.* [1994, Figure 3b]; also see more complete data of *Searle et al.* [1997] for Zanskar) but may be expressed by the Sheru-Gyanze fold-thrust system. Characteristically, this thrust system strongly affects the Indian passive-margin rocks but only slightly deforms the wildflysch unit and dies out to the south away from the suture. The emplacement of the ophiolite nappe - wildflysch complex resulted in a thickened crustal wedge. During the early Eocene this pre-collisional stack (Figure 4) partly underthrust the Tethyan accretionary complex and the Asian continental margin, i.e., the Gangdese arc, the forearc basin (up to 70 km wide, *Ratschbacher et al.* [1992]), and the Xigaze ophiolite complex. Upon entering the subduction zone, the thick wedge containing a rheologically strong core of oceanic lithosphere most probably terminated suturing at an early stage of continental collision and thus prevented large-scale deformation at the suture (e.g., as testified by the weak early Tertiary deformation of the forearc basin, *Ratschbacher et al.* [1992]). Parts of the ophiolite nappe - wildflysch complex, i.e., those parts constituting the YZR, became more deeply buried by the Gangdese thrust system from the north and the Backthrust system from the south. Though important, the initial underthrusting is not solely responsible for the burial of the YZR to midcrustal depth. The large-scale displacement along the Gangdese thrust [*Yin et al.*, 1994] and the upper greenschist grade rocks at the base of the Backthrust system hanging wall [*Ratschbacher et al.*, 1992; *Quidelleur et al.*, 1997] imply a significant role for these secondary thrusts in the burial history.

Throughout the Himalayan orogeny the buried YZR oceanic lithosphere would have constituted a rigid sheet. Though the ophiolite sheet comprising the YZR may be broken internally on a scale not resolvable by the wide-angle data (1-5 km), rigidity would stem from a substantial thickness of ultramafic-mafic rocks (up to a few kilometers), as observed, for example, in Oman (~ 10 km ultramafic rocks) or the western ophiolite belt of Pakistan (3-5 km for the whole ophiolitic sequence). A currently exposed (but offset by the backthrusts) equivalent of the YZR ophiolitic nappe - wildflysch complex is the wildflysch cropping out along the present-day northern Indian margin in southern Tibet. The ophiolite sheet, not exposed in southern Tibet, has either been eroded or, more likely, was never thrust so far to the south.

Is there any direct geological evidence for the presence of an ophiolitic sheet buried underneath the suture zone in southern Tibet? One of us [*Ratschbacher et al.*, 1994, Figure 10] has mapped slices of strongly serpentinized ultramafic and mafic rocks, exhumed along backthrusts surfacing within Indian passive-margin rocks. Note that the backthrusts bring up these rocks south of both the Xigaze ophiolite complex and the Tethyan accretionary wedge. We speculate that these slices may come from the buried southern tip of the ophiolite nappe constituting the YZR (Plate 2b).

The MHT, the top of the Indian continental crust currently underthrusting the Tethyan Himalaya [*Hauck et al.*, 1998; *Zhao et al.*, 1993], was reliably imaged on INDEPTH CMP profiles to a point ~10 km south and ~50 km west of where the southern end of the YZR was imaged (Plate 2a) [*Brown et al.*, 1996]. Evidence for the continuation of the MHT to the north beneath the Yarlung Zangbo suture is ambiguous. *Nelson et al.* [1996] and *Hauck et al.* [1998] suggest on the basis of geometric relationships that the MHT ramps ~20 km downward to the northeast from the point that it is last imaged. They also suggest that the doming within central southern Tibet (e.g., the Kangmar dome) is a recent consequence of a large duplex ramp anticline in the hanging wall of the MHT [*Hauck et al.*, 1998]. However, the fact that the YZR is sub-horizontal, i.e., was presumably not displaced or significantly folded, only a short distance to the north (or northeast) of the suggested ramp seems inconsistent with the ~20-km suggested vertical amplitude for the ramp. Furthermore, subtle wide-angle reflected phases (Plate 1) suggest (as discussed in section 6) that the MHT continues north with a constant dip. We therefore suggest (Plate 2b) that Indian continental crust underthrusts the Yarlung Zangbo suture with an approximately constant dip. If the MHT were to continue north with a constant dip, it would reach the Moho >100 km north of the Yarlung Zangbo suture; alternatively, the MHT may step down more steeply at some point north of our northernmost reflections. Similarly, the continuity of the YZR as a precollisional to syncollisional lithological unit seems to exclude significant postcollisional strike-slip or steep-dip displacements along the Yarlung Zangbo suture [e.g., *Tapponnier et al.*, 1986; *Allègre et al.*, 1984]. Dipping reflectors at a depth of 45-75 km beneath the Gangdese belt [*Hirn et al.*, 1984; *Brown et al.*, 1996; *Alsdorf et al.*, 1998b] would, in our model, be related to deformation in the underthrusting Indian lithosphere or ramping of the MHT [cf. *Alsdorf et al.*, 1996]. In contrast to the *Hauck et al.* [1998] model, we suggest that the dome structure in central southern Tibet (Kangmar dome) results from Miocene basement imbricates along the Backthrust system at the southern tip of the YZR and underneath the Kangmar dome (Plate 2b). We propose that owing to stress concentrations imposed by the southern end of the YZR ophiolitic sheet, the crust south of the YZR ophiolite sheet and above the MHT broke in the Miocene and hinterland-directed imbricates formed. Note that in our interpretation we (1) emphasize the structures which actually dominate this part of the Tibetan orogenic belt (the backthrusts) and (2) do not require an ad hoc interpretation (e.g., the partial melt zone or steep dip of the north dipping part of the *Hauck et al.* [1998] ramp anticline) to explain why north dipping reflectors are not imaged.

Finally, we note that the YZR may be identifiable with the boundary between resistive upper and conductive lower crust at 15-to-20-km depth, observed for 50 km north and south of the Yarlung Zangbo suture [*Chen et al.*, 1996]. This identification, if correct, provides supporting evidence for the existence and importance of the lithologic unit marked by the YZR. Possibly, the YZR inhibits the upward flow of fluids that originate as water-rich dehydration products in or above the underthrusting Indian plate [*Makovsky and Klemperer*, 1999] and that possibly generate melt in the southern Tibet lower-to-middle crust [*Nelson et al.*, 1996]. These fluids could be consumed by serpentinization of ultramafic parts of the YZR, producing the observed 7 km s^{-1} seismic velocity. Similar velocities are observed for partially serpentinized ultramafic sections of the Xigaze ophiolite [*Horen et al.*, 1996]. North of the YZR these fluids are free to make their way to ~15-km depth, where they concentrate and appear as "bright-spot" reflections on INDEPTH seismic data (Plate 2a).

In our interpretation the YZR marks the top boundary of Indian continental margin rock units underthrust beneath the surface exposure of the suture zone (Plate 2b), and therefore the YZR maps the midcrustal extent of the suture itself. Our interpretation is therefore in agreement with models depicting the Yarlung Zangbo suture in southern Tibet as a subhorizontal feature [e.g., *Argand*, 1977; *Allègre et al.*, 1984; *Yin et al.*, 1994] and in contrast to depictions of the suture as a steep to subvertical feature [e.g., *Gansser*, 1964; *Mattauer*, 1986] or to suggestions that the suture is unrecognizable in the middle crust owing to partial melting [e.g., *Nelson et al.*, 1996]. Our paper thereby contributes to the long-standing debate regarding the mechanism of crustal thickening in southern Tibet [e.g., *Nelson et al.*, 1996, and references therein] by showing that the crust at the latitude of the Lhasa block, the southernmost and thickest block of the Tibetan plateau, has been thickened by the underthrusting of Indian continental crust, including the ophiolite nappe-accretionary wedge complex.

12. Conclusions

We used INDEPTH wide-angle seismic data to produce a seismic reflection section across the Yarlung Zangbo suture in a region too rugged for conventional near-vertical reflection profiling. The outcrop of the Yarlung Zangbo suture is underlain in the middle crust at 17-to-24-km depth by a continuous reflector, which has a gentle (~4°) regional northward dip, large lateral (>80 km) extent, and seismic velocities of ~7 km s^{-1} We suggest that this reflector represents the top of a mafic-to-ultramafic lithologic unit, an ophiolitic complex that marks the Yarlung Zangbo suture at midcrustal level. The presence of a rigid ophiolite sheet and the constraints it might impose on the deformation field provide natural explanations of why opposite-verging mid-Tertiary thrust structures and doming form the characteristic structures in central southern Tibet. Our interpretation implies that the YZR reflector marks the Yarlung Zangbo suture, subhorizontal in the middle crust, thereby providing a new geometric constraint on Himalayan orogeny in place of the highly variable geologic cross sections presented over the last 75 years.

Key arguments for the interpretation of the YZR as an ophiolitic nappe complex are the following: (1) The high YZR reflection amplitudes at large offsets (>100 km) imply a positive impedance contrast, i.e., a high-velocity reflector; (2) YZR refractions have an apparent velocity of ~7 km s^{-1}, suggesting a mafic-ultramafic composition; (3) the YZR appears as a similar feature on all wide-angle data (in-line and broadside array), implying that the YZR is a continuous reflector of large areal extent; (4) the suggested precollisional emplacement of an ophiolite nappe - accretionary wedge complex in southern Tibet is in accord with observations of intra-oceanic emplacement and continental margin subduction along the entire (north)western Indian passive margin and is the classical way to generate and preserve a large and intact ophiolite sheet; (5) the suggested emplacement of an ophiolite nappe explains the precollisional wildflysch and precollisional, southward vanishing high-strain deformation recorded along the northern Indian passive margin both in southern and western Tibet; (6) the subduction of a thickened continental margin supplies a plausible interpretation for early termination of suturing and the observed minor synsuturing deformation evidenced both by the preservation of a forearc basin and its minor deformation during the early Tertiary; (7) the Backthrust system exposes deep levels of the Indian passive-margin sedimentary sequence in its hanging wall, locally thrusting shelf sediments directly onto the Gangdese belt rocks. Thus the Backthrust system, together with early Tertiary underthrusting and the Gangdese thrust system, is capable of burying the ophiolite sheet to midcrustal depth; and (8) backthrusts expose slivers of ophiolitic rocks south of both the Xigaze ophiolite and the Tethyan accretionary wedge, requiring the presence of ophiolitic material south of both units at depth.

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