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Structural elements of the southern Tethyan Himalaya crust from wide-angle seismic data

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Abstract. A deep seismic common midpoint (CMP) profile, shot across the southern margin of the Tethyan Himalaya as the first stage of Project International Deep Profiling of Tibet and the Himalaya (INDEPTH), imaged the top (Main Himalayan Thrust or MHT) and bottom (Moho) of the Indian continental crust underthrusting the Himalaya. We used portable seismographs to record the CMP-profile shots at a wide range of offsets, up to 155 km. Our short-offset data corroborate the CMP-profile data, while our large-offset data are dominated by a band of reflectivity. We interpret the bright onset of this reflective band as the basal detachment of the South Tibetan Detachment system and a phase at the end of the reflective band as the MHT. We used the CMP-profile first-break data to model the uppermost 2 km in detail. The depth of young extensional basins of the Yadong rift system along the CMP profile was constrained to a maximum of 2 km, yielding a throw of 4.6 km across the eastern flank of the rift and a rough estimate of approximately 1.5% east-west extension by normal faulting in the Tethyan Himalaya. -The wide-angle data were used to construct a crustal seismic-velocity model down to the MHT. The South Tibetan Detachment System (STDS) basal detachment reflector is observed dipping 12.5°NNE from a depth of about 6 km beneath the surface under the south end of the CMP profile to a depth of 22 km, then flattening to a dip of only 2.5°NNE. Thus our observations suggest that the STDS basal detachment is a deep-rooted basement fault. For the MHT we observe a dip of 7.5°NNE from 20 km depth below sea level at the crest of the High Himalaya crystalline sheet to 36 km below sea level (40 km beneath the surface) at a distance of about 70 km south of the Indus-Yarlung Suture (IYS). From geometrical arguments we suggest that Indian crust underthrusts the surface expression of the IYS within the crust but does not form the lower crust of central and northern Tibet.

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Introduction

The International Deep Profiling of Tibet and the Himalaya (INDEPTH) seismic profile [*Zhao et al.*, 1993] extends across the southern part of the Tethyan Himalaya (Figure 1), or Tibetan zone of the Himalayas, which is composed of Tethyan sedimentary and crystalline basement rocks imbricated by a series of south verging thrusts [e.g., *Burg and Chen*, 1984; *Ratschbacher et al.*, 1994]. Thrusting resulted from diachronous continent-continent collision between India and Asia along the Indus-Yarlung Suture zone starting at 60 ±5 Ma [*Beck et al.*, 1995]. Much of the convergence between India and Asia in the Miocene occurred across the Main Central Thrust (MCT) and subsequently shifted to the south to the Main Boundary (MBT) and Main Frontal (MFT) Thrusts (Figure 1) [*Gansser*, 1964]. The MCT and MBT are thought to be thick-skinned contractional structures rooting in a low-angle décollement fault along which India underthrusts the Himalayas [*Argand*, 1924; *Powell and Conaghan*, 1973; *Schelling and Arita*, 1991]. The existence of such a décollement is supported by earthquake hypocentral locations and focal mechanisms [*Seeber et al.*, 1981; *Ni and Barazangi*, 1984]. An alternate view is that the MBT and MCT are two separate crustal-scale thrusts and that the MCT was folded and uplifted when deformation was taken up by the MBT [e.g., *Le Fort*, 1975; *Butler*, 1986].

A north dipping low-angle normal fault system (the North Himalayan Normal Fault, also called South Tibetan Detachment System (STDS)) of Miocene age marks the surface boundary of the Tethyan Himalaya sedimentary pile with the High Himalaya crystalline basement rocks to the south [*Burg and Chen*, 1984; *Burg et al.*, 1984; *Burchfiel and Royden*, 1985; *Pêcher*, 1991; *Burchfiel et al.*, 1992] (Figure 1). The outcrop locations of the STDS within the Yadong valley, along or south of the INDEPTH profile, are not yet known.

A series of north-south trending graben systems cross the Tethyan Himalaya and extend into the Lhasa block north of the Indus-Yarlung Suture (IYS). These basins have been extending since at least 2 Ma and probably since before 6 Ma

c.

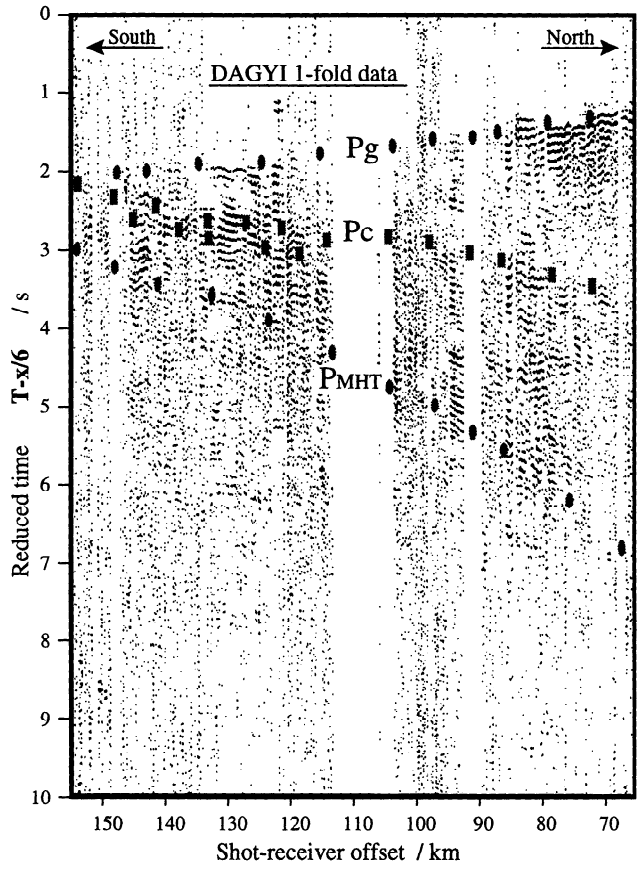


Figure 2. (continued)

imaged at 3 to 6 s on the southern part of the CMP profile data [*Hauck et al.*, 1994] (Figure 2a).

Dagyi station, the northernmost of the wide-angle stations (Figure 1), recorded the CMP profile shots at offsets of 65-155 km. Three phases can be recognized in the receiver gather of this station after correction for shot statics and plotting with a reduction velocity of 6 km s^{-1} (Figure 2c). The direct arrival, P_g, fades away at offsets larger than about 100 km beyond which a bright band of arrivals (P_c) becomes more prominent. P_c seems to show a triplication in the travel time around 120-130 km offset that may be the cause of the particularly strong amplitudes observed there. We correlate the onset of this bright band of reflectivity with the P_c phase observed at near offsets (P_c in Figures 2a and 2b), and a phase at the bottom of this band of upper crustal reflectivity as the MHT reflection (P_{MHT} in Figures 2a and 2b). Far-offset reflections from the Moho cannot be recognized on our data.

Modeling

We calculated "shot statics" from the CMP profile data to model the effects of shallow structure. We picked first breaks from the 470 CMP-profile shot gathers (with source-receiver offsets to 6 km and the "big" shots with offsets to 12 km) and used them to construct a refraction-statics velocity model to a depth of 1.5 km (Plate 1a) using a "time-delay" algorithm [*Lawton*, 1989] (implemented by ProMAX™, from Advance Geophysical Corporation). From this velocity model we calculated shot statics to correct for delays caused by shallow structure and shot elevations, with respect to a constant velocity of 6 km s^{-1} and datum elevation of 4200 m.

Our main objective was to put constraints on the depth and dip of the P_c and P_{MHT} reflectors by producing a crustal seismic velocity model using the wide-angle data. To pick the phases to be modeled, we used receiver gathers corrected for shot statics, which considerably smoothed the first breaks and gave good phase continuity in the wide-angle receiver gathers at medium to far offsets (Figure 2c). Application of the same static shifts was less efficacious at near offsets (<20 km) because the wide-angle recorders were located up to 1 km off line from the CMP profile, on bedrock sites. Rays traveling to near offsets sampled the structure between the station and the CMP profile and not the structure directly beneath the shots that is accounted for in the shallow velocity model. For velocity modeling we used the original uncorrected receiver gathers. Using ray tracing [*Luetgert*, 1988] we iteratively modeled the travel times of reflections/refractions observed on the wide-angle data until good agreement was obtained. Receiver gathers were bulk shifted by up to 500 ms to remove a DC shift between the data and the model predictions, thereby accounting for receiver statics (elevation and shallow velocities) that were not accounted for by the shallow velocity model because the wide-angle stations were not located on the CMP line.

A good fit to the shape of the P_g phase in the wide-angle data (Figures 2b and 2c) was obtained by incorporating a simplified version of the shallow velocity model (Plate 1a) as the topmost part of our crustal model (Plate 1b). We model the P_c phase with a north dipping reflector between the surface and the MHT (Plate 1b) with a change of dip required to match the detailed travel times and focusing effects (travel time triplication and high amplitudes) at offsets of 120 to 145 km (Figure 2c). The MHT phase could be simply modeled by a reflector with constant dip. The consistency of our model with the vertical-incidence CMP data [*Zhao et al.*, 1993; *Hauck et al.*, 1994] (Figure 2a) was examined at every stage of our modeling. By perturbing the depths of the different nodes in our model until the misfit between the modeled travel time and the data was clear to the eye, we estimate possible errors of 3 km in the depth and 2° in the dip of the P_{MHT} and P_c reflectors. Our model is less constrained south of Dogen and north of Samada (Figure 1 and Plate 1) because of the survey geometry.

Though, like any forward modeling result, our model is inherently nonunique, we have sought the simplest model required by the data. Our model assumes two dimensionality of the deep structure as three-dimensional effects could not be resolved by our data. However, we believe that no gross errors result from this approximation because no three-dimensional effects were found from 5 to 25 s on the short CMP cross line across Dogen valley.

Shallow Velocity and Structure

Our shallow velocity model (Plate 1a) can be characterized by three major layers. The shallowest and best-constrained

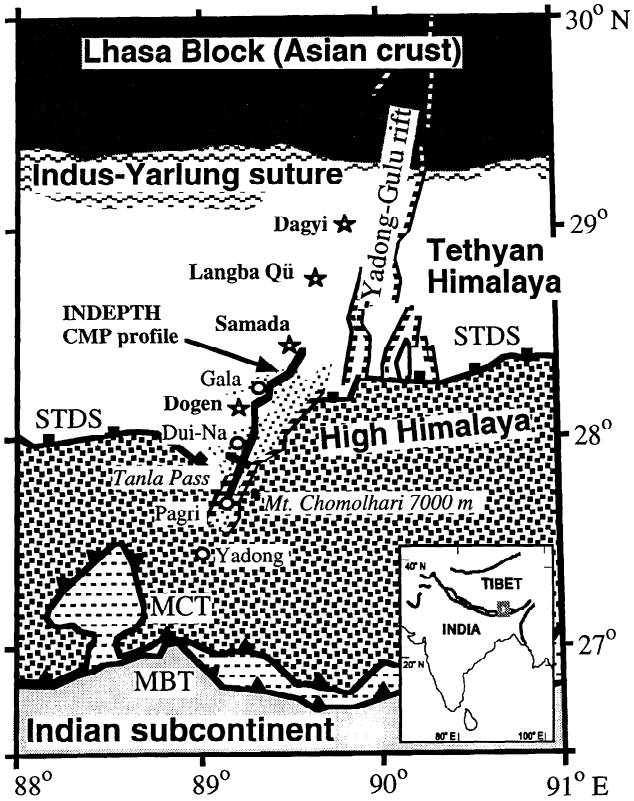


Figure 1. Generalized geologic map showing the location of the International Deep Profiling of Tibet and the Himalaya (INDEPTH) common midpoint CMP profile (solid black line) and the four wide-angle Reftek stations (open stars: Dogen, Samada, Langba Qü, Dagyi). MBT is the Main Boundary Thrust; MCT is the Main Central Thrust; STDS is the South Tibet Detachment System.

[*Harrison et al.*, 1992, and references therein]. The INDEPTH profile runs through the Pagri, Dogen, and Gala valleys, the southern basins of the Yadong-Gulu rift, which is the largest north-south trending graben system in southern Tibet (Figure 1). *Armijo et al.* [1986] mapped Dogen valley as a half graben above a west dipping master fault with a throw of ≥2.6 km based on the topographic relief.

The system of thrusts (MCT, MBT), the STDS, and the young extensional basins are the main structural features of the southern Tethyan Himalaya crust. In this paper we present our results from modeling wide-angle data of the 1992 INDEPTH experiment that constrain these structural elements.

The INDEPTH-1 Near-Vertical CMP Profile

The INDEPTH common midpoint (CMP) reflection profile was shot in summer of 1992 as a combined effort of Cornell University and the Chinese Ministry of Geology and Mineral Resources (MGMR) [*Zhao et al.*, 1993]. The CMP profile runs about 100 km from Pagri to Samada (Figure 1). Four hundred fifty-six shots, nominally of 50 kg dynamite, were fired at 200 m spacing. An additional 14 "big" shots (mostly 200 kg dynamite) were fired at a nominal 6 km spacing along the profile. The shots were placed in drill holes of depth 5 to 50 m, sometimes as an array of up to 12 holes per shot. The shots were recorded by an array of 120 channels with 50 m spacing (total length 6 km). A short cross-line (14 shots) was acquired across the Dogen valley near Dui-Na (Figure 1) close to the southern end of the INDEPTH profile.

The CMP profile, a 15-fold, 60-s stack section (Figure 2a), and its interpretation, are described by *Zhao et al.* [1993]. A strong band of reflections dipping from 8-s two-way time (twt) in the south to 12 s at the north end of the line is interpreted as the main décollement at the top of the underthrust Indian crust and named the Main Himalayan Thrust (MHT). This interpretation is supported by the southward extrapolation of this reflector toward the surface, which is collinear with the décollement inferred by *Ni and Barazangi* [1984] from earthquake data and also with the basal décollement in the balanced cross sections of *Schelling and Arita* [1991]. An additional band of reflections, imaged between 23 and 25 s twt, is interpreted as the Moho of the Indian crust [*Zhao et al.*, 1993].

The INDEPTH-1 Wide-Angle Data

A wide-angle experiment was carried out as an opportunistic piggyback by a combined Stanford University-MGMR team in order to measure the seismic velocity structure of the Tethyan Himalaya. We deployed Reftek portable digital seismographs with 4.5 Hz three-component geophones for the duration of the CMP experiment at four sites (Dagyi, Langba Qü, Samada, Dogen; Figure 1). Data from additional Refteks deployed in temporary in-line and off-line locations will be discussed elsewhere. The four fixed stations were timed with Omega radio clocks and recorded continuously during working hours of the CMP shooting crew. Shot times were obtained by recording the shot trigger with an additional Reftek. After correction for the clock drifts on the different Refteks, receiver gathers of 60 s traces were constructed for each station.

Wide-angle reflections were recorded to the maximum source-receiver offset of 155 km (Figures 2b and 2c). Though data quality is poor by any absolute standard, data quality is remarkable given the small shot size (50 kg) relative to conventional refraction shot size (1000 to 3000 kg). We attribute the achievement of recording small shots at large offsets to the low ambient noise in Tibet, to care in choice of recording sites on or near bedrock, and to burial of geophones approximately 0.5 m deep. Lateral correlation of seismic phases in our data is difficult due to several data gaps in the CMP profile, problems recording shot times at some locations, and large static shifts resulting from the complex shallow structure. However, shot statics corrections, made taking into account the shallow structure (see discussion below), give good phase continuity.

We show (Figures 2b and 2c) examples of data from the northern and southern of our fixed wide-angle stations (Figure 1). Data from the other two stations are transitional between the two receiver gathers shown.

Dogen station, located near the middle of the CMP profile (Figure 1), recorded shots from south and north at offsets of up to 40 km. The receiver gather of this station is dominated by arrivals of direct waves traveling through the upper crust (P_g) and of surface waves. However, after filtering, amplitude gain control (AGC), and normal move out (NMO) correction

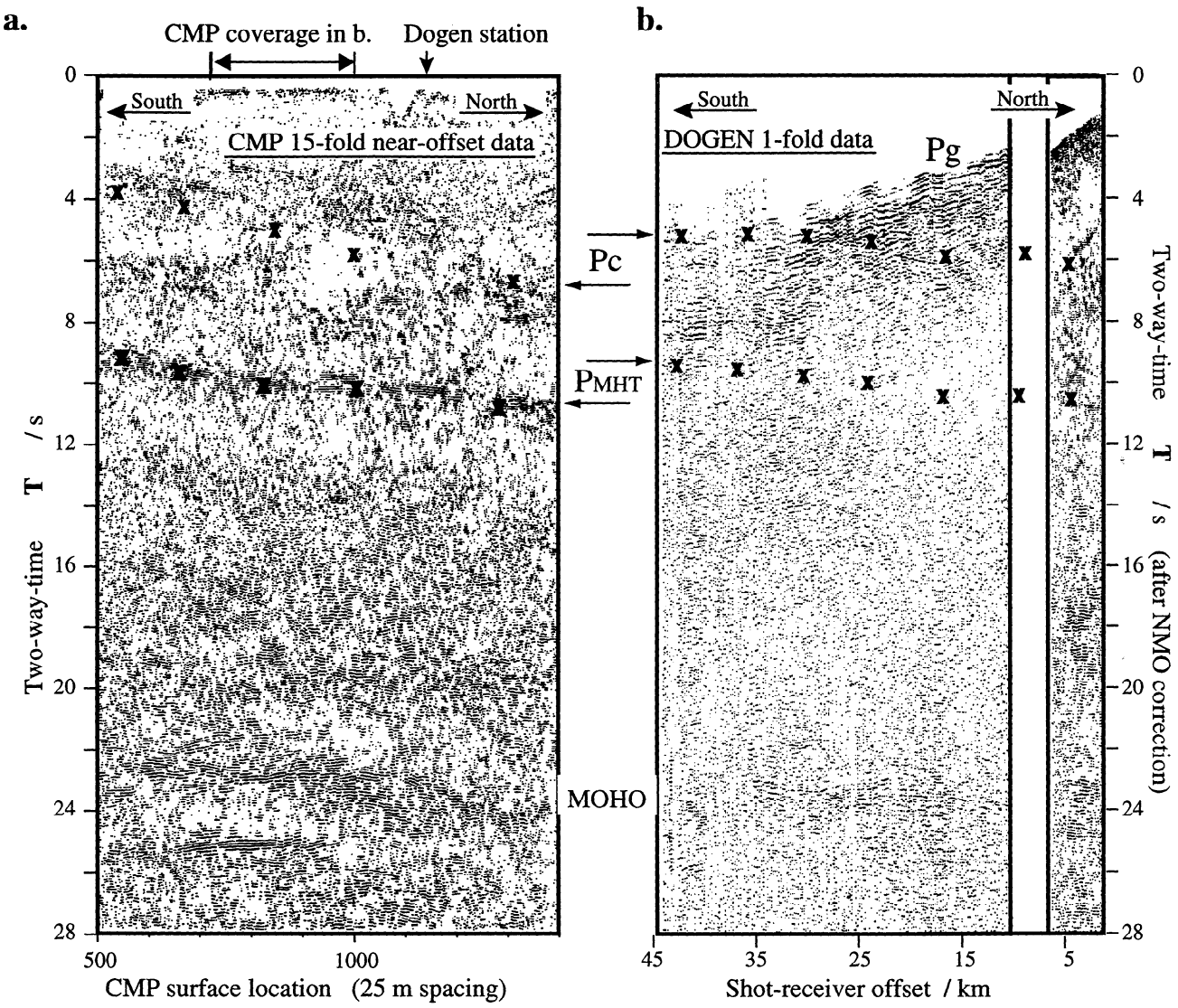


Figure 2. (a) Part of the INDEPTH CMP profile 15-fold stacked section [*Zhao et al.*, 1993; *Hauck et al.*, 1994]. The results of near-vertical ray tracing through the model in Plate 1b (P_C and P_{MHT}) are shown with crosses. (b) Dogen station receiver gather (southern half) supplemented at near offsets by a CMP shot gather shot near this station. Figure 2b is plotted with amplitude gain control (AGC) and normal moveout (NMO) corrected with velocity of 6 km s^{-1}. The results of ray tracing through the model in Plate 1b (P_C and P_{MHT}) are shown with crosses. (c) Dagyi station receiver gather plotted with reduced velocity of 6 km s^{-1}, band-pass filtered 5-15 Hz, and corrected for shot statics calculated from the model in Plate 1a. The results of ray tracing through the model in Plate 1b (corrected for shot and receiver statics) are shown with solid circles (P_g and P_{MHT}) and solid squares (P_C).

with velocity of 6 km s^{-1}, two bands of reflectivity can be seen from 5 to 9 s and from 23 to 25 s (Figure 2b). By correlation with the CMP profile data [*Zhao et al.*, 1993] (Figures 2a and 2b), we identify their MHT as the phase at the base of our upper reflective band and their Moho as our deeper reflective band. The MHT, imaged on the CMP profile data as a strong band of reflectivity beneath scattered upper crustal reflections (Figure 2a), appears as a weak phase at the base of upper crustal reflectivity on our data. This difference may be due to the difference in recording offsets between the near-vertical (CMP) and the wide-angle data sets. As recording offsets increase, the angle of incidence of the seismic waves on a reflector approaches a critical angle and the relative amplitude of the reflected waves strongly increases. Our wide-angle data were recorded at an offset range at which the incidence angle approaches the critical angle for the upper crustal to midcrustal reflectors but is still a relatively low angle for the MHT. As a result the relative amplitude of the midcrustal reflectivity is exaggerated with respect to the amplitude of the MHT reflections. An additional phase crossing the P_g reverberations (named P_C, denoting a crustal phase, in Figure 2b), can be correlated with reflectivity

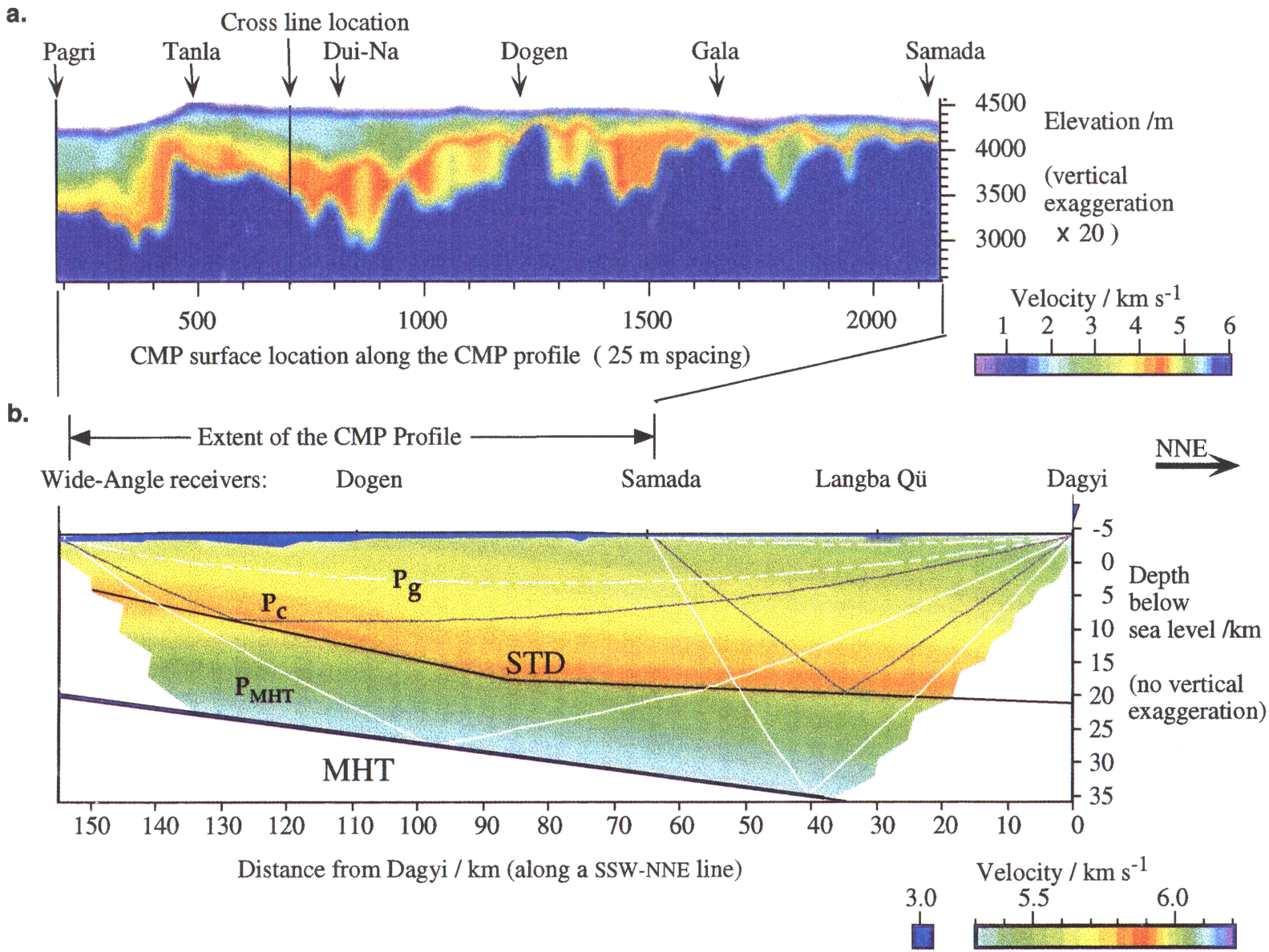


Plate 1. (a) Shallow velocity model obtained from the CMP first-break data (smoothed version). Horizontal axis is CMP number (25 m spacing) from the CMP profile. Vertical exaggeration is times 20. (b) Velocity model down to the Main Himalayan Thrust (MHT), obtained by ray-tracing, with no vertical exaggeration. Horizontal axis is the distance from Dagyi station in the direction SSW-NNE. The extent of ray coverage at Dagyi station is marked for the three phases P_g, P_c and P_{MHT} shown in Figure 2.

layer has seismic velocities of 1 to 3 km s^{-1}. This layer extends from the surface down to about 700 m depth where the CMP profile passes through the Gala, Dogen, and Pagri valleys but only to 100 to 200 m where the profile passes through canyons between outcrops of Mesozoic rocks and at the Tanla pass (crest of the High Himalaya). The deepest and least-constrained layer of the model has velocities >5 km s^{-1}. In between is a layer with velocities in the range of 3.5 to 4.5 km s^{-1}. This layer reaches a maximum thickness of 800 m, and maximum depth of 1500 m, under the open valleys (Dogen, Gala), and pinches out in several places, typically where the CMP profile runs through narrow passes and canyons (Tanla, between Dogen and Gala, Samada).

We interpret the upper layer (velocities 1 to 3 km s^{-1}) as Quaternary basin fill and the lower layer (velocities >5 km s^{-1}) as "basement" composed here of Mesozoic and older Tethyan sediments. The nature of the middle layer is not clear, but it has seismic velocities higher than we would expect for unconsolidated Quaternary alluvial fans. The higher seismic velocities, and the very rough correspondence between the thicknesses of the upper and middle layers (both are thickest in the broadest valley between Dui-Na and Dogen) are both compatible with pre-Quaternary (Neogene) basin formation in the area. Pre-Quaternary extension was previously recognized from observations of Pliocene synsedimentary normal faulting in the Takkhola and Gyirong basins 400 km west of the Yadong valley in the Tethyan Himalaya [*Mercier et al.*, 1987], and from cooling ages of 4 to 8 Ma for rocks exposed adjacent to a detachment fault near Yangbajian in the northern part of the Yadong-Gulu rift [*Pan and Kidd*, 1992].

The total depth of the young basins (velocities <5 km s^{-1}) along the CMP profile is constrained by our refraction measurements to a maximum of about 1.5 km. A shallow velocity model constructed in the same way from the shot gathers of the CMP cross line indicates that the Dogen basin floor dips to the east at about 6° to a maximum depth of about 2 km. Adding our observed basin depth to the throw estimated from topographic relief of 2.6 km between the valley floor and Chomolhari (7000 m) in this area [*Armijo et al.*, 1986] gives an estimated throw of 4.5 km across the 65°-70° west dipping fault at the eastern boundary of this part of the Yadong valley, presumably incorporating both Quaternary and earlier movement.

Velocity and Structure Down to the MHT

Our crustal model (Plate 1b) has an average velocity of 5.9 to 6.0 km s^{-1} down to the MHT in agreement with the "upper crustal" velocity of 6 km s^{-1} previously estimated from fan profiling in the same area [*Hirn et al.*, 1984]. Our model is characterized by two layers: the upper, with velocity of 5.5 to 5.8 km s^{-1}, extends from the surface to the P_C reflector and probably represents the imbricated Tethyan sedimentary pile and its associated crystalline basement [cf. *Ratschbacher et al.*, 1994]; the lower, with velocities of 6.0 to 6.2 km s^{-1}, extends down to the MHT and probably represents the northern continuation of the High Himalaya crystalline basement.

The P_C reflector is modeled as an ~ 0.2 km s^{-1} velocity increase across a north dipping interface between the surface and the MHT (Plate 1b), projecting to the surface about 20 km south of the CMP profile, dipping about 12.5°NNE, and flattening to a dip of 2.5°NNE about 20 km south of the north end of the CMP profile.

The MHT dips from about 20 km below sea level at the south end of the CMP profile to about 36 km at our northernmost reflection point, just 30 km north of the north end of the CMP profile. We observe a dip of about 7.5° along the general NNE trend of our model, in agreement with that estimated by *Zhao et al.* [1993].

In our model, P_{MHT} is an interface with constant dip, whereas in the CMP profile [*Zhao et al.*, 1993] (Figure 2a) the MHT reflector undulates. Near-vertical rays traced through our velocity model reproduce the undulatory shape of the MHT reflection (Figure 2a) due to low-velocity basins in the upper crust, so that we can explain the undulatory shape on the CMP time section as an artifact of velocity pull down. Nonetheless, some deformation at depth and disruption of the MHT may be suggested by diffractions with their apices overlying the MHT reflections on the CMP stacked section [see *Zhao et al.*, 1993, Figure 2b].

Tectonic Significance

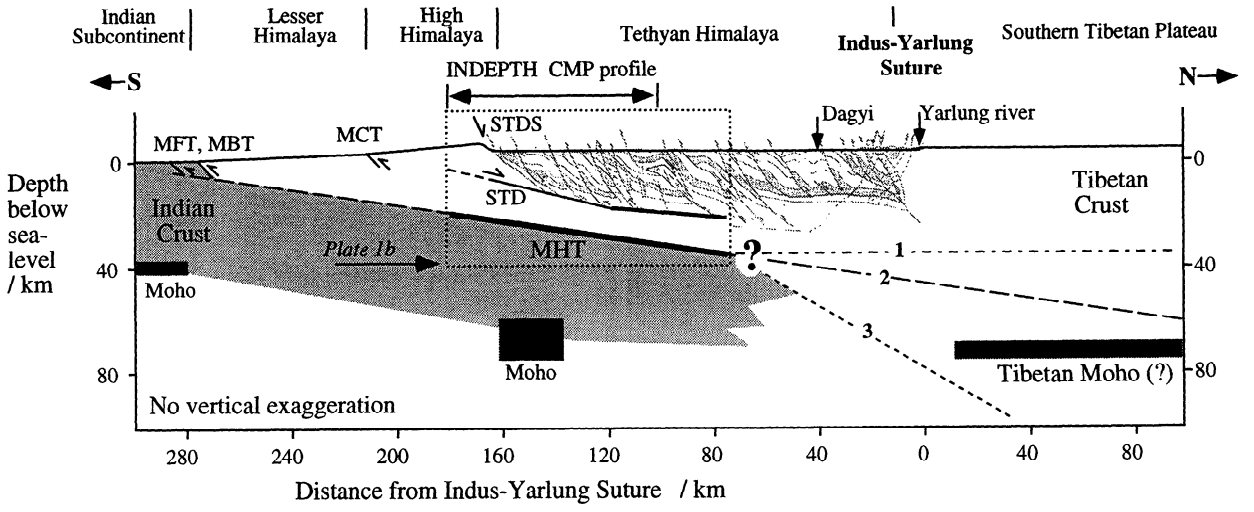
Estimate of the Extension Across the Tethyan Himalaya

We crudely estimate 2 km extension across the Yadong valley using the throw we obtained (4.5 km) and assuming the extension took place on a single normal fault dipping approximately 65° W at the eastern side of the valley [*Armijo et al.*, 1986]. The Yadong-Gulu rift is one, probably the largest, of the seven major rift systems in southern Tibet [*Armijo et al.*, 1986]. Multiplying our estimate for the Yadong valley by the number of rifts provides a crude estimate of about 15 km or about 1.5% east-west extension by normal faulting across the 1000-km-wide Tethyan Himalaya, in agreement with the estimate of about 2% made by *Armijo et al.* [1986]. Our estimate is highly simplistic but nonetheless suggests very limited east-west extension within the Tethyan Himalaya.

The South Tibetan Detachment System (STDS) ?

The basal detachment of the STDS juxtaposes rocks of two different metamorphic environments, with crustal omission of 1015 km and displacements of tens of kilometers [*Burchfiel and Royden*, 1985; *Burchfiel et al.*, 1992]. An unresolved question is, how does this fault continue at depth? As discussed below we interpret P_C (Figure 2) as coming from the basal detachment of the STDS and suggest that this detachment is a deep-rooted basement fault that penetrates to about 20 km depth before flattening presumably into a ductile layer within the crystalline basement of the Tethyan Himalaya.

P_C appears to come from a midcrustal interface (Plate 1b) representing a velocity increase (5.8 to 6.0 km s^{-1}) that dips north to about 20 km depth before flattening. The depth of flattening of the P_C reflector is clearly greater than the maximum (about 15 km) thickness of the Tethyan sedimentary pile estimated in this area by *Burg and Chen* [1984], and by *Ratschbacher et al.* [1994] in their balanced cross section along the INDEPTH profile route (Figure 3). Therefore we conclude that the P_C reflector does not represent



Conceptual Models for the India-Asia Suture:

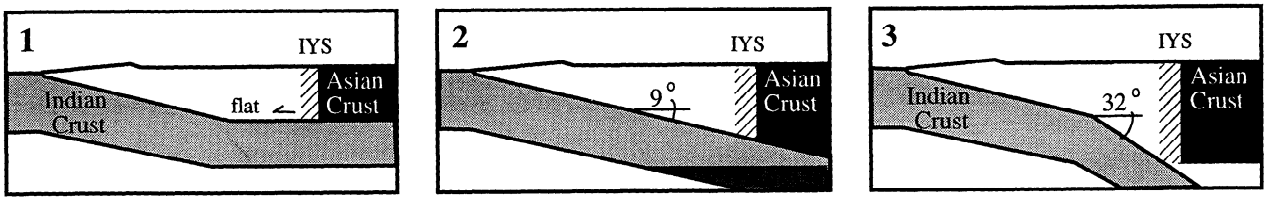


Figure 3. The model from Plate 1b projected onto a north-south line and combined into the general context of the Himalaya and southern Tibetan plateau. See discussion in the text; STD denotes the basal detachment of the STDS; MBT and MCT locations are projected east from *Schelling and Arita* [1991]; balanced cross section of the imbricated Tethyan sediments north of the STDS outcrop is projected east from *Ratschbacher et al.* [1994]; Indian Moho is from *Qureshy and Midha* [1986]; Tibetan Moho is from references cited in the text. IYS is the Indus-Yarlung Suture; MFT is the Main Frontal Thrust.

the base of the Tethyan sedimentary pile at depth. One possible interpretation is that the P_C reflector is the top of an old thrust sheet (possibly the MCT) that was refolded and uplifted when movement shifted to a younger, more southerly thrust (e.g., the MBT). However, our preferred interpretation is that the P_C interface is the basal detachment of the STDS as the velocity increase of 0.2 km s^{-1} across the P_C reflector can be more easily understood if the interface is a normal fault juxtaposing rocks of lower metamorphic grade above significantly higher-grade rocks. The dip of this reflector (12.5°NNE) in the south part of the CMP profile is in fair agreement with an average dip of 10°N observed on the STDS at the surface [*Burchfiel et al.*, 1992]. The projection of the P_C reflector to the surface is to the south of the outcrop of the STDS basal detachment where it was mapped to the west of Yadong valley (Figure 3). However, outcrop of Tethyan rocks in the Yadong valley up to about 25 km south of there [*Gansser*, 1964] suggests that within the Yadong valley, the location of the basal detachment of the STDS may be in agreement with the projection of P_C to the surface. Better control on our interpretation awaits detailed geological mapping of the STDS in the Yadong valley.

The Main Himalayan Thrust (MHT)

The geologic map of the Himalaya near longitude 90°E shows that most large-scale geologic features like the IYS, the MBT, and the MCT strike in a general east-west direction. We therefore follow the widespread assumption that the main décollement between the Indian and Tethyan crusts (the MHT) dips due north, so that our model (trending NNE) is not in the true dip direction and the 7.5° dip of the MHT in our model is an apparent dip. In Figure 3 we plot the results of our wide-angle modeling (Plate 1b) projected onto a north-south line with the appropriately steeper dip of about 9.5°N, our estimated true dip of the MHT. This is steeper than most basal décollements observed in the foreland of orogenic belts and fits better into the category of crustal-scale ramps that project down to the Moho in the orogenic hinterland [e.g., *Cook and Varsek*, 1994].

To obtain the position of the MBT and MCT in Figure 3 with respect to the IYS, we projected the *Schelling and Arita* [1991] surface observations east onto our line. Their balanced cross section, when projected in this manner (as done by *Zhao et al.* [1993]), overlaps the southern part of the INDEPTH profile by about 15 km. The basal décollement in their NNE trending balanced cross section dips 6° in good agreement with the dip of 7.5° observed by us in the same (NNE) direction. However, Schelling and Arita place the décollement 5 km deeper than is obtained by us. This difference may arise because, for the MHT at a depth range of 20-35 km, we are probably modeling the depth to a wide ductile shear zone, for which balanced cross sections can only give a crude depth

estimate. The MCT that is exposed as a several-kilometer-thick shear zone [*Bouchez and Pêcher*, 1981] was probably equivalent, when it was active, to the MHT of today. The >1-s-(twt)-thick MHT reflection observed on the CMP profile (Figure 2a) is compatible with such a shear zone.

The Northern Limit of Indian Crust

The role of Indian crust in doubling the thickness of the Tibetan crust is still a subject of debate. Our results tighten the geometrical constraint on the northern extent of the Indian crust (Figure 3). We observe the MHT continuing with a uniform dip of 7° to 10° to a depth of about 40 km beneath the surface at a distance of only 70 km south of the IYS where the Tibetan Plateau crust is 65 to 70 km thick [*Chun and Yoshii*, 1977; *Hirn and Sapin*, 1984; *Jobert et al.*, 1985; *Zhu et al.*, 1993]. Assuming that the Indian crust remains intact with a thickness of 30 to 40 km and that it penetrates north of the Tethyan Himalaya there are three alternative conceptual models for its northern extent:

1. The Indian crust flattens and underthrusts Asian crust to produce the double-thickness Tibetan crust (Figure 3, model 1) [*Argand*, 1924; *Powell and Conaghan*, 1973; *Ni and Barazangi*, 1984]. However, because the top of India is already at a depth of about 40 km, the Indian crust must flatten abruptly immediately to the north of where we last observe it, or its thickness must be considerably reduced, in order for it to be stacked into the 70-km-thick Tibetan crust.

2. The Indian crust continues to dip to the north at the observed 7° to 10°, or only gradually steepens, and so underthrusts the IYS within the lower crust for about 100 km to the north but does not constitute the lower half of the Tibetan crust through central and northern Tibet (Figure 3, model 2) [*Allègre et al.*, 1984; *Harrison et al.*, 1992]. Model 2 predicts that the IYS dips north at lower crustal depths. However, this model also predicts that the Moho at and north of the IYS is considerably deeper than 70 km, which is not in agreement with existing data. An alternative explanation is that the Moho beneath the IYS represents a phase transition from gabbro to eclogite rather than a lithological boundary.

3. The Indian crust is subducted into the mantle south of the IYS and does not constitute a part of the Tibetan crust (Figure 3, model 3) [*Dewey and Burke*, 1973; *Molnar*, 1988]. However, for this to happen, the Indian crust must bend downward by > 20° immediately north of our northernmost observation to dip > 30°N. Such a bend has a radius of curvature of 200 km which is as sharply curved as some of the most sharply curved Benioff zones in the world (New Hebrides, Marianas, 150 to 200 km [*Isacks and Barazangi*, 1977]) along which thinner and denser oceanic crust is subducting, whereas in the Pamirs, deep intracontinental earthquakes seem to define a continental subduction zone with an approximately 350 km radius of curvature [*Burtman and Molnar*, 1993].

The new geometric constraints given by our wide-angle results render models 1 and 3 unlikely. However, all three models depend on the assumption that India remains as a 30 to 40-km-thick intact plate. We therefore prefer model 2 and suggest that Indian crust continues north of the Tethyan Himalaya and underthrusts the IYS within the lower crust, in which case the Moho beneath the IYS represents a phase transition or the underthrust Indian crust does not remain an intact plate. Resolving the detailed structure of the IYS is the main goal of phase two of project INDEPTH that took place in the summer of 1994.

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References

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

Argand, E., La tectonique de l'Asie, in *13th Internationa Geological Congress, Brussels*, pp. 170-372, 1924.

Armijo, R., P. Tapponnier, J. L. Mercier, and T.-L. Han, Quaternary extension in southern Tibet: Field observations and tectonic implications, *J. Geophys. Res., 91*, 13,803-13,872, 1986.

Beck, R. A., et al., Stratigraphic evidence for an early collision between northwest India and Asia, *Nature, 373*, 55-58, 1995.

Bouchez, J., and A. Pêcher, The Himalayan Main Central Thrust pile and its quartz-rich tectonites in central Nepal, *Tectonophysics, 78*, 23-50, 1981.

Burchfiel, B. C., and L. H. Royden, North-south extension within the convergent Himalayan region, *Geology, 13*, 679-682, 1985.

Burchfiel, B. C., Z. Chen, K. V. Hodges, Y. Liu, L. H. Royden, C. Deng, and J. Xu, *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., M. Brunel, D. Gapais, G. M. Chen, and G. H. Liu, Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China), *J. Struct. Geol., 6*, 535-542, 1984.

Burtman, V. S., and P. Molnar, *Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir, Spec. Pap. Geol. Soc. Am.*, 281, 76 pp., 1993.

Butler, R. W. H., Thrust tectonics, deep structure and crustal subduction in the Alps and Himalayas, *J. Geol. Soc. London, 143*, 857-873, 1986.

Chun, K., and T. Yoshii, Crustal structure of the Tibetan Plateau; a surface-wave study by a moving-window analysis, *Bull. Seismol. Soc. Am., 67*, 735-750, 1977.

Cook, F. A., and J. L. Varsek, Orogen-scale décollements, *Rev. Geophys., 32*, 37-60, 1994.

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

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

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

Hauck, M.L., L.D. Brown, D. Alsdorf, A.S. Calvert, A.R. Ross, K.D. Nelson, J.T. Kuo, W. Zhao, J. Che, and J. Guo, Analysis and interpretation of INDEPTH 1 CMP profile with ties to INDEPTH 2 (abstract), *Eos Trans. AGU, 75* (44), Fall Meet. Suppl., 632, 1994.

Hirn, A., and M. Sapin, The Himalayan zone of crustal interaction: Suggestions from explosion seismology, *Ann. Geophys., 2*, 123-130, 1984.

Hirn, A., et al., Crustal structure and variability of the Himalayan border of Tibet, *Nature, 307*, 23-25, 1984.

Isacks, B. L., and M. Barazangi, Geometry of Benioff zones: Lateral segmentation and downwards bending of subducted lithosphere, in *Island Arcs, Deep Sea Trenches, and Back-Arc Basins*, Maurice Ewing Ser., Vol. 1, edited by M. Talwani and W. C. Pitman, pp. 99-114, AGU, Washington, D.C., 1977.

Jobert, N., B. Journet, G. Jobert, A. Hirn, and S. K. Zhong, Deep structure of southern Tibet inferred from the dispersion of Rayleigh waves through a long-period seismic network, *Nature, 313*, 386-388, 1985.

Lawton, D. C., Computation of refraction static corrections using first-break traveltime differences, *Geophysics, 54*, 1289-1296, 1989.

Le Fort, P., Himalayas: The collided range. Present knowledge of the continental arc, *Am. J. Sci., 275-A*, 1-44, 1975.

Luetgert, J. J., *Users Manual for MacRay84/R83PLT: Interactive two-dimensional raytracing/synthetic seismogram package, U.S. Geol. Surv. Open File Rep., 88-238*, 1988.

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 geophysical constraints on the deep structure of the Tibetan plateau, the Himalaya and the Karakoram, and their tectonic implications, *Philos. Trans. R. Soc. London*, A326, 33-88, 1988.

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.

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

Pêcher, A., The contact between the higher Himalaya crystallines and the Tibetan sedimentary series: Miocene large-scale dextral shearing, *Tectonics, 10*, 587-598, 1991.

Powell, C. M., and P. J. Conaghan, Plate tectonics and the Himalayas, *Earth Planet. Sci. Lett., 20*, 1-12, 1973.

Qureshy, M. N., and R. K. Midha, Deep crustal signatures in India and contiguous regions from satellite and ground geophysical data, in *Reflection Seismology: The Continental Crust*, edited by M. Barazangi; and L.D. Brown, *Geodyn. Ser.*, vol. 14, pp. 77-94, AGU, Washington, D.C., 1986.

Ratschbacher, L., W. Frisch, G. Liu, and C. Chen, Distributed deformation in southern and western Tibet during and after India-Asia collision, *J. Geophys. Res., 99*, 19,917-19,945, 1994.

Schelling, D., and K. Arita, Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal Himalaya, *Tectonics, 10*, 851-862, 1991.

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

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

Zhu, L.P., R.S. Zeng, F. T. Wu, T. J. Owens, and G. E. Randall, Preliminary study of the crust-upper mantle structure of the Tibetan Plateau by using broadband teleseismic body waveforms, *Acta Seismol. Sinica, 6*, 305-316, 1993.

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