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Key Points:

- We investigate the west-east lithospheric structure beneath the Tethyan Himalaya using P and S receiver functions
- The Main Himalayan Thrust, Moho and a low velocity zone characterized by the pronounced eastward inclined trends are clearly imaged
- The eastward dipping shape of the underthrusting Indian lithosphere is likely caused by the eastward steepening subduction angle

Supporting Information:

- Supporting Information S1

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Eastward Dipping Style of the Underthrusting Indian Lithosphere Beneath the Tethyan Himalaya Illuminated by P and S Receiver Functions

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Abstract To explore the west-east variations in the underthrusting Indian lithosphere, we investigate the lithospheric structure using P and S receiver functions obtained from a west-east linear array of 19 broadband stations spanning the Tethyan Himalaya at 85.5–88.5°E. Our observations of the Main Himalayan Thrust (MHT) and Moho serving as the top and bottom boundaries at depths of 42–54 km and 60–72 km, respectively, suggest that a thinning Indian lower crust with an eastward inclined geometry is underthrusting beneath the Tethyan Himalaya. An intra-crustal low velocity zone (LVZ) immediately above the MHT at depths of 32–42 km is imaged, likely resulting from the presence of crustal dehydration partial melting. We propose that this LVZ induces the southward extrusion of melt-weakened crustal material with itself as a channel and facilitates the development of duplexing structures, by which Indian lower crustal materials could be accreted into the Himalayan wedge along the north-south mid-crustal ramp in the MHT. The eastward dipping lithosphere-asthenosphere boundary is clearly observed ranging from 90 to 126 km, which generally coincides with the changing trends of the MHT and Moho. These observations can be attributed to the eastward steepening subduction angle of the Indian lithosphere.

1. Introduction

The Himalaya, extending for almost 2,500 km along strike, resulted from the India-Asia collision and convergence beginning at ~65 Ma (DeCelles et al., 2014; Ding et al., 2005). Global positioning system (GPS) measurements estimate a shortening rate of ~15 mm/year along the Himalaya (Zheng et al., 2017), leading to the development of an upper crustal fold-thrust belt. Three major north-dipping thrust faults, namely, the Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT), merge with the Main Himalayan Thrust (MHT) at depth. These thrust faults together with the South Tibetan Detachment System (STDS) divide the Himalaya from south to north into the sub-Himalaya, lesser Himalaya, higher (greater) Himalaya, and Tethyan Himalaya (DeCelles et al., 2014; Yin, 2006). Over the past decades, seismological images from various south-north profiles have clearly revealed that the Indian plate underthrusts the Himalaya along the MHT, which separates the overlying Himalayan fold-thrust wedge from the downgoing Indian lithosphere (Caldwell et al., 2013; Nabelek et al., 2009; Schulte-Pelkum et al., 2005; W. J. Zhao et al., 1993). However, the detailed geometry of the underthrusting Indian lithosphere along strike remains controversial.

The geometry of the MHT, which is linked to the occurrence of several great earthquakes, has been investigated in different locations within the Himalaya. Receiver function images (Caldwell et al., 2013) and magnetotelluric (MT) inversions (Rawat et al., 2014) indicate that the MHT exhibits a flat-ramp-flat shape beneath the Garhwal Himalaya and that the local seismicity mainly focuses on the ramp zone. Receiver function studies from the Himalayan-Tibetan Continental Lithosphere during Mountain Building (Hi-CLIMB) experiment across central Nepal reveal a ramp-flat-ramp geometry for the MHT from the sub-Himalaya to the Higher Himalaya, and the 2015 Gorkha earthquake ruptured the flat part of the MHT (Duputel et al., 2016), which is consistent with the results derived from the refined focal mechanisms and locations of the 2015 Gorkha earthquake sequence (Wang et al., 2017). Furthermore, the P-wave velocity structure together with relocated aftershocks of the 2015 Gorkha earthquake suggest that the geometry of the MHT with along-strike and cross-strike variations limited the rupture length of the main shock. More specif-

Figure 1. Topographic map of the south-central part of the Tibetan Plateau, illustrating the major geologic provinces divided by the blue solid lines. The blue triangles indicate the locations of broadband seismometers utilized in this study. The red rectangle in the inset map shows the location of our study area on the Tibetan Plateau. MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; MCT, Main Central Thrust; STDs, South Tibetan Detachment System; YZS, Yarlung Zangbo suture.

ically, the mid-crustal ramp structure stopped the rupture propagation (Bai et al., 2019; Wang et al., 2017). Since these morphological features of the MHT are mainly imaged to the south of the STDs, the west-east depth variations in the northward deepening ramp of the MHT beneath the Tethyan Himalaya are unclear.

Adjoint tomography and surface wave models show that the Indian lithosphere underthrusts beneath southern Tibet at a low angle (M. Chen et al., 2018; Priestley et al., 2006), while body wave tomographic images suggest a change in the Indian mantle lithosphere from flat underthrusting in western Tibet to steep subduction at a moderate angle in central and eastern Tibet (C. Li et al., 2008). The analysis of receiver functions along the Hi-CLIMB and the second stage of Array Network of Tibetan International Lithospheric Observation and Probe Experiments [ANTILOPE-2] profiles favors the coupled underthrusting of the Indian crust and mantle lithosphere extending to $\sim 31^\circ\text{N}$ (Nabelek et al., 2009; Xu et al., 2011, 2015; J. M. Zhao et al., 2010). In contrast, other receiver function studies show that the Indian lithospheric mantle detaches from the Indian lower crust beneath the Tethyan Himalaya ~ 50 km south of the Yarlung Zangbo suture (YZS) along 92°E , and near the YZS along the INDEPTH profile at $\sim 90^\circ\text{E}$ (Kosarev et al., 1999; Shi et al., 2015). P and S velocity images report the lateral segmentation or tearing of the Indian mantle lithosphere dissected by three north-south low-velocity strips (J. T. Li & Song, 2018; Liang et al., 2016). Although the large-scale along-strike variations in the underthrusting Indian lithosphere have been suggested according to previous results mainly from the north-south-oriented profiles, the details of these west-east variations below the Tethyan Himalaya remain poorly constrained.

In this study, we investigate the lithospheric structure along a west-east linear array beneath the Tethyan Himalaya using P and S receiver function (PRF and SRF) techniques. Our results determine the depths of the MHT, Moho and lithosphere-asthenosphere boundary (LAB), allowing us to illuminate the west-east geometric variations of the underthrusting Indian lithosphere with much higher resolution.

2. Data and Methods

2.1. Data

We collected the teleseismic waveform data recorded at 19 broadband stations of a west-east passive-source linear seismic profile (hereafter called ANTILOPE-3B) in the Tethyan Himalaya to the north of central Nepal. This seismic experiment shown in Figure 1 was operated from December 2014 to December 2015 with an average station spacing of 10 km. Here we select earthquakes with magnitudes greater than M_b 5.5 and at epicentral distances from 30 to 95° to calculate the PRFs, while those with epicentral distances of 60 – 85° for the S wave and 85 – 115° for the SKS wave are utilized to calculate the SRFs. After all the seismograms are filtered with a bandpass filter of 1–30 s, we manually pick all the traces with high signal-to-noise ratios and clear onsets of P waves or S phases (S and SKS waves). Figure 2 shows the spatial distribution of 138 events used for subsequent RF analysis.

2.2. Receiver Function Analysis

The PRFs contain P-to-S (P_s) conversions and their associated multiples from the subsurface discontinuities beneath a seismic station, which have been widely used to image the interfaces in the crust and the mantle transition zone (Burdick & Langston, 1977; Vinnik, 1977). However, the P_s converted phase from the LAB, mostly located within the depth range of 100–200 km, is not easily interpreted due to the interference of crustal multiples. In the SRFs, the S-to-P (S_p) converted phases and crustal reverberations arrive on the op-

Figure 2. Distribution of the teleseismic events used to calculate PRFs (green crosses) and SRFs (red squares). The blue triangle represents the center of the seismic array. PRF, P receiver function; SRF, S receiver function.

posite sides of the direct S or SKS waves (Farra & Vinnik, 2000). This natural separation makes the SRFs suitable to explore the LAB.

The calculation of the PRF and SRF involves coordinate rotation and deconvolution (Kind et al., 2012). We first rotate the original ZNE-component seismograms into the P-SV-SH system. Instead of the theoretical back azimuth and incidence angle used for PRF, we determine an optimal incidence angle for SRF that minimizes the amplitudes of the P component around the arrivals of the S phases. Then we yield the PRF and SRF using a time-domain spiking deconvolution. The deconvolved SV component by the P component is called the PRF, and the SRF corresponds to the deconvolved P component by the SV component. We further reverse the time axis and amplitudes of the SRF for direct comparison with the PRF.

The Moho depth and V_p/V_s ratio beneath each station are estimated using the delay times of the Moho Ps and PpPs phases (Xu et al., 2017). These delay times are picked on the two separate stacked traces by stacking all the PRFs after moveout correction for Ps and PpPs phases, respectively. A reference slowness of 6.4 s/° is used for the moveout correction. Uncertainties in the Moho depth and V_p/V_s ratio at each station can partly come from the picking errors of the Ps and PpPs delay times. We use 100 bootstrap realizations of the above-mentioned processing with the resampled PRFs from the raw data set (K. H. Liu et al., 2003) and then calculate the two standard deviations of the mean values as the uncertainties in the estimated Moho depth and

V_p/V_s ratio. In addition, a regional crustal V_p of 6.2 km/s is used during this analysis, based on the crustal velocity model from a wide-angle seismic profile (Zhang & Klemperer, 2010). If we assume that the average crustal V_p varies between 6.0 and 6.5 km/s, the uncertainties caused by different V_p can reach about ± 4.0 km for the Moho depth and ± 0.01 for the V_p/V_s ratio.

To intuitively trace the lateral variations in the lithospheric discontinuity structure, we construct the depth migrated images using a common conversion point (CCP) stacking method (Dueker & Sheehan, 1998). The amplitudes of each PRF or SRF are back projected along their ray paths to their appropriate locations within a Fresnel zone around the conversion points. The 2D velocity model for ray tracing is interpolated from the 1D modified IASP91 model of each station in which the crustal parameters have been changed using the obtained Moho depths and V_p/V_s ratios. This model may produce errors in the absolute depths of the tectonic interfaces in the CCP stacking image due to possible deviations from the real velocity structure. If 5% V_p and V_s changes down to 200 km with respect to the 2D velocity model used are assumed, the depth errors are 3 km with the Moho at a depth of 60 km and 6 km for the LAB at a depth of 120 km. These errors are less than the vertical resolution of the PRF and SRF, determined by their central frequencies.

3. Results

We calculate the PRFs and SRFs for each station. Examples of individual PRFs and SRFs with summation traces for station SLG04 are shown in Figures S1 and S2. For comparison, Figure S3 shows the individual radial-component PRFs and the stacked traces of the radial-component PRFs and SV-component PRFs used in this study for station SLG04. It is clearly seen that both stacked traces fit very well except for the first 0–1 s which are dominated the P wave energy for radial-component PRF and the Ps conversions from sedimentary layer for SV-component PRF. In Figure 3, we present the stacked traces of PRFs at each station after moveout correction for Ps (Figure 3a) and PpPs (Figure 3b) conversions, respectively. The Moho phases with positive amplitudes (marked by red lines) are clearly resolved between 6.6 and 8.4 s at 17 stations. Another positive phase before the Moho (indicated by green lines) corresponding to the conversion at the MHT is coherently observed between 4.8 and 6.4 s at 16 stations. Based on a short time window (labeled by the blue lines) predefined by the Moho Ps arrival time and two V_p/V_s ratios of 1.6 and 2.0, we reliably pick

Figure 3. Stacked traces of PRFs at each station with the completed moveout corrections for Ps (a) and PpPs (b). (a) The red and green vertical lines mark the arrival times of Ps conversions at the Moho and MHT discontinuities, respectively. (b) The red squares indicate the picked delay times of the Moho PpPs phases within a predicted time window bounded by the blue vertical lines. MHT, Main Himalayan Thrust; PRF, P receiver function; SRF, S receiver function.

Figure 4. CCP stacking image of PRFs along the west-east profile. Positive (negative) amplitudes are colored red (blue), representing velocity increases (decreases) with depth. The green and pink dashed lines denote the recognized MHT and LVZ, respectively. For cross verification, the calculated Moho depths using Moho Ps and PpPs arrival times (cyan crosses) are superimposed on the well-resolved Moho (black dashed line). CCP, common conversion point; LVZ, low velocity zone; MHT, Main Himalayan Thrust; PRF, P receiver function.

the Moho PpPs phases at 15 stations, which vary from 25.1 to 30.1 s (Figure 3b). Then, the resulting Moho depths and V_p/V_s ratios as well as their uncertainties from all the available stations are summarized in Table S1. The V_p/V_s ratio along this profile ranges from 1.62 to 1.75 with a standard deviation of 0.03. These low V_p/V_s ratios suggest felsic bulk crustal compositions possibly resulted from the upper-middle crustal thickening below the Tethyan Himalaya (Ji et al., 2009).

Figure 4 illustrates the depth migrated image of PRFs along a preferred profile determined based on the distribution of the Ps piercing points at Moho depth corresponding to the calculated PRFs (Figure S4). The pronounced positive signal (velocity increasing with depth) agrees well with the superimposed Moho depths (cyan crosses) computed by the Moho Ps and PpPs arrival times, so we attribute this signal to the Moho. This consistency of Moho depths from the two independent methods justifies the 2D velocity model in the CCP stacking approach. The Moho lies at 60 km in the west, gradually deepens toward the east and reaches 72 km at the eastern end of this profile. Above the Moho, a negative-over-positive signal pair, arising from such a structure with a low velocity zone (LVZ) above the MHT, is clearly observed along this profile. Similar to the Moho, both the LVZ and the MHT show overall trends of deepening eastward. Along this cross section, the LVZ depth slightly increases from 32 to 42 km from west to east, whereas the MHT depth undulates and increases from 42 to 54 km.

In Figure 5b, we show the depth migrated image of SRFs within 100 km of a selected profile. The location of this profile is determined according to the distribution of Sp piercing points of SRFs at a depth of 100 km (Figure 5a). The strongest conversion corresponds to the Moho, which appears smoother than that imaged by the PRFs due to the lower frequencies of the SRFs. The Moho depths agree well with those derived from the PRFs (green crosses), which also confirms the accuracy of this migrated image. A negative conversion below the Moho is associated with the LAB, which can be clearly identified along this profile. The LAB is generally inclined from 90 to 126 km toward the east along this transect except for a ~10 km upwarped zone between 87.4 and 88.2°E.

We also assess the stability of the migrated images of the PRF and SRF by a bootstrap approach. We perform 100 CCP stacks with the same number of RFs randomly selected from the original data set (Liu et al., 2003) and calculate the standard deviations of each grid based on the 100 stacking values. We adopt grids with amplitudes greater than 1.5 standard deviations as reliable observations when interpreting the above-mentioned observations (Figures S5 and S6).

4. Discussion

4.1. Synthetic Tests for the Characteristics of the LVZ and MHT

We conduct the synthetic tests to check the structural resolution of the identified LVZ and MHT. A simple velocity model is designed with the averaged depths of the observed LVZ and MHT, where the V_s contrast is 0.3 and 0.6 km/s, respectively (Figure 6a). Synthetic PRF is computed for this given model using the RAYSUM package (Figure 6b) (Frederiksen & Bostock, 2000) and is used to generate CCP stacking image using the same al-

Figure 5. (a) Distribution of Sp piercing points at 100 km depth. (b) Migrated image of SRFs along the optimum profile marked by the red line in (a). The pink dashed line traces the well-identified LAB. For comparison, we superimpose the Moho depths computed by the Moho Ps and PpPs arrival times (cyan crosses) on the apparent Moho (black dashed line). LAB, lithosphere-asthenosphere boundary; SRF, S receiver function.

gorithms as those for the filed data (Figure 6c). The negative-over-positive conversions in the synthetic PRF and the CCP stacks reproduce the LVZ and MHT at expected depth, which proves the feasibility of PRF to detect the interpreted LVZ and MHT structure. Due to the absence of the coherent converted signals at shallower depth in Figure 4, it is unlikely that the prominent negative-over-positive conversions correspond to crustal multiples. The Ps conversions from LVZ and MHT at station SLG04 exhibit no significant variations in polarity and amplitude with the back azimuth (Figure S1), which suggests that the dip and/or anisotropy have little effect on our observations of LVZ and MHT. Furthermore, such a structure with a LVZ above the MHT seems to be pervasive along the Himalaya (Caldwell et al., 2013; Hazarika et al., 2017; Subedi et al., 2018; Zhang & Klemperer, 2010), which supports our interpretation.

In order to estimate the Vs contrasts responsible for the LVZ and MHT, we compute the synthetic PRF for a representative station BLG03 with almost the maximum amplitudes of the LVZ and MHT. Assuming a crustal model with a homogeneous layer overlying the LVZ and MHZ, the synthetic PRF fits reasonably well with the observed data when the Vs contrast at the LVZ and MHT is 0.4 and 0.7 km/s, respectively (Figure 7a). Previous studies indicate that the minimum Vs contrast at an interface which will generate an observable Ps conversion in PRF is 0.3 km/s (Cassidy, 1991), so the Vs contrast of 0.3–0.7 km/s can explain our observed Ps amplitudes of the LVZ and MHT in PRFs.

The sharpness of the LVZ and MHT can be determined by measuring the boundary width (h) associated with the wavelength of the Ps conversion that retains or deviates from the simple pulse shape. We adopt a conservative estimate of h computed as $h \sim \lambda_s = V_s/f$, where λ_s is the wavelength of the Ps phase, f is the highest frequency and $V_s = 3.7$ km/s (Levin, Van-Tongeren, & Servai, 2016). Constructed PRFs with frequencies ranging from 0.25 to 3.0 Hz for station BLG03 are shown in Figure 7b. The Ps pulse of LVZ becomes complex at the highest frequency $f = 0.5$ Hz corresponding to $\lambda_s = 7.4$ km, and the Ps pulse of MHT does not decrease in width starting from frequency $f = 2.0$ Hz corresponding to $\lambda_s = 1.9$ km.

Figure 6. Synthetic tests for our identified LVZ and MHT. (a) 1D isotropic velocity model using the averaged depths of the observed LVZ and MHT. (b) Synthetic PRF computed from the velocity model (a). (c) The CCP stacks created with the synthetic PRF (b). CCP, common conversion point; LVZ, low velocity zone; MHT, Main Himalayan Thrust; PRF, P receiver function.

Figure 7. (a) Comparison between the synthetic and observed PRFs for the amplitudes of Ps conversions from LVZ and MHT at station BLG03. (b) Observed PRFs arranged with frequency content for station BLG03. The LVZ and MHT have a simple pulse shape up to 0.5 Hz and 2.0 Hz, respectively (marked by red triangles). LVZ, low velocity zone; MHT, Main Himalayan Thrust; PRF, P receiver function.

After applying this conservative technique to all of the available stations, our estimates for sharpness of the interfaces are ~ 3.7 – 7.4 km for LVZ and ~ 1.9 – 3.7 km for MHT.

4.2. The Role of the MHT in the Underthrusting Indian Crust

Many disputes continue about the selection of the conversion phase interpreted as the MHT in previous studies. The MHT is defined with a changing polarity due to the lithologic juxtapositions in the Garhwal Himalaya (Caldwell et al., 2013), a negative conversion in western and central Nepal (Nabelek et al., 2009; Subedi et al., 2018) and a major crustal anisotropic shear zone in eastern Nepal and Bhutan (Schulte-Pelkum et al., 2005; Singer et al., 2017). We prefer to interpret the positive conversion at depths of 42–54 km as the MHT, which is consistent with a strong P wave velocity increase downward from seismic reflection (Zhao et al., 1993) or the bottom of a LVZ from the wide-angle seismic experiment (Zhang & Klemperer, 2010). Likewise, the positive conversion before the Moho reported in the northwest Himalaya and ANTILOPE-2 experiment at 86°E is also regarded as an indicator of the MHT (Hazarika et al., 2017; Xu et al., 2015).

We compare the imaged MHT and Moho structure with the previous results for other regions of the Himalaya (Figure S7). The depths of both the Moho and the MHT are easily concluded to exhibit significant variations along the west-east strike and across the strike of the Himalaya. Most studies to the south of our profile reveal that the MHT begins to dip northward at depths of 16–20 km beneath the Higher Himalaya (Singer et al., 2017; Subedi et al., 2018). Taking this feature as the reference, our findings suggest the existence of a north-south mid-crustal ramp in the MHT, which reaches northward to 42–54 km beneath the Tethyan Himalaya with a dip angle of $16 \pm 2^\circ$. This inferred ramp and its angle are generally consistent with the imaged MHT in profiles 81°E (Subedi et al., 2018), 85°E (Nabelek et al., 2009), 86°E (Xu et al., 2015), $86.5 \pm 1.5^\circ$ E (Schulte-Pelkum et al., 2005), $89 \pm 1^\circ$ E (Acton et al., 2011), and 89.5°E (Singer et al., 2017) by PRFs and in profile 90°E (Hauck et al., 1998) by deep seismic reflections, although these studies illustrate a shallower ramp than our observations largely due to the differences in local velocity and definition of the MHT. Below the MHT, our observed Moho depths are consistent with the results from PRFs along profiles 85°E (Nabelek et al., 2009), 86°E (Xu et al., 2015), and $86 \pm 1.5^\circ$ E (Schulte-Pelkum et al., 2005). Moreover, our estimated depths of the MHT and Moho are apparently deeper than the results along profiles 79°E (Caldwell et al., 2013) and $89 \pm 1^\circ$ E (Acton et al., 2011). These discrepancies are likely attributed to the different lithologic units where these sections with the same distance from the MFT are located and the sparse station coverage.

The imaged mid-crustal LVZ immediately above the MHT in this study is supported by the crustal velocity structure from a west-east wide-angle seismic profile within the same region, which determines a LVZ with a V_p of 5.8 km/s at depths of 30–40 km (Zhang & Klemperer, 2010). Our observation of this LVZ corre-

sponds well with the southern end of the south-dipping LVZ derived from the PRF depth migrated image along profile ANTILOPE-2 at 86°E (Xu et al., 2015). Furthermore, the existence of the mid-crustal LVZ is also suggested by the RF results beneath the northwest Himalaya (Hazarika et al., 2017) and along the Hi-CLIMB profile at 85°E (Duputel et al., 2016). We suggest that the formation of this mid-crustal LVZ observed in the Tethyan Himalaya could be due to the presence of crustal dehydration partial melting, which is justified by the conclusion drawn from a comparison between the experimental conductivity measurements of Himalayan Miocene metamorphic rocks and the present geophysical MT data (J. Y. Chen et al., 2018). The results of 3D thermomechanical modeling indicate that radioactive, shear and basal heating during crustal thickening provide important heat sources for generating such mid-crustal partial melting (L. Chen et al., 2019). In addition, the exposed gneissic domes in the Tethyan Himalaya and the pervasive migmatites as well as the intruded leucogranites in the Higher Himalaya show the presence of mid-crustal melting (Harris, 2007).

Our observations suggest that the MHT and Moho acting as the top and bottom boundaries, respectively, characterize the eastward tilted geometry of the underthrusting Indian crust. The inferred mid-crustal ramp in the MHT terminated the occurrence of aftershocks at this depth and the northward rupture propagation along the sub-horizontal MHT associated with the 2015 Gorkha earthquake (Bai et al., 2019), which is compatible with the presence of a mid-crustal melt layer above the MHT dominated by ductile deformation. The thickness of the underthrusting Indian crust beneath the Tethyan Himalaya is estimated to average 18 km, which is approximately 10 km thinner than that at the starting position of the mid-crustal ramp beneath the Higher Himalaya obtained from PRF studies south of our profile (Schulte-Pelkum et al., 2005). As suggested by studies of a deep seismic reflection profile in the western Himalaya (Gao et al., 2016), we prefer the interpretation that this marked crustal thinning is achieved mainly by structural duplexes that transfer Indian lower crustal materials into the Himalayan wedge along the mid-crustal ramp in the MHT. Our imaged LVZ not only facilitates the development of duplexing structures due to the decoupling between the footwall and hanging wall of the MHT, but also induces the southward extrusion of crustal melt material with itself as a channel driven by north-south compression and gravitational potential energy (Beaumont et al., 2001; Chen et al., 2019). These processes also correlate well with the greater exhumation rates in the Higher Himalaya (Harris, 2007). We therefore propose that the crustal deformation mechanisms beneath the Tethyan Himalaya, to a lesser extent, involve a combination of the underthrusting Indian lower crust, tectonic duplexing and southward extrusion of melt-weakened crustal material.

4.3. West-East Variations in LAB Depth and Their Implications

Our SRF image clearly indicates the prominent eastward deepening of the LAB from 90 to 126 km, which is not well constrained by previous studies. The observed LAB depths are in agreement with the results of SRFs along profiles Hi-CLIMB and ANTILOPE-2 (Kumar et al., 2013; Xu et al., 2011). The tilt angle of this LAB topography is less than 7°, indicating that our resolved LAB depth is fairly reliable, as demonstrated by the synthetic modeling of SRFs (Lekic & Fischer, 2017). In addition, we note that the eastward deepening trend of the LAB is the same as those observed for both the MHT and the Moho, suggesting coupled subduction between the Indian lower crust and mantle lithosphere beneath the Tethyan Himalaya.

This pronounced easterly dip of the LAB along this profile could be explained by the subduction angle of the Indian lithosphere increasing eastward. Body wave tomographic images clearly reveal that the horizontal distance of the underthrusting Indian lithosphere has undergone an abrupt decrease from 85 to 90°E, as shown by the 100 and 200 km depth contours on the top of the Indian plate (Li et al., 2008), implying a conversion from flat to steeper subduction of the Indian lithosphere, which is broadly consistent with our interpretation. Another distinct change from underplating to steep subduction occurs at ~91.5°E, as revealed by the CCP stacks of PRFs along closely spaced profiles (Shi et al., 2015). These west-east variations in the subduction angle of the Indian lithosphere are compatible with the fragmentation of the subducting Indian mantle lithosphere inferred by finite-frequency tomography (Liang et al., 2016) and the tearing of the underthrusting Indian lithosphere beneath the Yadong-Gulu rift suggested by SRFs and anisotropy investigations (Z. Liu et al., 2020; Wu et al., 2019).

Figure 8. Sketch showing our observations and their interpretations. The Indian lower crust and mantle lithosphere with an eastward dipping geometry are underthrusting under the Tethyan Himalaya within our study area. The LVZ facilitates the southward extrusion of melt-weakened materials and the development of tectonic duplexing. ILC, Indian lower crust; IUMC, Indian upper-middle crust; ILM, Indian lithospheric mantle; LVZ, low velocity zone; HUMC, Himalayan upper-middle crust.

5. Conclusions

We present the detailed lithospheric structure beneath the Tethyan Himalaya using PRF and SRF approaches from a west-east linear profile of 19 broadband seismometers spanning the region at 85.5–88.5°E. Our findings provide new constraints on the west-east geometric features of the underthrusting Indian lithosphere. The main results of this study together with their implications are illustrated in Figure 8 and summarized as follows:

- 1) We recognize the MHT and the Moho, which characteristically deepen eastward along this profile at depths of 42–54 km and 60–72 km, respectively. We infer that there exists a north-south mid-crustal ramp in the MHT beneath the Higher and Tethyan Himalaya, which blocked aftershock activity and northward rupture propagation associated with the 2015 Gorkha earthquake. The MHT and Moho representing the top and bottom interfaces, respectively, suggest that a thinning Indian lower crust with an eastward inclined shape is underthrusting beneath the Tethyan Himalaya.
- 2) Our observations reveal an intra-crustal LVZ just above the MTH in the 32–42 km depth range, caused by the presence of crustal dehydration partial melting. This LVZ induces the southward extrusion of melt-weakened crustal material with itself as a channel and facilitates the formation of the proposed duplexing structures, which transfer Indian lower crustal materials into the Himalayan wedge along the mid-crustal ramp in the MHT.
- 3) We identify the eastward dipping LAB varying from 90 to 126 km, which is consistent with the changing style of the MHT and Moho. These observations can be reconciled by the eastward steepening subduction angle of the Indian lithosphere.

Data Availability Statement

The data used in this study are publicly available at <https://doi.org/10.5281/zenodo.3696431>. Most figures were produced with the Generic Mapping Tools (GMT) (Wessel & Simth, 1998).

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