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Mapping crustal structure beneath southern Tibet: Seismic evidence for continental crustal underthrusting

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ABSTRACT

Receiver function imaging along a temporary seismic array (ANTILOPE-2) reveals detailed information of the underthrusting of the Indian crust in southern Tibet. The Moho dips northward from ~50 km to 80 km beneath the Himalaya terrane, and locally reaches ~85 km beneath the Indus–Yalung suture. It remains at ~80 km depth across the Lhasa terrane, and shallows to ~70 km depth under the Qiangtang terrane. An intra-crustal interface at ~60 km beneath the Lhasa terrane can be clearly followed southward through the Main Himalaya Thrust and connects the Main Boundary Thrust at the surface, which represents the border of the Indian crust that is underthrusting until south of the Bangong–Nujiang Suture. A mid-crustal low velocity zone is observed at depths of 14–30 km beneath the Lhasa and Himalaya terranes probably formed by partial melt and/or aqueous fluids.

1. Introduction

The Himalayan–Tibet orogeny as the product of India–Asia continental collision starting at ~50 Ma (e.g., Molnar et al., 1993), has attracted much attention for its complex geodynamic settings and evolution history in the past three decades (e.g., Guan et al., 2012; Zhang and Santosh, 2012; Zhang et al., 2012; Zhu et al., 2013; Zhang et al., 2014). For southern Tibet, a model of Argand-type underthrusting of the Indian plate, where the Indian upper crust has been stripped off to form the Himalaya while the Indian lower crust extends further northward with eclogitization beneath the Lhasa terrane, is proposed to explain the crustal shortening and thickening (e.g., Searle et al., 2011). It has long been argued that the crustal thickening beneath Tibet was caused by northward underthrusting of the Indian crust that begins from the Main Boundary Thrust (MBT) at the surface (Ni and Barazangi, 1984), follows the Main Himalaya Thrust (MHT) in the mid-crust (Zhao et al., 1993; Nabelek et al., 2009) and terminates at a Moho doublet in the lower crust (Kind et al., 2002; Nabelek et al., 2009). No direct observations along one transect have yet been able to present all these individual features.

The crustal structure beneath Tibetan plateau and surrounding regions have been constrained by many experiments (e.g., Zhao et al., 2001; Kind et al., 2002; Schulte-Pelkum et al., 2005; Nabelek et al., 2009; Zhao et al., 2010; Zhang et al., 2011; Chen et al., 2013; Tian and Zhang, 2013), but the details of the crustal structure are still insufficient. Previous seismic studies have suggested the presence of abrupt steps in the Moho beneath suture boundaries and major strike-slip faults (Hirn et al., 1984; Wittlinger et al., 2004; Xu et al., 2010, 2013), but their observations could be partly affected by wrong phase identification and shallow lateral velocity variations. In addition, it remains unclear whether there is a direct relation between the Moho topography and suture zones at the surface such as Indus–Yalung suture (IYS) and Bangong–Nujiang suture (BNS) that formed during plate convergence.

A widespread mid-crustal low velocity zone has been observed by different geophysical means (e.g., Nelson et al., 1996; Yuan et al., 1997; Alsdorf and Nelson, 1999; Wei et al., 2001; Hetenyi et al., 2011; Xu et al., 2011; Yang et al., 2012) and is commonly interpreted as partially molten middle crust. However, the regional extent of the low velocity zone still needs to be constrained.

Here we employ the P receiver function technique to investigate crustal structure along a N–S oriented profile named ANTILOPE-2 (the second stage of Array Network of Tibetan International Lithospheric Observation and Probe Experiments) deployed by the geophysics group from Institute of Tibetan Plateau Research, Chinese Academy of Science (ITPCAS) (Fig. 1). We constructed a detailed image of the Indian–Eurasian crustal contact zone that provides a base for identifying crustal properties and understanding the subducting process of Indian lithosphere beneath southern Tibet.

2. Data and method

The ANTILOPE-2 profile consists of 52 portable broadband seismic stations with an average station spacing of ~10 km, operated from

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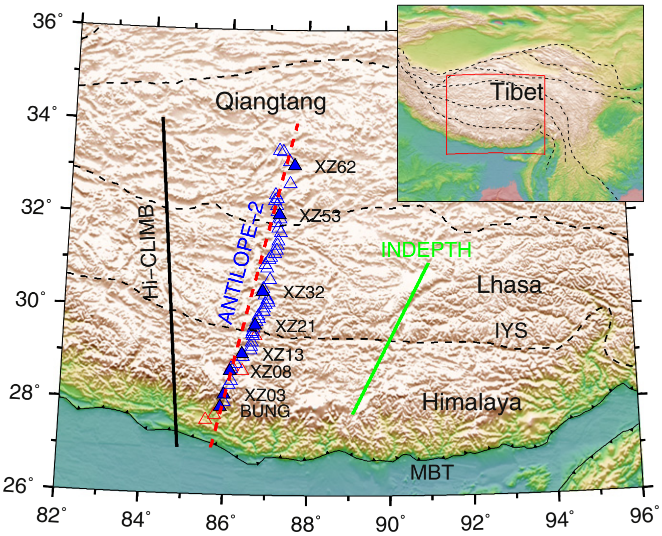

Fig. 1. Topographic map showing the major tectonic divisions and seismic stations of ANTILOPE-2 (blue triangles) and HIMNT (red triangles) experiments used in this study. Also shown are the approximate positions of Hi-CLIMB (black line) and INDEPTH (green line) projects for comparison. The inset illustrates the location of the study region with respect to the Tibetan plateau. The red line marks the location of the cross-section in Fig. 6, and the blue solid triangles represent the locations of stations whose individual P receiver functions are displayed in Figs. 3 and 4. IYS, Indus–Yarlung suture; BNS, Bangong–Nujiang suture; MBT, Main Boundary Thrust. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

September 2005 to October 2006 (Zhao et al., 2010). Zhao et al. (2010) analyzed P and S receiver functions and SKS splitting and found evidence for the boundary between the Indian and Eurasian mantle lithospheres. In this study we focus on the detailed crustal structure and image the crustal boundary of the two converging plates. In addition to our stations, we also include 6 seismic stations close to this profile, which belong to the HIMNT experiment during 2001–2003 (Schulte-Pelkum et al., 2005) (Fig. 1). For each station, we select the teleseismic events with body wave magnitudes greater than 5.5 and epicentral distances ranging from 30° to 95° based on the PDE catalog (Fig. 2). All the records are cut using a window of 10 s prior and 100 s after the P wave

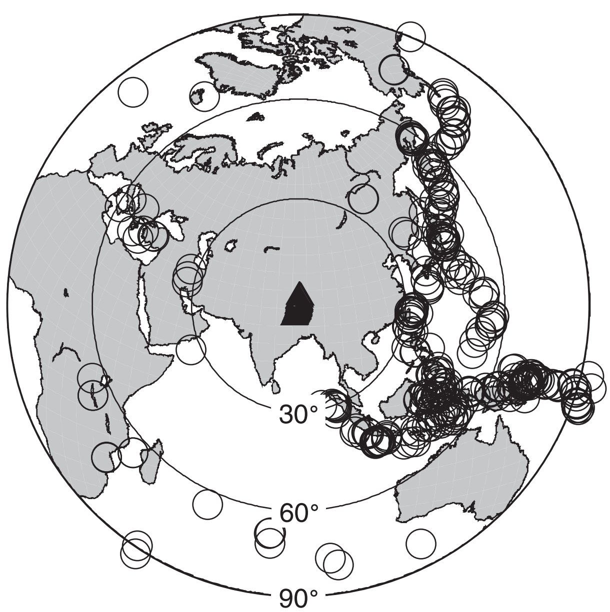

Fig. 2. Location of earthquake epicenters used in the P receiver function analysis. Contours show the distances in degree to the approximate position of the network.

arrival. We use careful inspection in order to harvest seismic waveforms with clear P wave onsets and high signal-to-noise ratios for the calculation of P receiver functions (PRFs).

We follow the same processing steps as described by Yuan et al. (1997) to compute the PRFs. First the original Z, NS and EW (ZNE) components are rotated into the local P–SV–SH ray-based coordinate system using theoretical back azimuths and incidence angles, determined by the geographical locations of the earthquakes and the receivers. Then the PRFs are generated by deconvolving the SV components from the P components by a time domain Wiener filtering method. Finally, we take the arithmetic mean of all the PRFs at each station as the stacked trace to strengthen weak coherent signals. Before summation, we perform moveout correction to the Ps conversions of all the PRFs using a fixed reference slowness of 6.4 s/° to eliminate the difference in Ps arrival times caused by the different epicentral distances and focal depths (Yuan et al., 1997; Kind et al., 2012).

The PRFs contain the amplitudes and delay times of the Ps direct converted waves and multiples generated at discontinuities at different depths. We construct a subsurface cross section along the profile by a Common Conversion Point (CCP) stacking algorithm, which has been used in many studies of the Tibetan plateau (e.g., Kind et al., 2002; Schulte-Pelkum et al., 2005; Nabelek et al., 2009; Zhao et al., 2010; Caldwell et al., 2013). This method attempts to back project the Ps amplitudes of each receiver function to their true spatial locations by ray-tracing. The 1-D layered velocity model used for CCP imaging consists of a 90 km thick crust with an average P velocity of 6.2 km/s and a Vp/Vs ratio of 1.73 and the IASP91 mantle structure. The extremely large value of the crustal thickness used guarantees that the deepest Moho is located with crustal velocities. Prior to the migration, we perform an elevation correction to 7 stations in the southernmost Himalaya. All depths are relative to a ground level of ~5 km.

For the crustal structure imaging, the profile is divided into grids and each grid is set to be 1 km by 1 km in horizontal and vertical directions. All amplitudes per bin are stacked and normalized by the number of the traces hitting the same bin, whereas the values of bins with no rays are assigned to be zero. We use the size of one Fresnel zone as the distance of horizontal smoothing to generate the final structural image. The width of the Fresnel zone represents the lateral resolution of the CCP stacking and varies with depth (Kind et al., 2002). As tested by Kind et al. (2002) and Caldwell et al. (2013), the uncertainties in the Moho depth resulting from a 5% change in crustal P wave velocity or Vp/Vs ratio relative to the 1-D velocity model are less than 3 km.

3. Results and discussion

Overall, we obtained 4823 PRFs for the 58 stations along the profile, which involve 328 teleseismic events, mainly distributed to the east of the study region (Fig. 2). Fig. 3 illustrates examples of individual PRFs for six stations located in Himalaya and Lhasa terranes. Two prominent Ps conversions marked by green and red ticks are clearly identified in summation traces, which correspond to a lower crustal discontinuity and Moho, respectively. Another significant positive signal denoted by black ticks appears at ~0.5 s for all stations in Fig. 3, which is likely the Ps conversion of the sedimentary layer. In contrast, we also present two examples for stations in the Qiangtang terrane, which show clear Moho Ps conversions marked by red ticks in the summation traces (Fig. 4).

Fig. 5 shows the summation traces for all the stations. Fig. 6 is the migrated image along the profile shown in Fig. 1. Intriguingly, apart from the Ps conversions of the Moho, marked by red ticks in Fig. 5 and black crosses in Fig. 6, we also clearly observe another Ps conversion of an intra-crustal discontinuity denoted by green ticks and crosses in Figs. 5 and 6, respectively. For a comparison, the depths of the Moho and the intra-crustal discontinuity calculated based on the picked delay times and the same 1-D velocity model as used for the CCP stacking, are overlaid in Fig. 6 as the black and green crosses. In addition, the

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