Earth and Planetary Science Letters 428 (2015) 172–180

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Is the Asian lithosphere underthrusting beneath northeastern Tibetan Plateau? Insights from seismic receiver functions

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 16 July 2015
Accepted 18 July 2015
Available online xxxx
Editor: A. Yin

Keywords:
lithosphere–asthenosphere boundary
Northeastern margin of the Tibetan Plateau
Receiver functions

ABSTRACT

Whether or not the Asian lithosphere has underthrusted beneath the Tibetan Plateau is important for understanding the mechanisms of the plateau's growth. Using data from the permanent seismic stations in northeastern Tibetan Plateau, we studied seismic structures of the lithosphere and upper mantle across the plateau's northeastern margin using P and S receiver functions. The migrated P- and S-receiver function images reveal a thick crust and a diffuse lithosphere–asthenosphere boundary (LAB) beneath the Tibetan Plateau, contrasting sharply with the relatively thin crust and clear, sharp LAB under the bounding Asian blocks. The well-defined LAB under the Asian blocks tilts toward but does not extend significantly under the Tibetan Plateau; this is inconsistent with the model of Asian mantle lithosphere underthrusting beneath the Tibet Plateau. Instead, our results indicate limited, passive deformation of the bounding Asian lithosphere as it encounters the growing Tibetan Plateau.

1. Introduction

The formation of the Tibetan Plateau through the Cenozoic has been driven by the northward moving Indian plate colliding with the Eurasian plate (Molnar and Tapponnier, 1975; Dewey et al., 1988; Royden et al., 2008; Yin and Harrison, 2000; Yin et al., 2002). On the southern side of the plateau, the plate convergence is marked by large-scale underthrusting of the Indian plate under the Tibetan Plateau, as indicated by seismic images (e.g., Nábělek et al., 2009; Nelson et al., 1996; Owens and Zandt, 1997), although the northern limit of the underthrusting Indian plate remains debated (Nábělek et al., 2009; Zhao et al., 2010).

On the northern and the eastern sides, the Tibetan Plateau is bounded by relatively stable blocks of the Asian lithosphere (Fig. 1). How these Asian lithospheric blocks responded to the Indo–Eurasian collision is critical for understanding the mechanisms of the growth of the Tibetan Plateau. Numerous models, based on geological reconstructions and geophysical data, suggested for substantial underthrusting (subduction) of the Asian lithosphere under the Tibetan Plateau (Tapponnier et al., 2001; Yin et al., 2008a, 2008b; Kind et al., 2002; Zhao et al., 2011), similar to the underthrusting of the Indian plate beneath Himalaya. Meyer et al. (1998) studied the growth of Tibetan Plateau based on satellite image analysis and suggested that south-directed subduction in the northeastern Tibet may have resulted from Palaeozoic and Mesozoic accretion on the southern margin of the Eurasian plate. Tapponnier et al. (2001) proposed several possible onsets of southward mantle underthrusting beneath northeastern Tibetan Plateau. However, in contrast to the abundant seismic evidence for the subducting Indian plate under southern Tibetan Plateau, evidence for subduction of the Asian lithosphere under northern Tibet has been limited and inconclusive (Kind et al., 2002; Zhao et al., 2011). Zhao et al. (2011) and Ye et al. (2015) reported evidence for possible southward underthrusting of Asian lithosphere beneath central and northern Tibet based on receiver functions of local temporary seismic array. However, the results of receiver functions can be affected by station coverage, which might lead to the overgeneralization of the lithosphere deformation. A seismic tomography study (Liang et al., 2012) observed a low velocity upper mantle beneath northern Tibet, which argues against underthrusting of the Asian lithosphere. Furthermore, whereas underthrusting of the Indian plate is marked by abundant seismicity, no earthquakes with focal mechanisms consistent with underthrusting of Asian lithosphere have been observed in northern Tibet.

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http://dx.doi.org/10.1016/j.epsl.2015.07.041

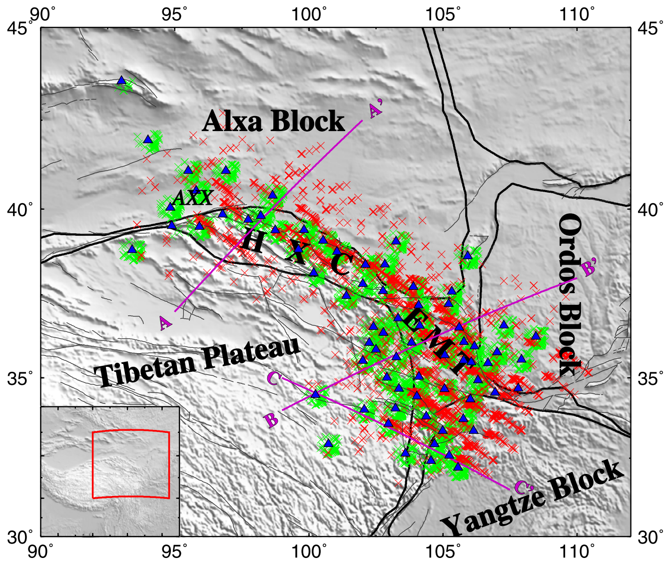

Fig. 1. Map of topographic relief and seismic stations (blue triangles) used for this study. Thick black lines denote the boundaries of major tectonic blocks (Deng et al., 2003). Thin gray lines show the main faults. Green and red crosses represent the location of P-to-s and S-to-p pierce points at 100 km depth, respectively. Purple lines are locations of receiver function profiles shown in Figs. 5–8. HXC: Hexi corridor; EMT: eastern margin of the Tibetan Plateau. Inset map shows the study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

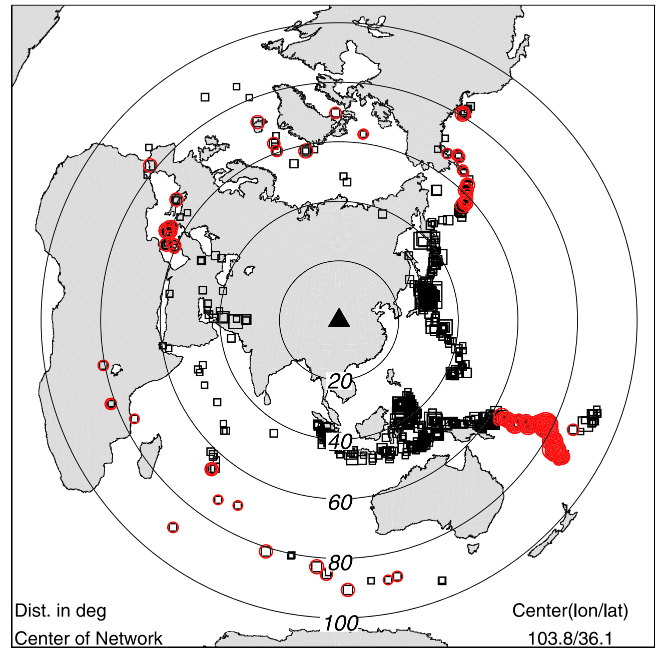

Fig. 2. Map of teleseismic events used in this study. The triangle is the centroid location of the seismic network. Black squares and red circles are the events used for calculation of P and S receiver functions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A key place to investigate the hypothesized underthrusting of the Asian lithosphere is northeastern Tibetan Plateau, where the collision-driven crustal shortening and uplift may have started as early as Eocene (Clark et al., 2010; Yin, 2010; Yuan et al., 2013), and active crustal deformation is indicated by GPS measurements (Gan et al., 2007; Liang et al., 2013; Zhang et al., 2004), precise leveling data (Hao et al., 2014), and intensive seismicity (Deng et al., 2003; Liu et al., 2007). Bounded by the relatively stable Alxa, Ordos, and Yangtze blocks (Fig. 1), northeastern Tibetan Plateau is also the primary site of geological studies that led the models of large-scale underthrusting of the Asian lithosphere under the Tibetan Plateau, because the sequences of anticlinal thrust systems at the plateau's northern edges indicate detachment of the growing plateau from the underlain Asian lithosphere (Meyer et al., 1998; Tapponnier et al., 2001).

For various reasons, seismic studies in northeastern Tibetan Plateau have been limited. In this work, we use the P- and S-receiver functions, derived from data collected from four local networks of permanent seismic stations (Fig. 1) which well cover the north Tibet and the bounding Asian blocks, to image the lithospheric and upper mantle structures along and across the margins of northeastern Tibetan Plateau. Our results show no significant underthrusting of the Asian lithosphere beneath the Tibetan Plateau.

2. Data and method

The seismic waveforms used in this study are from four seismic networks of 75 permanent stations distributed in the Gansu, Qinghai, Ningxia and Sichuan provinces, China (Fig. 1). An instrument update in 2008 has equipped all stations with broad-band seismometers, most of them are CMG-3ESPC made in UK.

We used the receiver function method to image the Moho and LAB in the study area. Receiver functions, derived from analyzing P-to-S or S-to-P wave conversions, have been proven an effective tool for detecting seismic discontinuities in the upper mantle (Langston, 1979; Farra and Vinnik, 2000; Yuan et al., 2006; Li et al., 2004; Kumar et al., 2005). P receiver function (PRF) is good for detecting the Moho and upper mantle discontinuities, but can be difficult for identifying the LAB because of the interference with multiples from the Moho or shallow structures. For this reason, S receiver function (SRF), although more difficult to analyze, is better suited for studying the LAB. Hence we used both the PRF and SRF in our studies. The reverberations from shallow structures in the PRFs are separated from the primary conversions in the SRFs. The arrivals of the converted phases are earlier than the S phase, whereas multiples arrive after the main phase. On the other hand, the amplitude of S-to-P phase may be higher than the corresponding P-to-S phase, given the stronger anelastic attenuation of the S waves than that of the P waves (Wittlinger and Farra, 2007).

The calculation of PRF is usually stable, and the results from different studies are generally repeatable, because the initial P wave and its coda are relatively simple, and there are no signals before the arrival of P wave. The signals around the S phase are more complicated than P wave, so it is no easy way to separate S-to-P phase from S phase. To ensure the objectivity and rationality of SRF, we used the P-to-S phase from the Moho on PRFs as a criterion to evaluate the validity of SRFs.

For P receiver functions, records of teleseismic events with $Ms > 5.5$ from January 2008 to April 2011, with epicentral distances in the range of 30–90 deg, are collected. The source parameters were taken from the US Geological Survey global catalog (http://neic.usgs.gov/neis/epic/epic_global.html). Fig. 2 shows the locations of these events. We selected records with high signal-to-noise ratio and clear onset of P-waves. The waveforms were rotated from the north–east–vertical (N–E–Z) to the radial–transverse–vertical (R–T–Z) coordinates using the back-azimuth. The three-component records were then cut in the time window of 20 s prior to and 100 s after the P-arrival. We then constructed the receiver functions by deconvolving the vertical component from radial component using an iterative approach (Ligorria and Ammon, 1999). A low-pass Gaussian filter with half-width constant $a = 2.5$ was applied to smooth the PRFs. All traces are moveout corrected before summation, using a reference slowness of 6.4 s/deg based on the