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Seismic signature of the mantle transition zone beneath eastern Tibet and Sichuan Basin

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ABSTRACT

The strong interaction between the eastward flow escaping from Tibet and the rigid Sichuan Basin resulted in the rise of the Longmenshan. However, the detailed dynamics in the mantle remains controversial. In this study, the structure of the mantle transition zone (MTZ) beneath eastern Tibet and Sichuan Basin is investigated using 5080 receiver functions from 51 broadband stations. The depth of the 410 km discontinuity is close to the global average, except for the Longmenshan where the 410 and 660-km discontinuities are found to be depressed by up to 10–25 km and 5–10 km, respectively. The observed simultaneous depressions of the 410 and 660-km discontinuities distributed along the LMS, together with proofs from tomography and regional tectonics, suggest that asthenospheric flow sinks into the MTZ, resulting in a high velocity zone, as well as variation in the MTZ thickness. The depressions are not from the traditional Clapeyron slopes or temperature variation. Also, the depression of the 410 km discontinuity and the dehydration of wadsleyite are syngenetic, both of which originate from the dry mantle flow traveling across the old 410 km interface.

1. Introduction

Tibetan Plateau was generated by the continuous collision between the Indian plate and the Eurasian plate which has been taking place over approximately 45 million years. As a result, the crust in the collision zone has been shortened by at least 1500 km (Molnar and Tapponnier, 1975; Armijo et al., 1986; England and Molnar, 1997; Yin, 2000). Such a large horizontal crustal shortening is accompanied by a vertical thickening of the Eurasian plate, as well as by the subduction of the Indian mantle lithosphere (Kosarev et al., 1999; Kumar et al., 2006; Li et al., 2008) beneath the Eurasian lithosphere (Willett and Beaumont, 1994; Kind et al., 2002). According to the eastward extrusion model (Chen et al., 1994; Tapponnier et al., 2001), several major strike–slip faults, such as the Xianshuihe–Anninghe fault, Jinshajiang–Red river fault and the Longmenshan (LMS) fault in eastern Tibet reflect an eastward extrusion of crustal and lithospheric materials (Royden et al., 1997, 2008; Clark and Royden, 2000). GPS displacement vectors (Gan et al., 2007) and SKS anisotropy measurements (Wang et al., 2008) indicated that the Tibetan crust (and possibly the lithosphere even to the asthenosphere) is escaping eastward, redirected into southeast and northeast movements after encountering the rigid Sichuan Basin (Fig. 1). Copley and McKenzie (2007) modeled the measured surface velocity around Tibet and suggested that the viscosity in eastern Tibet is smaller than that in Sichuan Basin, and thus the surface motion in eastern Tibet may be driven by gravity.

As shown in Fig. 1, the Jinshajiang–Red river fault, the Longmenshan fault, and the Lijiang–Jinhe fault separate our study region into three main geological units: the Songpan–Ganze (SG) fold belt, Sichuan Basin (SB), and the diamond-shaped Sichuan–Yunnan (SY) terrane. The boundary between the Songpan–Ganze fold belt and Sichuan Basin is the Longmenshan fault, while the boundary between the Sichuan–Yunnan terrane and the SG/SB is the Xianshuihe–Anninghe fault. The crustal motion of the Sichuan–Yunnan terrane, which is interpreted as an eastward or southeastward extrusion of crustal materials from central and eastern Tibet, is dominated by a clockwise rotation around the eastern Himalayan Syntaxis. The Xianshuihe–Anninghe fault forms a natural boundary of the clockwise rotation. The northward movement of the Indian plate pushed eastern Tibet against Sichuan Basin, resulting in a steep topography with elevation over 4 km within less than 100 km distance across the Longmenshan. An earthquake of Ms. 8.0 was triggered on 12 May 2008 by a rupture along the middle segment of the Longmenshan that caused a crustal shortening of 8.5 m and an uplift of 7.5 m.

The Longmenshan fault is a tectonic boundary that separates Sichuan Basin from the Songpan–Ganze fold belt, and its formation still remains controversial. Some researchers suggested that the middle/lower crustal channel flow from Tibet thrusts onto the surface to form the LMS (Royden et al., 1997, 2008; Clark and Royden,

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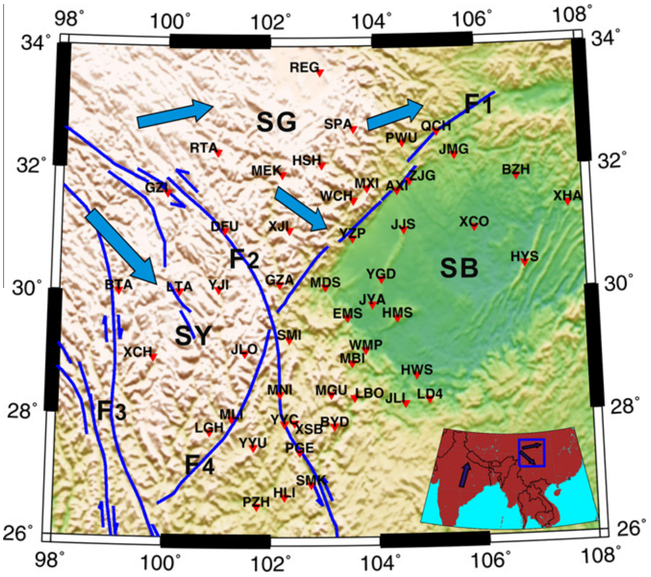

Fig. 1. Topography of eastern Tibet and location of seismic stations (represented by red triangles). The background shows the topography of eastern Tibet, the major faults, and the tectonic units: F1 – Longmenshan Fault; F2 – Xianshuihe–Anninghe Fault; F3 – Jinshajiang–Red River Fault; F4 – Lijiang–Jinhe Fault; SG – Songpan–Ganze Fold; SB – Sichuan Basin; SY – Sichuan–Yunnan Terrane. The blue arrows indicate the directions of GPS velocity vectors, while the inserted small map is a geographic map of the study region.

2000; Robert et al., 2010a,b), while other researchers proposed a lithospheric escape (Wang et al., 2008) coupled with subduction and underthrusting of Sichuan Basin beneath eastern Tibet (Tapponnier et al., 2001). The study approaches include receiver function (Zhang et al., 2009, 2010) and travel time tomography (Guo et al., 2009). Previous observation confirmed that the Moho deepens from 50 km under the SG to 60 km beneath the Longmenshan and then shallows to 35 km under western Sichuan Basin (Zhang et al., 2009; Yang et al., 2011). Beneath the basin, a positive velocity anomaly from tomographic result extends to a depth of at least 200 km, but beneath the Songpan–Ganze fold belt is a negative velocity anomaly which probably arises from the hot lithosphere there (Li et al., 2008).

The mantle transition zone (MTZ) is bounded by two discontinuities at approximately 410 and 660 km deep, respectively. The depths of these two interfaces provide an important constraint for the thermal and compositional nature of the upper mantle. The 410 km discontinuity is interpreted as a mineralogical phase transition from the olivine α-phase to the modified spinel β-phase, while the 660 km discontinuity is a phase transition from ringwoodite (γ-phase) to perovskite and magnesiowustite. In the Earth, pressure increases with depth, and a lateral variation in temperature can generate topographic variations on these two discontinuities. For the 410 and 660-km interfaces, the Clapeyron slopes are positive and negative, respectively (Bina and Helffrich, 1994), so that temperature anomaly can cause local uplift or depression of these interfaces. However, the uplift or depression is not solely caused by the temperature variation, and other mechanisms such as dynamic depression and dehydration may cause the variation in the topography. In this paper, teleseismic P receiver functions are employed to detect the Ps phases from the 410 and 660-km discontinuities, and the lateral variations in the depths of these discontinuities beneath eastern Tibet and Sichuan Basin are mapped using data from 51 broadband seismic stations.

Receiver functions that utilize the Ps phases converted from the 410 and 660-km discontinuities have emerged as a high-resolution tool for investigating the variations of these discontinuities (Langston, 1977; Vinnik, 1977; Yuan et al., 1997). With a rapidly growing number of permanent and temporary seismic stations deployed in the study region during the last 5 years, information regarding the crust and lithosphere has been extracted (e.g., Zhang et al., 2009, 2010; Yang et al., 2011). However, the structure of the MTZ beneath this region remains poorly understood. Study of the MTZ structure can provide us with a substantial insight into the associated mantle dynamics. Singh and Kumar (2009) mapped the MTZ structure beneath eastern Himalaya and southern Tibet using ~9000 receiver functions from 96 broadband stations. Nonetheless, their results did not adequately cover eastern Tibet and Sichuan Basin. Zhang et al. (2010) investigated the MTZ structure across the Longmenshan from P receiver functions, their result however, was along a linear profile of 380 km long, thus being limited in lateral coverage.

2. Data and methodology

Seismic data are collected from 51 permanent broadband stations deployed in eastern Tibet and Sichuan Basin. The radial receiver functions are computed using an iterative deconvolution in the time domain (Ligorria and Ammon, 1999). Raw seismograms are windowed between −40 and +150 s around the arrival of the direct P wave, and are rotated into the vertical, radial, and transverse components. The components are projected into the LQT coordinates to get the P, SV and SH components. Then a transformation (Reading et al., 2003; Svenningsen and Jacobsen, 2004) is applied to remove the effect of the free surface. The converted phases are then isolated from the P coda by deconvolving the P from the SV component through the iterative deconvolution. A Gaussian filter (cutting off the signals with frequency higher than 0.5 Hz) is used to detect the low frequency conversions from the discontinuities. A total of 5080 receiver functions, resulting from 162 teleseismic events with magnitude larger than 6.2 and epicentral distances between 30° and 95°, are eventually obtained. As shown in Fig. 2, the large amount of data provides a good coverage in ray angle and azimuth.

To detect the depths of the 410 and 660-km discontinuities precisely, a reference earth model has to be used. Previous studies (e.g., Zhang et al., 2009, 2010; Yang et al., 2011) confirmed that the crustal thickness and velocity vary dramatically across the Longmenshan. Accounting for this difference, two 1D velocity models are constructed using the P velocities inferred from Wang et al. (2007) and the Moho depth and mean V_p/V_s ratio in the crust from Yang et al. (2011). One is for the Songpan–Ganze fold belt and Sichuan–Yunnan terrane, called model A in which the crustal thickness is set to be 60 km, while the other is for Sichuan Basin, called model B in which the crustal thickness is set to be 40 km. The P wave velocity in the depth from 60 to 660 km is modified from the IASP91 (Kennett and Engdahl, 1991) based on the P wave anomalies (Li et al., 2008), while the V_p/V_s ratio is set to be 1.732.

The receiver function signals, assumed to be the converted waves (hereafter referred to as Pds, where *d* represents the conversion depth), are back-projected along the ray path determined from the ray parameter, the event backazimuth, and the velocity model. To demonstrate the suitability of the models, we stack all receiver functions in 1°distance bins, and compare the results to the predictions of the primary crustal conversion, the crustal reverberations, and the conversions from the 410 and 660-km discontinuities (see Fig. 2). The observed positive and negative phases are often interpreted as the converted phases from the positive and negative velocity gradients, respectively.

As shown in Fig. 2b, the Pms phase arrivals are at 8–9 s in the stacked traces. However, the broad distribution of the Pms arrivals in the bin-stacking traces indicates significant horizontal