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Crustal shear-wave velocity structure of northeastern Tibet revealed by ambient seismic noise and receiver functions

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ABSTRACT

The Tibetan plateau is formed by the persistent convergence between the Indian and Eurasian plates. The northeastern Tibetan plateau is undergoing young deformation that has been noticed for a long time. We conduct a passive-source seismic profile with 22 stations in NE Tibet in order to investigate the crustal shear-wave velocity structure and its relationship with tectonic processes. In this paper we obtain the Rayleigh-wave phase velocity dispersion data among all station pairs within the period bandwidth of 5–20 s from the method of ambient noise cross-correlations. Phase velocity variations correlate well with surface geological boundaries and tectonic features, for instance, low phase velocity beneath the Songpan–Ganzi block and the Guide basin. We also compute P-wave receiver functions based on the selected teleseismic events with similar ray parameters, and perform the joint inversion of surface wave dispersion data and receiver functions to obtain the 2-D crustal shear-wave velocity structure along the profile. The inversion results show that low shear-wave velocities beneath the Songpan–Ganzi block are widespread in the middle-to-lower crust. In together with high crustal *Vp*/*Vs* ratios and high temperature suggested by the P-wave velocities obtained from the active-source seismic study, we suggest that the low velocity zone beneath the Songpan–Ganzi block is probably attributed to partial melting. Across the North Kunlun fault, there is no crustal LVZ found beneath the Kunlun block. This structural difference may have already existed before the collision of the two blocks, or due to limit of the northward extension for the crustal LVZ across the North Kunlun fault.

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1. Introduction

Uplift of the Tibetan plateau is the most spectacular tectonic event during the Cenozoic created by the collision of India and Eurasia. Fundamental questions persist concerning the initiation of the convergence (e.g., Molnar and Tapponnier, 1975; Rowley, 1996; Aitchison et al., 2011; Sun et al., 2012; Zhang et al., 2012; Hu et al., 2015) and the mechanism of lithospheric deformation (e.g., Tapponnier and Molnar 1976; England and Houseman, 1989; Royden et al., 1997; Replumaz et al., 2014; Chen et al., 2015). Many models have been proposed to explain its dynamic responses to collision and its consequent deformation patterns. To this respect, three models have received wide attention, that is, the rigid block extrusion (Tapponnier and Molnar 1976; Tapponnier et al., 1982), the thin-viscous-sheet model (England and Houseman, 1986, 1989), and the crustal channel flow model (Royden et al., 1997).

The northeastern (NE) Tibetan plateau, viewed as a young outgrowth of its evolution and deformation (Meyer et al., 1998), has been a focus of many studies (e.g., Galvé et al., 2002; Vergne et al., 2002; Clark et al., 2010; Duvall and Clark, 2010; Karplus et al., 2013; Tian and Zhang, 2013; Xia et al., 2011; Deng et al., 2015). Deformation mechanisms that work here at present may resemble what happened in the central plateau and participated in the formation of the Tibetan plateau. This is one of the motivations for this study, which will help us understand the earlier deformation of central Tibet. On the other hand, some studies in the southeastern (SE) Tibetan plateau have found that low shear-wave velocities exist in the middle-to-lower crust (Yao et al., 2008, 2010; Liu et al., 2014). We are concerned about whether this phenomenon also exists in the NE Tibetan plateau. It will be very helpful to understand how the eastward expansion of the Tibetan plateau material is bifurcated by the rigid Sichuan Basin on the basis of comparing deformation patterns in the NE and SE Tibetan plateaus. Many works have been done from different perspectives

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to discuss this issue. There may exist a mechanically weak lower crust that accounts for crustal channel flow in the surrounding regions of the Sichuan Basin (Clark and Royden, 2000). Resistivity models obtained from magnetotelluric data show evidences for penetration of partial melting crust across the Kunlun Fault into northern Tibet (Pape et al., 2012).

Galvé et al. (2002) collect the wide-angle reflection–refraction data by active-source seismic survey. The obtained P- and S-wave velocities support predominant felsic composition for the crust and suggest that only the upper crust has been thickened to the north of the Kunlun fault; to the south of this fault the thicker crust is composed by two layers, which could be the superposition of the originally thin crust of the Bayar Har Terrane on the lower crust of the domain to the north. However, Liu et al. (2006) suggest that crustal thickening mainly happens in the lower crust in the NE Tibetan plateau, based on the Darlag–Lanzhou–Jingbian seismic refraction profile.

Seismic interferometry technique using ambient seismic noise has rapidly become an important method to investigate the Earth structure at different scales. In fact, surface wave tomography based on the ambient noise method has provided essential constraints on crustal structure in the world (e.g. Shapiro et al., 2005; Yao et al., 2010; Zheng et al., 2011; Badal et al., 2013). Ambient-noise tomography results of northern Tibet based on INDEPTH-IV data (Yang et al., 2012; Karplus et al., 2013) show that the low velocities are widely distributed in the mid-lower crust of the Tibetan plateau. However, Poisson's ratio observations provided by a series of passive-source seismic surveys reveal more felsic composition of the whole crust and suggest that the upper crust is thickened to accommodate the north–south shortening from the collision of the India–Eurasia plates (Vergne et al., 2002; Jiang et al., 2006; Zhang et al., 2011; Xu et al., 2014).

In this study, we use the continuous ambient noise data as well as teleseismic P-wave data from a passive-source seismic experiment (a linear array with 22 stations) in the NE Tibetan plateau. We perform a joint inversion of short-period Rayleigh wave phase dispersion data from ambient noise tomography and P-wave receiver functions to construct the 2-D crustal shear-wave velocity structure beneath the array profile. Finally we discuss the tectonic implications of the crustal structure obtained in this study.

2. Tectonic setting

The inset in Fig. 1a denotes the study area in the NE Tibetan plateau and shows the northeast–southwest trending seismograph stations deployed between the cities of Xining (to the north) and Moba (to the south). The passive-source seismic survey line crosses the Songpan–Ganzi block and Kunlun block, and reaches the southern edge of the Qilian block from south to north. Regional tectonic characteristics are quite complicated, including several intracontinental sutures, strike-slip faults, thrust faults and Cenozoic basins (Fig. 1b). Here we briefly introduce them in the following content.

2.1. Songpan–Ganzi Block

The easternmost part of Songpan–Ganzi block is a roughly triangular-shaped tectonic unit surrounded by the Kunlun block to the north, the Qiangtang block to the south and the Sichuan Basin to the east (Fig. 1a). It is an ancient remnant ocean basin filled by Triassic turbidite sediments with thickness over 10 km, which is a witness of the evolutive history and deformation undergone in the adjacent blocks such as Qiangtang, east Kunlun, North China, western Qingling blocks, and even the Qinling–Tongbai–Hong'an–Dabie formation located several hundred kilometers to the east (Enkelmann et al., 2007). The closure of the Songpan–Ganzi remanent ocean during the Triassic to Early Jurassic partially sank the Songpan–Ganzi terrane beneath the Kunlun arc along the Animaqing–Kunlun–Muztagh suture (Burchfiel et al., 1995; Yin and Harrison, 2000). The eastern boundary of the Songpan–Ganzi Terrane meets the western edge of the Late Triassic/Early Jurassic Longmenshan thrust belts, which lies along the western edge of the South China (Yangtze) craton (Burchfiel et al., 1995; Zhang et al., 2010). Triassic strata overlies the Paleozoic shallow marine sequences of South China (Burchfiel et al., 1995), which suggests that a slope–shelf transition overlies a continental basement, at least in the easternmost part of the Songpan–Ganzi block (Yin and Harrison, 2000).

2.2. Kunlun Block

The Kunlun and Songpan–Ganzi blocks are separated by the Kunlun strike-slip fault, which probably began left-lateral slipping since ~10 Ma ago (Fu and Awata, 2007; Clark et al., 2010) and partially follows the trace of the Animaqing–Kunlun–Muztagh suture (Fig. 1b). This fault has already provoked five $Mw > 7.0$ earthquakes in the past century and more recently the 11/14/2001 Mw 8.1 Hoh Xil earthquake that results in a 430-km-long surface rupture. These earthquakes indicate that the Kunlun fault is still keeping active. GPS measurements along the Kunlun fault (Duvall and Clark, 2010) support that the deformation from the continental collision dissipates northward rather than eastward in the NE Tibetan plateau. The similar conclusion has been made based on shear-wave splitting parameters obtained from the previous work (see Fig. 7 in Chen et al., 2015).

The Kunlun fault, as a major sinistral strike-slip fault in the NE Tibetan plateau, plays an important role on the northward growth of Tibet. Many geophysical studies have been conducted to observe how the lithosphere of microcontinent plates deforms from the relative motions among different rigid blocks. However, how the blocks have been contacted along the Kunlun fault is still under debate, and both northward subduction and southward subduction beneath the plateau have been suggested (Yin and Harrison, 2000; Tapponnier et al., 2001; Kind et al., 2002; Zhang et al., 2010).

Further north, South Qilian suture separates the Kunlun block from the Qilian block (Fig. 1b). Previous tectonic studies indicate that the Qilian Shan thrust belt collides with the Qaidam–Kunlun block during the Early Paleozoic (Yu et al., 2012). The Kunlun block develops a series of intracontinental strike-slip faults and thrust faults, and most of them are younger than 10 Ma (Clark et al., 2010). The study of average slip rates for the Elashan and Riyue Shan faults, two north-northwest-trending dextral strike-slip faults, west and east of the Qinghai Lake, clearly shows the tectonic deformation in the northeastern margin of the Tibetan plateau since ca. 8–12 Ma (Yuan et al., 2011). The intramontane basins such as the Gonghe–Guide basin and the Xining basin are strongly controlled by these regional faults. The Gonghe–Guide basin is a typical intramontane sedimentary basin similar to the larger Qaidam basin to the west. The course of the Yellow River and its tributaries has exposed a rather complete Neogene sequence (Fang et al., 2005). Further north the Xining subbasin of the Langzhou basin has the largest and continuous Cenozoic sedimentary layer (Dai et al., 2006). Usually, these Cenozoic basins at the northeastern margin of the Tibetan plateau preserve the important stratigraphic records that provide the evidence of the deformation and evolution of this area.

3. Data acquisition

With the purpose on probing the response of the India–Eurasia tectonic collision in the NE Tibetan plateau, we conduct a passive-source seismic experiment between Xining and Moba (Fig. 1a) from November 2010 to June 2011, using 22 seismograph stations with Reftek-72A data loggers and Guralp CMG3-ESP sensors with bandwidths 0.02–30 s or 60 s. The station spacing is about 10 to 15 km (Fig. 1b). Stations S00–S01 are installed in the Qilian block, S02–S16 in the Kunlun block and S17–S27 in the Songpan–Ganzi block. Three-component ground movements are recorded with 40s sample-per-second (sps) at each station.

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