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Two crustal low-velocity channels beneath SE Tibet revealed by joint inversion of Rayleigh wave dispersion and receiver functions

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A B S T R A C T

Competing geodynamic models, such as rigid-block extrusion, continuous deformation, and the mid-lower crustal flow, have been proposed to describe the growth and expansion of eastern Tibet. However, the dynamic processes responsible for plateau evolution and deformation remain poorly understood partly due to resolution limitations of previous models of lithospheric structure. On the basis of joint inversion of Rayleigh wave dispersion and receiver functions using data from a newly deployed seismic array, we have obtained a high-resolution 3D image that reveals the distribution of low-velocity zones (LVZs) with unprecedented clarity. The prominent feature of our model is two low-velocity channels that bound major strike-slip faults in SE Tibet and wrap around the Eastern Himalaya Syntaxis, consistent with the clockwise movement of crustal material in this region. Most large earthquakes in this region occurred in the boundaries of the LVZs. We propose that ductile flow within these channels, in addition to shear motion along strike-slip faults, played a significant role in accommodating intensive lithospheric deformation during the eastward expansion of Tibet in the Cenozoic.

1. Introduction

The Cenozoic collision between India and Eurasia has resulted in the shortening and thickening of the crust and growth of the Tibetan Plateau (TP) (Harrison et al., 1992; Hubbard and Shaw, 2009; Molnar and Tapponnier, 1975; Royden et al., 2008; Tapponnier et al., 2001; Yin and Harrison, 2000). Several models have been proposed to explain the deformation of the eastern TP, including: (1) lateral extrusion of rigid blocks, in which deformation is primarily localized along strike-slip faults that bound the blocks (Molnar and Tapponnier, 1975; Tapponnier et al., 1982, 2001); (2) continuous deformation, in which deformation distributes through a continuously deforming lithosphere (England and Houseman, 1986; Yang and Liu, 2013); and (3) ductile channel flow in the middle/lower crust (Clark and Royden, 2000; Royden et al., 1997; Shen et al., 2001). The mechanisms for plateau deformation and expansion have remained enigmatic due to the resolution limitations of methods and/or data. Consequently, which of the aforementioned models best describes the deformation of the eastern TP has been the subject of enduring debate.

Our study region (white box in Fig. 1) is well situated to investigate the kinematics and dynamics of plateau expansion (Copley, 2008). It comprises four main geological blocks (Fig. 2): the Yunnan–Myanmar–Thailand Block (YMTB), the Indo–China Block (ICB), the Sichuan–Yunnan Diamond Block (SYDB), and the South China Block (SCB), which are separated by the Nujiang fault (NJF), the Jingshajiang–Red River fault system (JSJF and RRF), and the Anninghe–Zemuhe–Xiaojiang fault system (ANHF, ZMHF and XJF). The Xiaojinhe fault (XJHF) divides the SYDB further into the northern and southern parts. Previous studies have suggested that the low-velocity zones (LVZs) observed in SE Tibet may be truncated at depth by faults (Chen et al., 2014; Huang et al., 2002; Wang et al., 2003; Yao et al., 2008, 2010). However, the geometric relationships between LVZs and faults remain unclear due to insufficient spatial resolution or the limited geographic extent of previous lithospheric structure models.

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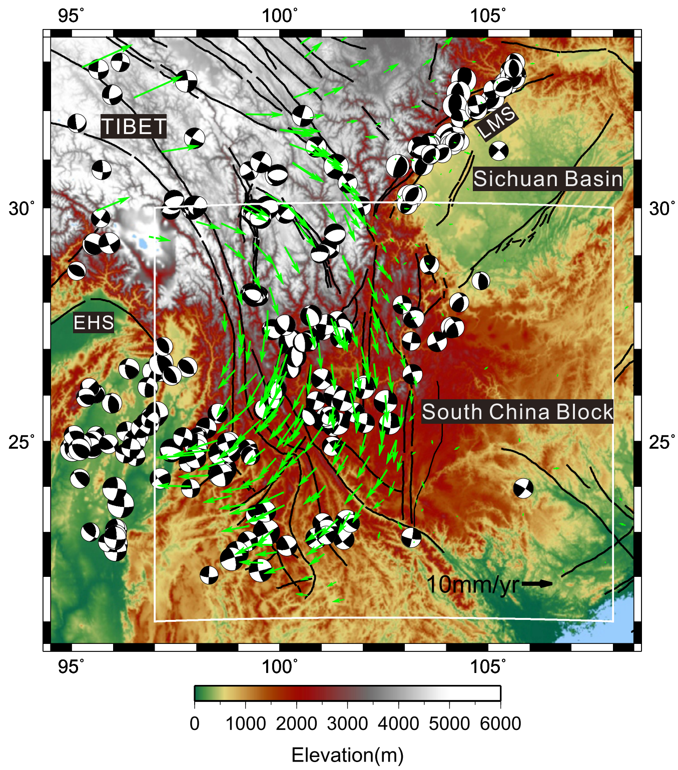

Fig. 1. Topographic map of Tibet and environments showing location of the study region (white box). Focal mechanism: from global CMT catalogue; Green arrows: GPS velocity field relative to the South China Block (Shen et al., 2005). EHS, Eastern Himalaya Syntaxis; LMS, Longmen Shan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the Global Positioning System (GPS) velocity field with respect to the SCB reference frame (Fig. 1), the clockwise rotation of the SYDB around the Eastern Himalaya Syntaxis (EHS) is particularly striking, suggestive of southeastward extrusion of crustal material from the interior of the plateau due to the convergence of India with Eurasia (Gan et al., 2007; Shen et al., 2005; Zhang et al., 2004). It is not yet well understood, however, why the GPS velocity field of this region changes its direction from southward to southwestward across ∼26°N, and even to westward farther south in western Yunnan. Due to the active and complex tectonic interaction of different blocks, our study region is characterized by the highest level of seismicity in Mainland China. Most earthquakes occurred along the main faults and their focal mechanism solutions are dominated by strike-slip offsets (Fig. 1). Since the 1970s, 8 large earthquakes with magnitudes ≥7.0 have occurred in this region. Most recently, on 3 August 2014, the magnitude 6.5 Ludian earthquake struck this region and caused significant casualties and damage; further understanding of the seismotectonics and crustal motion requires improved knowledge of the deep crustal structure.

In this study, we investigate LVZs beneath SE Tibet through joint inversion of P wave receiver functions and Rayleigh wave phase and group velocities. Using the newly deployed dense seismic array in SE Tibet, we seek to obtain a high-resolution three-dimensional (3D) image of crustal and upper-mantle shear-wave velocity (V_S) structure, with special attention to the detailed distribution of intra-crustal LVZs and the level of connectivity between them, since they are often regarded as diagnostic for zones of weak strength caused by the existence of fluids and/or partial melt (Liu et al., 2014; Nelson et al., 1996; Unsworth et al., 2005; Wei et al., 2001). Salient features of our models include: (1) two channels of LVZs in the mid-lower crust that wrap around the EHS, consistent with the clockwise pattern of crustal movement revealed by GPS measurements; (2) a geometric relationship in which the two channels bound with major strike-slip faults; and further that most large earthquakes in the region are located near the edge of the LVZs. These observational constraints provide fresh insights into the deformation and seismicity of SE Tibet.

2. Data

We used two independent data sets: P wave receiver functions and Rayleigh wave phase and group velocities. Receiver functions were computed from teleseismic P waveforms recorded at more than 300 temporary broadband seismic stations (Fig. 2b) from the ChinArray program during the time period from August 2011 to August 2012 in SE Tibet (Ding and Wu, 2013). These stations were deployed by the China Earthquake Administration and Nanjing University in September 2010, with an average interstation distance of ∼35 km. Each station consisted of a Guralp CMG-40 or CMG-3ESP seismometer and a Reftek 130 data acquisition system. Rayleigh wave phase and group velocities at periods of 10–70 s for each station were extracted from the results of the ambient noise tomography of Mainland China, which utilized more than 1000 stations mainly from the newly updated Chinese provincial seismic networks and several PASSCAL seismic arrays in Tibet and achieved a resolution of 1° in SE Tibet (Bao et al., submitted for publication). Fig. S1 (Supplementary material) shows several representative Rayleigh wave phase velocity maps and two V_s profiles from inversion of dispersion data along 25°N and 26°N, respectively.

3. Methods

3.1. Receiver functions

We selected 545 earthquakes with good signal-to-noise ratios, magnitudes ≥5 and epicentral distances between 30° and 90° (Fig. 3), and applied the time-domain iterative deconvolution method (Ligorria and Ammon, 1999) to calculate receiver functions. The time-domain deconvolution method applies a Gaussian low-pass filter to remove high-frequency noise. For each event, we set the Gaussian parameter to a value of 2.0 (corresponding to a corner frequency of 1 Hz). To obtain reliable receiver functions, we visually checked all the receiver functions at each station by Funclab (Eagar and Fouch, 2012), and discarded bad-quality events manually. A total of 10 702 radial receiver functions were finally obtained. Figs. S2–3 display individual radial and transverse receiver functions for stations 53 065 and 53 156, respectively. Fig. S4 shows a radial receiver function profile along 25°N, which reveals clear Pms conversions below most stations and strong negative intra-crustal phase conversions west of station 52 048. In this study, we only used radial receiver functions to resolve the isotropic velocity structure although the existence of transverse energy may be suggestive of a complex structure (such as azimuthal anisotropy or dipping interface) (Figs. S2–3).

3.2. Joint inversion

Joint inversion of receiver functions and surface wave dispersion has been established as an effective way of mapping V_s structure (Gilligan et al., 2014; Julià et al., 2000; Lawrence and Wiens, 2004; Liu et al., 2014; Shen et al., 2013; Sosa et al., 2014; Xu et al., 2013b). Here, we used a linear joint inversion method (Herrmann and Ammon, 2002; Julià et al., 2000), with a starting model based on AK135 (Kennett et al., 1995), to invert for the crustal and upper mantle V_s structure in SE Tibet. Receiver functions are mainly sensitive to velocity discontinuities, whereas