Gondwana Research 28 (2015) 121–132

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Tomographic imaging of the underthrusting Indian slab and mantle upwelling beneath central Tibet

Heng Zhang [a,*], Dapeng Zhao [b], Junmeng Zhao [a], Hongbing Liu [a]

[a] Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, PR China
[b] Department of Geophysics, Tohoku University, Sendai 980-8578, Japan

ARTICLE INFO

Article history:
Received 23 July 2013
Received in revised form 18 February 2014
Accepted 25 February 2014
Available online 28 March 2014

Handling Editor: A.R.A. Aitken

Keywords:
Tomography
Rift zones
Subduction processes
Mantle dynamics
Tibetan plateau
Earthquakes

ABSTRACT

To better understand the pattern of convergence between the Indian and Eurasian plates, we determine a high-resolution P-wave tomography of the crust and upper mantle under southern to central Tibet using a large number of high-quality data of local earthquakes and teleseismic events collected by the ANTILOPE-II and Hi-CLIMB projects. A significant low-velocity zone is detected above the northward underthrusting Indian slab beneath the Indus–Tsangpo suture, which may reflect fault zones or (incomplete) fragmentation as well as melts and/or fluids associated with the dehydration of the underthrusting Indian slab. The variations in the diving depth and extending distance of the Indian slab, under the ANTILOPE-II and Hi-CLIMB seismic profiles, may be caused by the differences in the viscosity contrast between the Indian slab and the surrounding mantle as well as strong structural heterogeneities in the upper mantle under the study region. Both high and low velocity anomalies are revealed in the mid- to lower crust under southern Tibet, which may reflect the complex pattern of crustal structure. The rifts in southern Tibet exhibit different velocity images, suggesting that different structures exist beneath those rifts.

1. Introduction

The Tibetan plateau (Fig. 1), comprising several terranes (Dewey et al., 1988), is the largest area with thickened crust (Royden et al., 2008) and high elevation (Fielding et al., 1994), and it is an ideal region to study continental dynamics. Although there are some discrepancies among the models for the tectonic evolution of the Tibetan plateau (e.g., Zhao and Morgan, 1987; Tapponnier et al., 2001; Maheo et al., 2002), these models hold the same viewpoint that the subduction of the Indian plate plays a key role in the evolution of the Tibetan plateau. However, the specific pattern of the subduction (or underthrusting) is still not well understood due to the restrictions of data and methods, even in central Tibet where more data have been collected than the other areas. Some important questions are, for example, where is the northern limit of the northward advancing Indian slab? Does it extend to the Bangong–Nujiang Suture, Jinsha River Suture or just the Main Boundary thrust (e.g., Priestley et al., 2006; Li et al., 2008; Hung et al., 2011; Zhang et al., 2012b)?

An obvious surface feature related to internal deformation of the Tibetan plateau is the north–south trending rifts. The formation mechanism of these rifts, however, remains controversial. The rifts may be confined only within the crust, or may extend to lithospheric depth (Yin and Harrison, 2000). The notion of vertical coherent deformation of the crust and upper mantle is supported by studies of earthquake focal mechanisms (England and Houseman, 1986). Normal faulting is likely to initiate when convective removal of the thickened lower lithosphere takes place (Molnar et al., 1993). Other explanations include a combination of eastward Tibetan extrusion and oblique convergence between the Indian and Eurasian plates (Tapponnier et al., 2001), and mantle upwelling induced by the delaminated lithosphere (Ren and Shen, 2008; Zhang et al., 2011).

Analyses of the seismic data recorded during the Hi-CLIMB project have resulted in several important findings on the structure beneath southern to central Tibet, such as crustal heterogeneity (Nabelek et al., 2009), pattern of the Indian slab underthrusting (Liang et al., 2011), and diversity of S-wave splitting between southern and northern Tibet (Chen et al., 2010). The main purpose of the present study is to image the three-dimensional (3-D) crustal and upper mantle structure under southern to central Tibet, using a large number of high-quality data recorded by the Array Network of Tibetan International Lithospheric Observation and Probe Experiments (ANTILOPE) project and the Hi-CLIMB project. Our present results shed new light on the 3-D seismic structure and dynamic evolution of the Tibetan plateau.

2. Data and method

We used arrival-time data of local, regional and teleseismic events recorded by two seismic arrays in central Tibet: ANTILOPE-II and Hi-CLIMB (Fig. 1). The Hi-CLIMB project has been well documented

* Corresponding author.
E-mail address: zhangheng415@itpcas.ac.cn (H. Zhang).

http://dx.doi.org/10.1016/j.gr.2014.02.012
1342-937X/

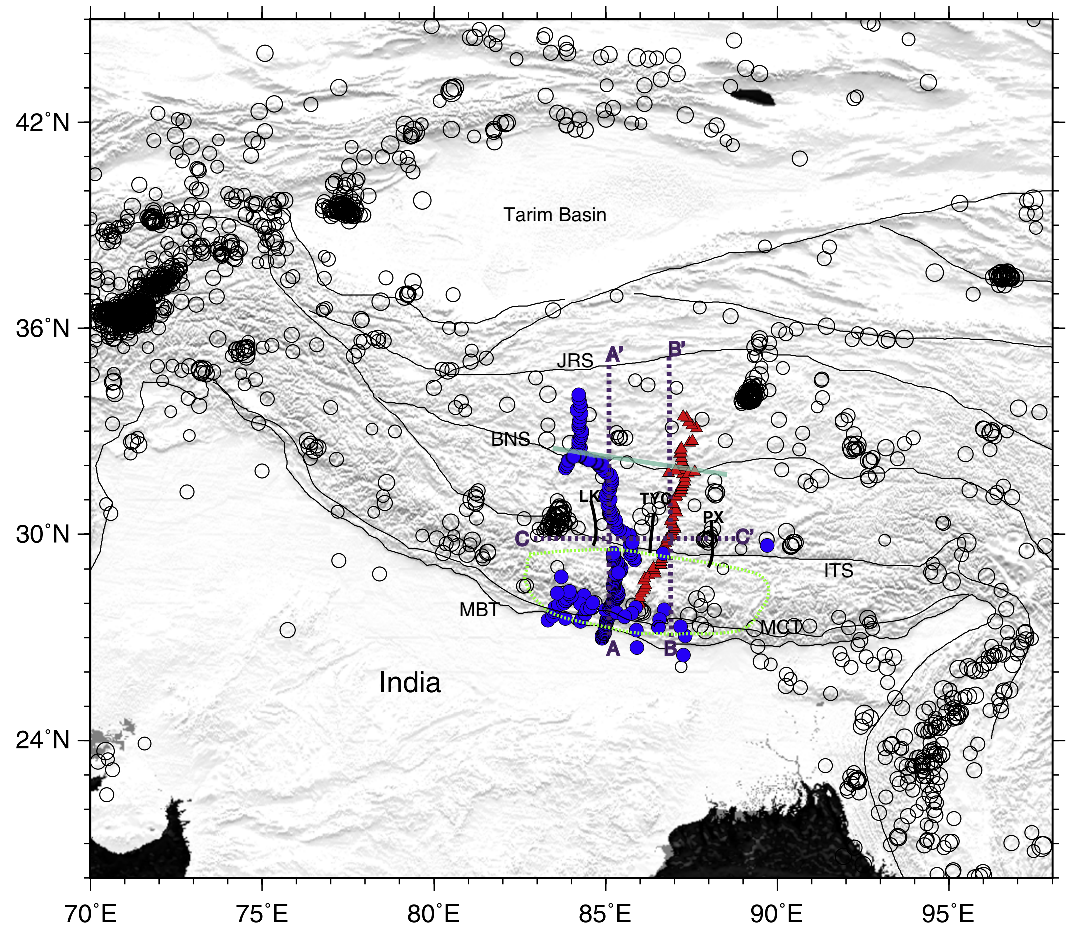

Fig. 1. Distribution of portable seismic stations of the ANTILOPE (red triangles) and Hi-CLIMB (blue dots) projects on the Tibetan plateau. The black lines denote the tectonic block boundaries in the region. MBT, the Main Boundary Thrust; MCT, the Main Central Thrust; ITS, the Indus–Tsangpo suture; BNS, the Bangong–Nujiang suture; JRS, the Jinsha River suture; LK, Lopu Kangri rift; TYC, Tangre Yum Co rift; PX, Pumqu–Xianza rift. The open circles denote the local and regional earthquakes used in this study. The purple dashed lines show the locations of vertical cross-sections in Fig. 7. The green dashed line shows the location of the interrupted low-velocity zones in southern Tibet. The cyan bold line indicates the northern limit of the descending Indian slab revealed by this study.

by several publications (e.g., Nabelek et al., 2009; Hung et al., 2011; Liang et al., 2011), whereas the ANTILOPE project has resulted in only one receiver-function (RF) study until now (Zhao et al., 2010). ANTILOPE was a project for investigating the seismic structure of the Tibetan plateau undertaken by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Our combined data set includes 231 portable seismic stations: 169 from the Hi-CLIMB and 62 from the ANTILOPE-II (Fig. 1). The ANTILOPE-II data were recorded from September 2005 to October 2006, while the Hi-CLIMB data were recorded from 2002 to July 2005.

The hypocentral parameters of the teleseismic events were determined by the United States Geological Survey (USGS), whereas those of the local and regional events were determined by the China Earthquake Network Center (CENC). We adopted the following criteria to select the local and regional seismic events for this study: (1) only earthquakes with magnitude (M) > 3.0 are selected; (2) the hypocentral parameters determined by the CENC are adopted, whereas poorly located events with a fixed focal-depth of 33 km are eliminated (the location accuracy and its effects are discussed in the next section); (3) the minimum epicentral distance of Pn wave is set to be 3°(because the Moho discontinuity under the present study region is deeper than that under the other areas) in order to distinguish Pn and Pg phases. Teleseismic events (M > 5.0) with epicentral distance from 30° to 90° are used in this study. All the selected events have over 8 P-wave arrivals, while over 90% of the events actually have more than 15 P-wave arrivals. As a result, our data set contains 30,605 P-wave arrivals from 1263 local and regional events (Fig. 1), and 54,468 first P-wave arrivals from 1578 teleseismic events (Fig. 2a). The ray path coverage is very good under the central part of our study region (Fig. 2b, c and d). In Fig. 2 the ray paths are shown schematically by straight lines connecting the hypocenters and seismic stations, but we actually used a 3-D ray tracing scheme (Zhao et al., 1992) to trace the rays precisely in the real computations. Note that the ray paths shown in the N–S and E–W vertical cross-sections in Fig. 2c,d are just part of the rays actually used: only the ray segments located with a 50-km width of profiles A–A′ and C–C′ (Fig. 1) are plotted.

By considering the influence of frequency-filtering on the accuracy of arrival-time pickings (1 s high-pass filter in this study), the picking error is estimated to be 0.1–0.3 s. Although applying the high or low pass filter could affect the onset points of arrivals, the actual difference in the arrival times is small, especially when the relative travel-time residuals are used. For more details of this issue, see Zhang et al. (2012a). Theoretical arrival times are taken into account for identifying the P-wave arrivals (red lines in Fig. 3). Moreover, all of the collected Pg, Pn and P phases are the first arrivals at different epicenter distances, so we could easily identify the onset point on the original seismograms. Note that the Pn wave mainly propagates the uppermost mantle directly below the Moho discontinuity, which is quite different from the direct Pg wave. Thus, the Pn wave travel times are strongly affected by the Moho geometry and 3-D velocity variation in the uppermost mantle. The Pg, Pn and P phases are generally distinguishable on the seismograms. The Pn waves exhibit smaller amplitudes (see the