Earth and Planetary Science Letters 459 (2017) 80–92

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Lithospheric structure across the northeastern margin of the Tibetan Plateau: Implications for the plateau's lateral growth

Xuzhang Shen [a,*], Mian Liu [b,c], Yuan Gao [d], Weijun Wang [d], Yutao Shi [d], Meijian An [e], Yuansheng Zhang [a], Xuzhou Liu [a]

[a] *Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou, 730000, China*
[b] *Department of Geological Sciences, University of Missouri, Columbia, MO 65211, USA*
[c] *Laboratory of Computational Geodynamics, Chinese Academy of Sciences, Beijing, China*
[d] *Institute of Earthquake Science, China Earthquake Administration, Beijing, China*
[e] *Institute of Geomechanism, Chinese Academy of Geological Sciences, China*

A R T I C L E I N F O

Article history:
Received 28 March 2016
Received in revised form 10 November 2016
Accepted 15 November 2016
Available online 1 December 2016
Editor: A. Yin

Keywords:
northeastern Tibetan Plateau
lithosphere deformation
P and S receiver functions
the Haiyuan and Liupan-shan faults
mantle flow

A B S T R A C T

Variations of lithospheric structure across the northeastern Tibetan Plateau and its bounding Asian blocks, the Alxa block to the north and the Ordos block to the east, are crucial for understanding the rise and lateral growth of the Tibetan Plateau. Using waveforms from high-density seismic arrays in northeastern Tibetan Plateau and the surrounding regions, we investigated the lithospheric structure with S- and P-wave receiver functions. The results show strong and relatively simple negative velocity gradients in the depth range of mantle lithosphere (∼70–150 km) under the Ordos and Alxa blocks, similar to those under typical stable continental lithosphere. In contrast, under northeastern Tibetan Plateau including its marginal regions, the velocity gradients are weak and diffusive for the mantle lithosphere, which may be explained by elevated temperature and presence of partial melts. The changes of lithospheric structures are sharp between the Tibetan Plateau and the bounding Ordos and Alxa blocks, suggesting that these two blocks have restricted the lateral growth of the Tibetan Plateau as rigid boundaries. However, across the northeastern corner of the Tibetan Plateau to the Yinchuan rift, the lithospheric mantle structures are similar, suggesting a lateral mantle flow from the Tibetan Plateau to the gap between the Ordos and the Alxa blocks. The crustal structures along this transition show evidence of lateral growth of the Tibetan Plateau. In particular, the edge of thickened crust and evidence of Moho superposition are found between the Haiyuan Fault and the Tianjin-shan Fault, which may have replaced the Haiyuan Fault as the front boundary of the laterally growing Tibetan Plateau in its northeastern corner.

1. Introduction

The rise and growth of the Tibetan Plateau are driven by the Indian–Eurasian continental collision 50–70 million years ago and the continued plate convergence ever since (Dewey et al., 1988; Yin and Harrison, 2000). How the Tibetan Plateau has grown in time and space, however, is unclear and controversial. Models that approximate the Asian lithosphere as a thin viscous sheet show that the indentation of a rigid Indian plate would cause gradual northward rise and growth of the Tibetan Plateau (England and Houseman, 1986). Other models emphasize lateral extrusion of Asian lithospheric blocks in accommodating the plate convergence (Tapponnier et al., 1982). Recent three-dimensional geodynamic models have shown that both lateral variations of lithospheric properties within the plateau and the boundary conditions could play a major role in the rise and growth of the Tibetan Plateau (Yang and Liu, 2013).

Geological evidence for the spatiotemporal growth of the Tibetan Plateau has been inconclusive (Yin and Harrison, 2000; Wang et al., 2014a, 2014b), but it is clear that northeastern Tibetan Plateau is one of the areas of concentrated crustal deformation through the late Cenozoic (Duvall and Clark, 2010; Wang et al., 2014a, 2014b). Yuan et al. (2013) have suggested that the rigid Indian indenter to the south and the Asian lithosphere to the north have largely confined the growth of the Tibetan Plateau in between, with only limited lateral expansion.

The different evolution models of the Tibetan Plateau predict distinct lithospheric deformation in the plateau's boundary zones. So the lithospheric structure across the northeastern margin of the Tibet Plateau, bounded by the Alxa and the Ordos blocks (Fig. 1),

* Corresponding author.
E-mail address: shenxzh@gmail.com (X. Shen).

http://dx.doi.org/10.1016/j.epsl.2016.11.027

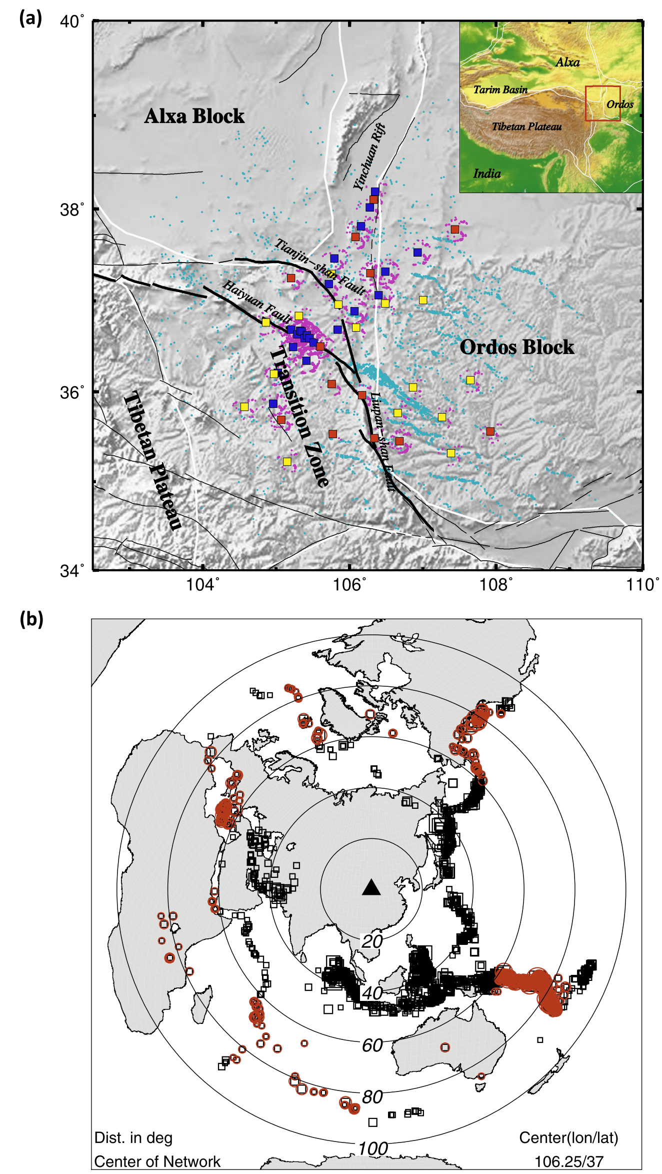

Fig. 1. Map of stations and teleseismic events. (a) Station locations on the topographic relief map. Red squares: permanent stations belong to the Gansu and Ningxia seismic network; blue squares: Haiyuan seismic array deployed by the Institute of Earthquake Science, China Earthquake Administration (CEA); yellow squares: Qingling seismic array deployed by the Institute of Geomechanics, Chinese Academy of Geological Sciences. Thick white lines denote the boundaries of major tectonic blocks. Gray lines show the main faults. The Haiyuan, Tianjin-shan and Liupan-shan faults are highlighted with thicker lines. Pink and azury dots represent the location of P-to-S pierce points at 50 km depth and S-to-P pierce points at 90 km depth, respectively. Inset map shows the study area. (b) 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 colors in this figure, the reader is referred to the web version of this article.)

are crucial for understanding how the plateau has grown. Some studies using receiver functions have suggested that the Asian lithosphere (i.e., North China craton) has subducted as a coherent slab underneath northern and central Tibet (Kumar et al., 2006; Ye et al., 2015). But the tomographic results using data from a more densely distributed network of seismic stations by Liang et al. (2012) suggested that the high-velocity bodies below central Tibet represent fragments of the Indian slab, rather than a coherent Asian mantle lithosphere from the north. Using seismic data from the permanent stations in northeastern Tibetan Plateau, Shen et al. (2015) imaged the lithosphere–asthenosphere boundary (LAB) in this region and found no significant underthrusting of the Asian lithosphere beneath northern Tibetan Plateau. However, the coverage of permanent stations in this region was not dense enough to image detailed variations of crustal and mantle lithospheric structures across the northeastern margin of the Tibetan Plateau, which are needed to determine whether and how the Tibetan Plateau has grown laterally.

In this study we used waveform data from two high-density temporary seismic arrays in northeastern Tibetan Plateau, in addition to the permanent seismic stations (Fig. 1a), to image the lithospheric structure using both S and P receiver functions. Our results show no clear evidence of significant lateral expansion of the Tibetan Plateau except across its northeastern corner into the Yinchuan rift, under which the mantle lithospheric structures are similar to those under the Tibetan Plateau, and the crustal structures across this boundary zone show clear signs of shortening and thickening.

2. Tectonic setting

Our study region is the northeastern corner of the Tibetan Plateau where it meets the Ordos and Alxa blocks (Fig. 1a). The Ordos block is a relic of the North China craton, whose eastern part was thermally reactivated in the Mesozoic (Zhu et al., 2012). The Ordos block has been tectonically stable throughout the Cenozoic (Zhang et al., 1998). The Alxa block is part of the old Asian lithosphere consisting mainly of early Precambrian basement overlain by Cambrian to middle Ordovician strata (Song et al., 2006). The Haiyuan Fault, which connects with the Qilian-shan orogen and joins the Altyn Tagh strike-slip faults further to the west, bounds the Tibetan Plateau from the Alxa block. Near its eastern terminal, the Haiyuan Fault branches into the Tianjin-shan Fault (Fig. 1a), whose age of activation is unclear. The west part of the Tianjin-shan Fault is left-lateral slip; it changes to thrust along the SEE direction around ∼105.2°E. The Tianjin-shan fault is thought to merge at depth with the Haiyuan Fault (Cavalié et al., 2008).

The Haiyuan and Tianjin-shan faults merger at their eastern ends with the Liupan-shan thrust fault, which separates the Tibetan Plateau from the Ordos block. The initial thrusting on the Liupan-shan Fault started before 7.3–8.2 Ma (Zhang et al., 2006), generally interpreted as indicating the age that the laterally expanding Tibetan Plateau reached the Ordos block (Wang et al., 2014a, 2014b).

The Alxa and the Ordos blocks are separated by the Yinchuan rift basin, part of the circum-Ordos rift system that initiated in the past few million years (Zhang et al., 1998). From the Yinchuan rift to the eastern margin of the Tibetan Plateau is the so called South–North Seismic Belt in China marked by intense seismicity.

3. Data and method

In this study, we used the seismic waveforms from two high-density portable arrays across the northeastern margin of the Tibetan Plateau: 1) the Haiyuan seismic array of 24 stations deployed by the Institute of Earthquakes, China Earthquake Administration, during December 2012–October 2014, and 2) the Qingling seismic array of 15 stations, deployed by the Institute of Geomechanics of the Chinese Academy of Geological Sciences during February 2011–February 2013. To further improved the coverage we also used data recorded during January 2008–December 2011 from 13 permanent stations of the Gansu and Ningxia seismic networks of China Earthquake Administration (CEA). Fig. 1a shows the map of the station locations. All the 52 stations used in this work are equipped with broadband seismometers.