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Anisotropic regime across northeastern Tibet and its geodynamic implications

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ABSTRACT

A dense linear array of 38 broadband seismograph stations was deployed to traverse the northeastern margin of Tibetan plateau (NE Tibet). Shear wave splitting measurements show significant lateral variations of seismic anisotropy across NE Tibet. Combined with previous tomography studies, the SKS travel-time analysis along the array supports the inference that a cold/rigid Asian lithosphere resides beneath the Qilian and Alxa blocks while a hot/soft Tibetan lithosphere resides beneath the Songpan-Ganzi (SPGZ) and Kunlun-West Qinling (KL-WQL) blocks. The observed variations of anisotropy along the array indicate the important role the major faults have been playing in the process of lithospheric deformation in NE Tibet. The West Qinling fault (WQLF) is reckoned as the boundary between the Tibetan lithosphere and the Asian lithosphere in the study area. The Kunlun fault to West Qinling fault (KLF-to-WQLF) zone may constitute a boundary accommodating the eastward extrusion of the Tibetan lithosphere, with the rigid Asian lithosphere in the north barrier to the northeastward tectonic flow of central-eastern Tibet. A significant character of two-layer anisotropy was identified in the Qilian orogen, which was inferred to be associated with the low velocity layer (LVL) acting as a thrust decollement in the mid-to-lower crust. A thorough analysis involving crustal anisotropy and the regional XKS splitting results in NE Tibet, in association with the crustal LVL feature, indicates that decoupling deformation may dominate the lithosphere beneath the Qilian orogen while coherent deformation may dominate the lithosphere beneath the WQL and SPGZ blocks. Anisotropy beneath the Qilian orogen seems consistent with recent deformation under the boundary forces related to possible lithosphere underthrusting from its northern margin. Our shear wave splitting analysis, combined with published results, reflects a regional anisotropic regime that emphasizes the dominance of eastward extrusion of lithospheric blocks on the present-day deformation in NE Tibet.

1. Introduction

The continental collision of the northward-drifting Indian plate and the relatively stationary Asian plate ~55 million years ago caused formation of the Tibetan plateau and continued to propel the growth and expansion of this plateau through on-going underthrusting of the Indian plate. As the leading edge of the plateau's northeastward expansion, the northeastern margin of Tibetan plateau (NE Tibet) are currently undergoing shortening/thickening and topographic uplift as being incorporated into the plateau (Meyer et al., 1998). To clarify the mode of lithospheric deformation in this boundary area is thus a key issue for understanding the mechanism of plateau growth and expansion. In addition to imaging the lithospheric structure in a direct way by using seismological methods such as receiver function and tomography, seismic anisotropy is another important facet that serves to examine deformation in the lithosphere and upper asthenosphere.

Shear wave splitting provides us with an effective method to identify the seismic anisotropy in the upper mantle. The method gives the measurements of the delay time between the two orthogonally polarized quasi-shear waves and the polarization direction of the fast quasi-shear wave (Silver, 1996; Savage, 1999). Quite a few shear wave splitting measurements have been carried out in NE Tibet, most of which are base on dataset of regional seismic networks (e.g., Li et al., 2011a,b; Zhang et al., 2012b; León Soto et al., 2012). These previous studies generally tended to support the vertically coherent deformation of the lithosphere (England and Houseman, 1986; Holt, 2000; Flesch et al., 2005; Wang et al., 2008) while Li et al. (2011b) argued for significant decoupling between the crust and mantle in favor of crustal flow (Clark and Royden, 2000; Royden et al., 2008).

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The published results based on regional seismic networks show us an overview of the regional anisotropy. Herein we add new data from a dense linear array to the dataset of observations to show the detailed knowledge of lateral variations of seismic anisotropy across NE Tibet. This is of great significance for more thorough understanding of deformation in this boundary area. Results of shear wave splitting based on a 550 km long and dense broadband seismic profile are present here. The profile traverses the entirety of NE Tibet and extends northward to the southern Alxa block (the westernmost NCC) (Fig. 1). We inspected the lateral variations of seismic anisotropy along the profile in detail and attempted to gain a new insight into the lithospheric deformation in NE Tibet, by integrating our analysis on anisotropy with other correlated geological/geophysical information.

2. Data and methods

We deployed 38 three-component broadband seismograph stations in NE Tibet in October 2011 and kept them in good running for 17 months till March 2013. Each of the stations was equipped with a Guralp 3T/3ESP sensor (32 Guralp 3T and 6 Guralp 3ESP) and a Reftek-130 data acquisition system. This observation profile is oriented NNE with an average station interval of ~15 km (Fig. 1).

Shear wave splitting analysis was applied on the teleseismic seismograms of earthquakes with magnitudes $Ms \geq 5.3$, using the procedure developed by Wüstefeld et al. (2008). A wide epicentral distance range 85–180° was set so as to involve several classic core phases including SKS, PKS and SKKS (denoted as XKS hereafter) that were often used in the shear wave splitting measurements. The minimum energy method (SC) (Silver and Chan, 1991) and the rotation-correlation method (RC) (e.g., Bowman and Ando, 1987; Levin et al., 1999) were simultaneously implemented in the procedure to identify the best fitting splitting parameter ϕ (fast axis) and δt (delay time) in a grid-search approach. The grid-search was performed in the ϕ–δt domain by minimizing the amount of energy on the reconstructed transverse (T) component (SC method) or maximizing the cross-correlation coefficient between the waveforms on the corrected fast and slow components (RC method). All the seismograms were band-pass filtered with a third-order Butterworth filter before the shear wave splitting measurements. Here we applied a weak filter of 0.02–1 Hz on most of the seismograms while others are 0.01–0.4 Hz, 0.01–0.3 Hz or 0.02–0.2 Hz, all of which include the dominant period of XKS wave. In the measurements, only XKS phases with high signal-to-noise ratio on the original seismograms (e.g., Fig. 5A and B) were selected for analysis and a measurement result was reserved if the corrected transverse (T) component has little amplitudes (approximate to a straight line) and the sub-elliptical particle motion has been linearized after splitting correction (Fig. 2). Given that the SC technique is more stable relative to the RC method (Wüstefeld and Bokelmann, 2007), we use the SC results for presentation in this paper but inspected their consistencies with the RC results to enhance the reliability during the processing. Examples of the SC measurements on the three XKS phases at three stations are presented in Fig. 2.

3. Results

3.1. Lateral variations of splitting parameters across NE Tibet

We finally obtained a total of 218 pairs of well-defined XKS splitting parameters (Supplementary Table S2) from high-quality measurements on the seismograms of 78 teleseismic events (Fig. 1C, Supplementary Table S1). The epicenters show a relatively good azimuthal coverage based on which we divided the events into three back-azimuthal (BAZ) ranges: BAZ-1 (90–180°), BAZ-2 (−45–45°) and BAZ-3 (180–315°), as shown in Fig. 1C. We then stacked the splitting

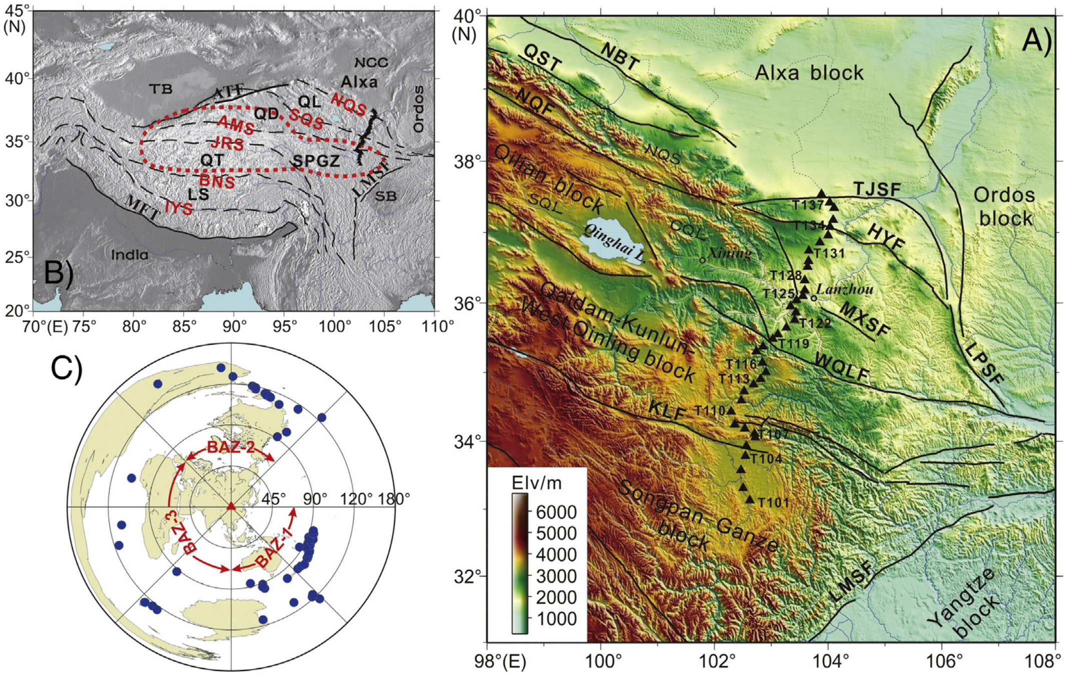

Fig. 1. (A) Topographic map of NE Tibet, showing locations of the seismic stations (black triangles). Black solid lines indicate main faults (after Taylor and Yin, 2009). (B) Tectonic sketch of the Tibetan plateau. Black triangles mark seismic stations. Red dashed line marks region of high attenuation of seismic waves (from Zhao et al., 2011). (C) Epicentral distribution of teleseismic events (filled blue circles) used in this study. Three back-azimuthal (BAZ) ranges: BAZ-1 (90–180°, involving events from the southwestern Pacific), BAZ-2 (−45–45°, involving events from the western coast of American continent) and BAZ-3 (180–315°, involving events from middle Atlantic) are marked. Blocks are LS: Lhasa; QT: Qiangtang; SPGZ: Songpan-Ganzi; QD: Qaidam-Kunlun-West Qinling; QL: Qilian (Qilian Shan); NCC: North China craton; TB: Tarim basin; SB: Sichuan basin. IYS: Indus-Yalu suture; BNS: Bangong-Nujiang suture; JRS: Jinsha River suture; AMS: Animaqing suture; SQS: South Qilian suture; NQS: North Qilian suture; MFT: Main frontal thrust; ATF: Altyn-Tagh fault; LMSF: Longmenshan fault; KLF: Kunlun fault; WQLF: West Qinling fault; MXSF: Maxianshan fault; HYF: Haiyuan fault; TJSF: Tianjingshan fault; NQF: North Qilian fault; LPSF: Liupanshan fault; QST: Qilian Shan frontal thrust; NBT: North Border thrust (Gao et al., 1999).