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Insight into NE Tibetan Plateau expansion from crustal and upper mantle anisotropy revealed by shear-wave splitting

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ABSTRACT

The northeastern Tibetan plateau margin is the current expansion border, where growth of the plateau is ongoing. We analyze shear-wave splitting at ChinArray stations in the NE Tibetan Plateau and its margin with the stable North Chine Craton. The measurements provide important information on the seismic anisotropy and deformations patterns in the crust and upper mantle, which can be used to constrain the expansion mechanism of the plateau. Along the margin and within the craton, the dominant NW–SE fast polarization direction (FPD) is NW–SE, subparallel to the boundary between the plateau and the North China Craton. The shear-wave splitting measurements on the NE Tibetan Plateau itself generally reflect two-layer anisotropy. The lower-layer anisotropy (with NW–SE FPDs) is consistent in the whole region and FPDs are the same as those in the North China Craton. The upper-layer FPDs are parallel to crustal motion rather than surface structures within the high plateau. The two-layer anisotropy implies the presence of deformed Tibetan lithosphere above the underthrusting North China Craton. The NE Tibetan shows similar deformation patterns at the surface (inferred from GPS) and within the mantle (inferred from shear-wave splitting), but significant crustal anisotropy (parallel to crustal motion) requires mid-lower crustal channel flow or detachment to drive further tectonic uplift of the plateau.

1. Introduction

The Tibetan Plateau has been forming in response to the Indo-Asian collision since ∼50 Ma (Fig. 1a) (e.g., Royden et al., 2008; Yin and Harrison, 2000; Zhu et al., 2015). Many different models have been proposed for its evolution, which generally include discrete intracontinental subduction coupled with lateral extrusion along major strike-slip faults (Tapponnier et al., 2001), underthrusting of Indian and Asian lithosphere beneath the Tibetan Plateau (e.g., Kind et al., 2002; Ye et al., 2015; Zhao et al., 2010, 2011), distributed shortening of the Asian crust or lithosphere (e.g., England and Houseman, 1986; Zhang et al., 2004), and lateral channel flow in the mid-lower crust (Clark and Royden, 2000; Royden et al., 1997, 2008). These models predict different deformation patterns and thus different patterns of seismic anisotropy in the crust and upper mantle (Silver, 1996).

Seismic anisotropy arises from preferred orientations of minerals or micro-structures in response to shearing (Karato et al., 2008). Dislocation creep aligns the constituent minerals such as amphibole and mica in the mid-lower crust and olivine in the upper mantle, causing lattice preferred orientation (LPO) (Ji et al., 2015; Karato et al., 2008). The fast orientation is generally parallel to the axis of maximum extension, which is aligned with the direction of maximum shear for large shear strains. It is often found to be subparallel to active strike-slip faults and orogenic fronts. For simple mantle flow in the asthenosphere, the fast orientation generally reflects the mantle flow direction due to shearing in the asthenosphere (Karato et al., 2008). In the special case of channelized plastic flow in the mid-lower crust, the relationship between the fast orientation and the flow direction depends on the differential stress level and temperature (Ko and Jung, 2015). For the high differential stresses and high temperatures under the Tibetan

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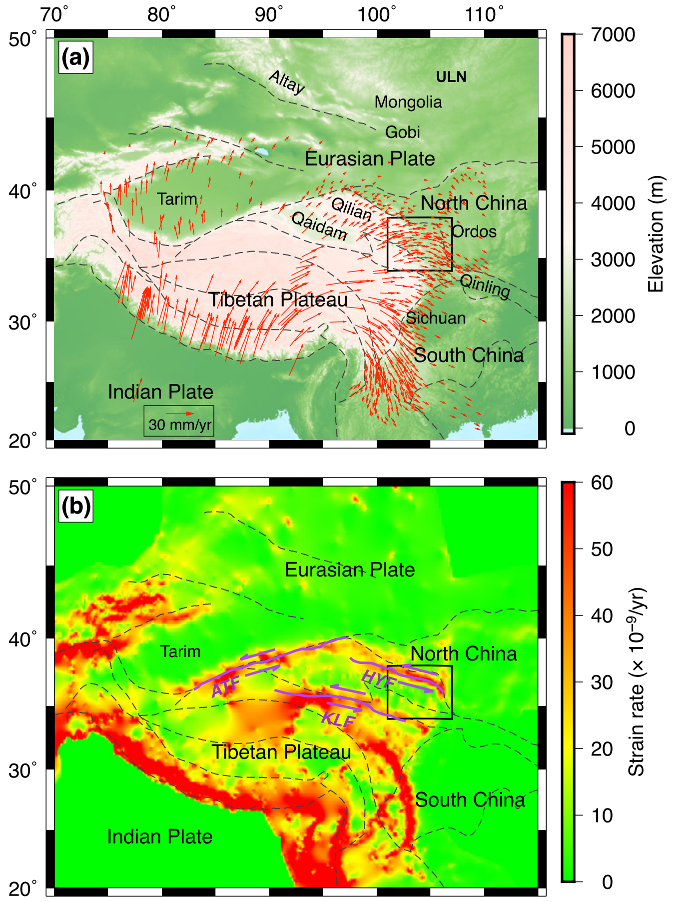

Fig. 1. (a) Tectonics in and around the Tibetan Plateau. Dashed lines denote major tectonic boundaries. Red arrows denote GPS observations relative to stable Eurasia (Gan et al., 2007). (b) The strain rates inverted from GPS measurements in and around the Tibetan Plateau (Kreemer et al., 2014). Purple lines show the major sinistral faults in the NE Tibetan Plateau, i.e., the Altyn-Tagh Fault (ATF), the Kunlun Fault (KLF), and the Haiyuan Fault (HYF). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Plateau, the fast orientation is sub-parallel to the flow direction (Ko and Jung, 2015).

The different models introduced earlier produce different seismic anisotropy patterns in the crust and upper mantle beneath the Tibetan Plateau. Lateral extrusion along strike-slip faults would induce extensive deformation along the boundary faults, hence the anisotropy near the boundary would be expected to be much stronger than in the block interior. In contrast, the distributed shortening model suggests only slowly varying vertically coherent anisotropy in the whole region, both near the boundary and in the interior. Lithospheric underthrusting would introduce another layer of anisotropy beneath the deformed Tibetan lithosphere and thus give rise to multi-layer anisotropy. Finally, lateral channel flow in the mid-lower crust would also produce similar two-layer anisotropy, but the anisotropy would be closely related to the channelized ductile deformation rather than the lithospheric deformation caused by the India–Asian convergence.

In this study, we analyze data from the ChinArray project, which deployed hundreds of broadband stations with a lateral spacing of ∼20–30 km across the NE Tibetan Plateau from 2013 to 2016. The dense array covered the eastern Qilian Orogen and West Qinling as well as the western North China Craton surrounding the NE Tibetan Plateau (Fig. 1a). The unprecedented high-quality data makes it possible to image high-resolution structures in the crust and upper mantle in this region. The NE Tibetan Plateau is of particular interest because here it interacts with the stable Eurasian Plate (e.g., North China Craton) (Fig. 1). Lateral extrusion along large sinistral strike-slip faults such as the Altyn-Tagh Fault, the Kunlun Fault, and the Haiyuan Fault probably plays an important role in shaping the crustal tectonics in the expansion frontier (e.g., Burchfiel et al., 1989; Cheng et al., 2015; Duvall et al., 2013; Yuan et al., 2013). However, extensive thrust systems, which have developed mainly in the Qilian Shan thrust belt and to a minor degree also in West Qinling and the Liupan Shan, could have accumulated more than 50% of the crustal strain in the Cenozoic (e.g., Cheng et al., 2015; Craddock et al., 2014; Gao et al., 2013; Lease et al., 2012; Yin et al., 2008; Zuza et al., 2016). The strain rates inverted from continuous GPS measurements are much higher near these faults and thrust belts than adjacent regions (Fig. 1b) (Kreemer et al., 2014).

Compared with the well documented crustal structures and tectonics, the structures and especially deformations in the upper mantle are less clear. Previous studies used shear-wave splitting method to reveal the general pattern of seismic anisotropy below the NE Tibetan Plateau (León Soto et al., 2012; Li et al., 2011; Wang et al., 2008, 2016; Wu et al., 2015; Ye et al., 2016; Zhang et al., 2012). In general, the dominant fast orientations of seismic anisotropy follow the large-scale trend of the tectonic boundary. Pms splitting (conversions from teleseismic P to S waves at the Moho) at permanent stations shows some notable variations that were interpreted as evidence for mid-lower crustal flow (e.g., Kong et al., 2016; Shen et al., 2015). These studies were based on sparse station sets, so they cannot provide details of the lateral variations especially in different blocks and their boundaries. Chang et al. (2017) measured shear-wave splitting with the data recorded by the ChinArray project in NE Tibetan Plateau. However, they assumed single-layer anisotropy and did not consider potential multi-layer anisotropy. In this study, we analyzed teleseismic shear-wave splitting and obtained reliable splitting parameters to study seismic anisotropy in the crust and upper mantle in the NE Tibetan Plateau. We measured and compared the shear-wave splitting in different tectonic units, especially contrasting the measurements close to the tectonic boundaries or faults from those farther away. Furthermore, we carefully analyzed the measurements for backazimuthal variations to reveal two-layer anisotropy, which indicates depth-dependency of the deformation pattern. These observations provide new information on the crustal and upper mantle deformation patterns and thus help us to better understand the tectonic models of the Tibetan Plateau evolution.

2. Data and methods

2.1. Data

The waveforms were recorded by 173 temporary broadband stations (Fig. 2a) deployed by the ChinArray project from October 2013 to March 2015. Each station was equipped with a Guralp CMG-3EPC three-component broadband seismometer and a Reftek-130 digitizer, all sampling at 100 Hz. We selected events with magnitudes greater than 5.5 and epicentral distances of 85°–150°. We visually inspected the core phases SKS, SKKS, and PKS phases and selected clear arrivals in the waveforms of 92 events (Fig. 2b) for further analysis. Most of the events are located near the Tonga and New Zealand subduction zones and in North America. Some mid-oceanic ridge events in the Atlantic and Indian oceans increase the back-azimuthal coverage.

2.2. Methods

Shear-wave splitting analysis describes the phenomenon that a shear-wave splits into two perpendicular waves traveling with different speeds. By analyzing the horizontal components of one