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Seismic anisotropy beneath the southern Ordos block and the Qinling-Dabie orogen, China: Eastward Tibetan asthenospheric flow around the southern Ordos

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ABSTRACT

SKS wave splitting analysis is performed to estimate the seismic anisotropy in the upper mantle using teleseismic data recorded by a temporary seismic array of 180 stations called SOSArray deployed in the southern Ordos block and the Qinling-Dabie orogen. The most important finding is that large delay times with NW-SE fast polarization directions in the northeastern Tibet are continuous across the boundary into the southwestern part of the Ordos block, where the SKS wave splitting results are significantly different from those in the rest of the Ordos block. Based on our SKS wave splitting results in addition to the results from previous studies, we propose an asthenospheric flow model for the eastward extrusion of the Tibetan upper mantle. The model consists of two corner flows around the southwestern corner and the southeastern corner of the Ordos block and the eastward flow along the Weihe graben and the Qinling-Dabie orogen for the escaping Tibetan upper mantle. Finally, the clockwise turning flow of the asthenosphere around the southwestern corner of Ordos block has currently extended laterally into the interior of the Ordos block, suggesting that the thick cold lithospheric root of the southwestern Ordos block there is currently being replaced with hot Tibetan asthenosphere at depths, that is, we observed an on-going process of thermal erosion of a cratonic lithosphere by lateral hot asthenospheric flow.

1. Introduction

It is widely believed that the India–Eurasia continental collision since the early Cenozoic has caused both significant crustal shortening (England and Houseman, 1986; Houseman and England, 1996) which leads to the construction of the Tibetan Plateau (Molnar, 1988; Yin and Harrison, 2000) and the lateral extrusion of crust and upper mantle materials from the Tibetan Plateau (Tapponnier et al., 1982; Peltzer and Tapponnier, 1988; McNamara et al., 1994). Recently the northeastward expansion of the Tibetan Plateau has been the focus of extensive studies (Meyer et al., 1998; Tapponnier et al., 2001; Zhang et al., 2004; Liu et al., 2007; Fan et al., 2015) since its interaction with the relatively stable Ordos block plays an important role in controlling the large-scale tectonics in East Asia.

The Ordos block, together with the Alxa block to the north, resists the northeastward expansion of the Tibetan Plateau, leading NW-SE trending lithospheric extension in the northeastern Tibetan Plateau (Chang et al., 2011). To the south, the Sichuan Basin, another cratonic block of the South China Craton, effectively blocks the eastward movement of the Tibetan crust and forces the Tibetan crust and mantle to turn sharply to the south, which has been observed by GPS measurements and SKS wave splitting observations (Shen et al., 2000; Wang et al., 2003).

As the suture zone of the North China Craton and the South China Craton, the thickness of the lithosphere of the Weihe graben and the Qinling-Dabie orogen is thin compared with that of the two old cratons of the Ordos block and the Sichuan Basin (An and Shi, 2006; Huang and Zhao, 2006; Huang et al., 2009). It has been postulated by number of studies that the Weihe graben and the Qinling-Dabie orogen could provide a channel for the eastward extrusion of the Tibetan upper mantle (Huang et al., 2008; Chang et al., 2011; Li et al., 2011).

Important questions remain such as how the northeastward expansion of the Tibetan Plateau controls the lateral asthenospheric flow and if there is a channel beneath the Weihe graben and the Qinling-Dabie orogen for the eastward extrusion of the Tibetan upper mantle. To explore these important questions here we have untilized SKS wave splitting analysis on teleseismic data collected

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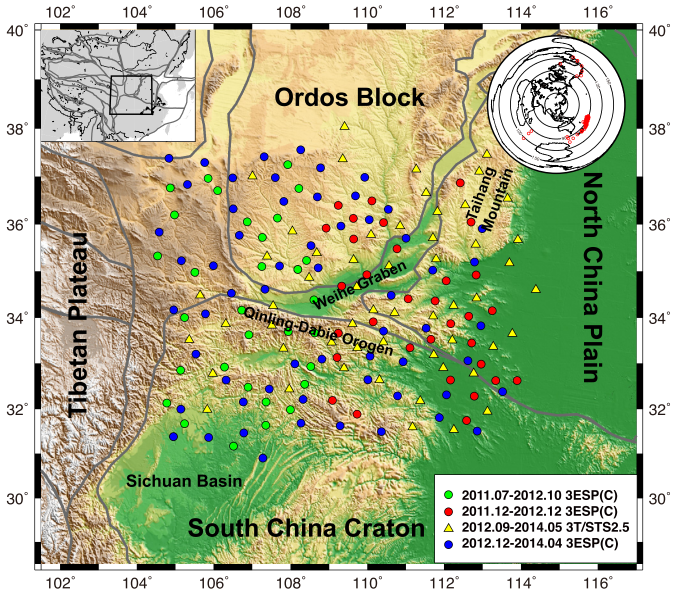

Fig. 1. Map of the temporary seismic array and tectonic settings. The map in the top left corner is a map of China, and the black rectangle encloses the research region; the map in the top right corner is the distribution of events used in SKS splitting analysis. The gray lines are boundaries of active tectonic blocks in China (Zhang et al., 2003). The circles and triangles with different colors represent seismic stations with different types of seismometers and different recording periods.

by a temporary seismic array in the region to image the upper mantle seismic anisotropy beneath the southern Ordos block and the Qinling-Dabie orogen. Based on the SKS wave splitting results along with results from previous studies we propose an asthenospheric flow model for the extrusion of the Tibetan upper mantle and the model consists of two corner flows around the southwestern corner and the southeastern corner of the Ordos block and the eastward flow along the Weihe graben and the Qinling-Dabie orogen.

2. Data and method

When a shear wave travels through an anisotropy media, it splits into two perpendicularly polarizing quasi-shear waves with different velocities. SKS wave converting from P wave to S wave at the core-mantle boundary (CMB) is one of the ideal phases utilized to study the anisotropy beneath the seismic station (Silver and Chan, 1991). The delay time of the two quasi-shear waves indicates the anisotropy intensity, which is the integration from the conversion point to the surface. As the contribution of the delay time from the crust and the lower mantle is much smaller than that from the upper mantle, results of SKS wave splitting mainly correspond to the seismic anisotropy in the upper mantle, which is generated by the lattice preferred orientation (LPO) of minerals such as olivine (Savage, 1999). SKS wave splitting analysis has been widely used to study the seismic anisotropy beneath continents (Silver, 1996; Fouch and Rondenay, 2006; Liu et al., 2014; Wang et al., 2014).

Peking University and Chinese Academy of Geological Sciences (CAGS) deployed a temporary seismic station array named SOSArray containing totally 180 broadband and ultra-broadband portable seismometers around the southern Ordos block and the Qinling-Dabie orogen from July 2011 to May 2014 (Fig. 1). The teleseismic data from this array was utilized to explore the seismic anisotropy beneath these stations using SKS wave splitting method. Earthquakes with Mb $\geq$ 5.5 at epicentral distance between 85° and 120° were analyzed in our study (Fig. 1). Besides, SKKS waves of teleseismic events with epicentral distance between 95° and 130° were also analyzed, but qualified results were very few. A band-pass filtering between 0.1 Hz and 0.5 Hz or between 0.05 Hz and 0.4 Hz was applied to the seismic data based on the main frequency of the SKS wave.

The software of SKS wave splitting analysis is semiautomatic and modified based on SplitLab (Wüstefeld et al., 2008). STA/LTA ratio analysis (Earle and Shearer, 1994) is performed to detect whether clear SKS waves exist. The eigenvalue method (Silver and Chan, 1991) is adopted to obtain the fast polarization direction ϕ and the delay time δt. The optimum time window of the measurement is the one containing the main energy of the SKS wave and the result changes little with moving, extending and shortening the time window. Then, the primary results are filtered according to the cross-correlation coefficient of the corrected fast and slow waves and the angle between the direction of the corrected polarization and the back azimuth. To verify the results, the filtered results are checked by hand mainly based on the quality of the waveforms and the ellipticity of the original and corrected particle motions, as well as the contour maps of the eigenvalue. Fig. 2 shows an example of a SKS wave splitting result of an event (2013/04/02 14:34:55) recorded by station SOD229.

3. Results

Stations with 2 or more results of SKS wave splitting are plotted as blue bars in Fig. 3. Also shown as brown bars here are the SKS wave splitting results from several PKU portable arrays including the one across the south boundary of the Ordos block at Baoji (Tang et al., 2015) and the two arrays at the west boundary at Fenyang and Linfen within the Shanxi graben (Yu et al., 2016), and a portable array in the northeastern Tibetan Plateau deployed by Peking University in collaboration with University of Missouri (León Soto et al., 2012). Single-layer anisotropy is assumed in this study, since no azimuthal variation of splitting parameters with a $\pi/2$ periodicity, a diagnostic of double-layer anisotropy with horizontal axis (Silver and Savage, 1994), is observed.

While our results show in general the east–west trending fast polarization with large delay times along the Qinling-Dabie orogen as previous SKS wave splitting studies in this region, the most interesting observation in this study is the significant difference in SKS wave splitting parameters between the southwestern and the rest of the Ordos block.

In the central and east-central Ordos block, the fast polarization directions are not uniform, and the delay times are lower than 0.70 s in general that is consistent with the cratonic nature of the Ordos block as expected. In the southwestern part of the Ordos block, however, we observed significant SKS wave splitting at the stations with delay times from 0.90 s to 1.23 s and fast polarization directions of NW-SE. These SKS wave splitting results are very similar to the stations to the west of Ordos block in terms of both fast polarization directions and delay times. It appears that the geological boundary of the Ordos block here does not separate the SKS wave splitting results, indicating the asthenospheric flow here continues through this western boundary of the Ordos block.

Along the Qinling-Dabie orogen and the Weihe graben, the fast polarization directions are WNW-ESE in general, parallel to the strike of the orogenic belt, and the delay times vary from 0.60 s to more than 2.00 s (some events recorded by station QS15). To the east of the Ordos block and the Qinling-Dabie orogen, the delay times are constantly larger than 1.00 s, and the fast polarization directions separate into two parts: WSW-ENE in the north and WNW-ESE in the south, and become WNW-ESE and W-E respectively further to the east. In the northern margin of the Sichuan Basin, the fast polarization directions of SKS wave are nearly W-E and the delay times are mostly below 0.70 s.