Fossilized lithospheric deformation revealed by teleseismic shear wave splitting in eastern China

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ABSTRACT

Global mantle convection significantly impacts the processes at Earth's surface and has been used to gain insights on plate driving forces, lithospheric deformation, and the thermal and compositional structure of the mantle. Upper-mantle seismic anisotropy has been widely employed to study both present and past deformation processes at lithospheric and asthenospheric depths. The eastern China region was affected by extreme mantle perturbation and crust-mantle interaction during the Mesozoic, leading to large-scale destruction of the cratonic lithosphere, accompanied by widespread magmatism and metallogeny. Here we use teleseismic shear wave splitting measurements to evaluate the lithosphere and upper mantle deformation beneath this region. Our results from some of the individual and station averages show WNW-ESE- to NW-SE–trending fast polarization direction, similar to those observed in eastern Asia in some previous studies, consistent with the direction of Pacific plate subduction during the Cenozoic. This feature suggests that the asthenospheric flow beneath the eastern China region is influenced by the subduction of the western Pacific or Philippine plate. However, most of our data show E-W- or ENE-WSW–trending fast polarization direction, which is inconsistent with subduction from the east. The seismic stations in this study are located near the Qinling-Dabie-Sulu orogenic belt, which formed through the collision between the North and South China blocks during the Late Paleozoic–Triassic, and the anisotropy with an E-W- or ENE-WSW–trending fast polarization direction parallel to the southern edge of the North China block suggests lithospheric compressional deformation due to the collision between the North and South China blocks. Although the deep root of the craton was largely destroyed by cratonic reactivation in the late Mesozoic, our results suggest that the "fossilized" anisotropic signature is still preserved in the remnant lithosphere beneath eastern China.

INTRODUCTION

The dynamics of Earth's interior, particularly global mantle convection, significantly impact the processes at Earth's surface. Understanding the global-scale velocity field associated with convection in Earth's mantle is important to constrain plate driving forces, lithospheric deformation, and the thermal and compositional structure of the mantle (e.g., Hager and O'Connell, 1981; Bull et al., 2010; Flament et al., 2014). Seismic anisotropy has been widely employed to gain insights on regional mantle flow patterns and mantle dynamics (e.g., Silver, 1996; Savage, 1999; Long and Becker, 2010; Díaz and Gallart, 2014). When a shear wave propagates through an anisotropic region of the upper mantle, it undergoes shear wave splitting and the quasi-shear wave polarizations, and the delay time between them can be used to constrain the geometry of mantle deformation. Anisotropy describes a medium that has a different elastic property when measured in different directions. Seismic waves in an anisotropic medium travel at different velocities depending both on their propagation and polarization (vibration) directions. The existence of seismic anisotropy indicates an ordered medium. In the middle to lower crust and the upper mantle, the order is produced primarily by the lattice preferred orientation (LPO) of anisotropic minerals in response to finite strain. In the middle to lower crust, the preferred orientations of biotite and amphibole are expected to be the major cause of seismic anisotropy (Barruol and Mainprice, 1993). The seismic anisotropy in upper mantle rocks is attributed mainly to the LPO of olivine (e.g., Silver, 1996), which is the most abundant and deformable mineral in the upper mantle. Seismic anisotropy is a powerful tool for imaging the style and geometry of crust and mantle deformation. For example, olivine LPO can be produced by ongoing deformation and flow of the asthenospheric mantle (Kaminski et al., 2004). However, anisotropy in the lithosphere is also generated from past and present deformational events. It has been demonstrated that earlier orogenic processes can imprint the lithosphere with a crystallographic fabric that remains stable and frozen, even after thermal relaxation, for as long as 2.5–2.7 b.y. (Silver and Chan, 1988). For mapping the seismic anisotropy of the upper mantle at a horizontal scale of several hundreds of kilometers, surface waves are effectively employed; at shorter length scales of a few tens of kilometers, seismic anisotropy can be measured through the splitting of teleseismic core-shear waves (e.g., Savage, 1999).

Eastern China includes the eastern parts of the North China block (NCB) and South China block (SCB), which constitute two of the major continental blocks of the Eurasian continent (Fig. 1). The Triassic collision between these two blocks generated the Qinling-Dabie-Sulu orogenic belt and associated ultra-high

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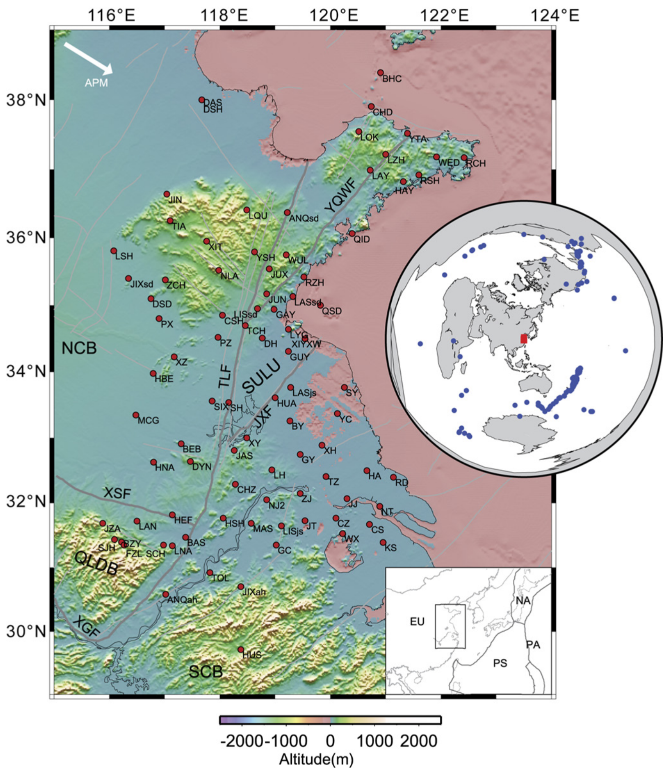

Figure 1. Topography of eastern China and the distribution of seismic stations (red points). Gray lines represent the boundaries between tectonic units or major faults; the large white arrow indicates the absolute plate motion (APM) of the Eurasian plate (Gripp and Gordon, 2002). Blue dots in inset show the spatial distribution of earthquakes used in this study. EU—Eurasian plate; JXF—Jiashan-Xianshui fault; NA—North American plate; NCB—North China block; PA—Pacific plate; PS—Philippine Sea plate; QLDB—Qinling-Dabie orogenic belts; SCB—South China block; SULU—Sulu orogenic belt; TLF—Tan-Lu fault; XGF—Xiangfan-Guangji fault; XSF—Xinyang-Shucheng fault; YQWF—Yintai-Qingdao-Wulian fault. All other abbreviations are station names.

pressure (UHP) metamorphic rocks (Guo et al., 2012; Yin and Nie, 1993). The eastward extension of the orogenic belt is thought to have been offset sinistrally several hundred kilometers by the Tan-Lu fault following the collision (e.g., Li, 1994). Some workers believe the collision first occurred in the east during the Early Triassic and propagated westward (e.g., Guo et al., 2012). However, the direction of convergence and the location of the suture remain ambiguous (e.g., Faure et al., 2001) because of the irregular shape of the northern edge of the SCB and the offset along the Tan-Lu fault (Yin and Nie, 1993). In the east, a north-south direction of convergence has been suggested based on linear aeromagnetic anomalies (Li, 1994). Whether this direction of convergence occurred on a lithospheric scale or not needs to be evaluated geophysically.

Following convergence between the SCB and NCB, extensive cratonic reactivation affected the eastern NCB during the late Mesozoic, and the thick cratonic lithosphere in this region lost a significant proportion of its deep mantle keel (e.g., Griffin et al., 1998). From the Late Mesozoic through the Cenozoic, deformation of the eastern Asian continent was dominated by extensional tectonics leading to the formation of several rift systems (Yin, 2010). The Pacific plate began to subduct along the eastern margin of the Asian continent at 180 Ma (Maruyama et al., 1997). The lithospheric deformation in eastern China caused by the convergence between the SCB and NCB was probably modified during these subsequent tectonic events.

In this study, we present shear wave splitting observations using data sets from eastern China and explore the "frozen" LPO that may be associated with the convergence between the SCB and NCB.

DATA, METHODS, AND RESULTS

We use teleseismic shear wave (including SKS, SKKS, and PKS) splitting measurements to evaluate the lithosphere and upper mantle deformation beneath this region. The broadband seismic data used in this study were recorded during August 2007 to April 2013 employing 75 permanent stations in the eastern China. These stations are widely distributed in the southeastern part of the NCB and the northeastern part of the SCB. Station locations are shown in Figure 1 and are listed in Table S1 (see the GSA Supplemental Data Repository[1]). In order to observe distinct, high signal-to-noise ratio shear wave phases, we systematically selected seismic events with magnitudes (M_W) larger than 5.3 occurring at epicentral distances of 85°–120° and 120°–150° for SKS and PKS phases, respectively. In these epicentral distances, the SKS or PKS phase are both well isolated from other shear-waves and are sufficiently energetic. We obtained 215 events that fit these criteria. All the events are shown in Figure 1 and listed in Table S2 (see footnote 1).

We used the measurement method of Tian et al. (2011) to extract (1) the difference in arrival times (or delay time, δt) between the fast and slow shear waves, which is a function of the thickness and intrinsic anisotropy of the anisotropic medium; and (2) the orientation of the polarization planes of the fast shear wave (or the fast polarization direction, ϕ), which reflects the orientation of the structure. The details of splitting measurement are provided in the supplemental appendix (see footnote 1).

We obtained a total of 1326 pairs of good splitting parameters ϕ (fast polarization direction) and δt (delay time). Figure 2A presents the whole set of individual splitting measurements plotted at each respective station. The station averages computed from the individual measurements are plotted in Figure 2B and listed in Table S1 (see footnote 1). At stations CSH, ANQsd and NLA, we obtained a large number of measurements (56, 44, and 37, respectively) and large back-azimuth variations. These back-azimuth variations of the splitting parameters are clearly not random but rather are well organized. Such back-azimuth variations have been suggested to result from the presence of two anisotropic layers (Silver and Savage, 1994). Following the scheme proposed by these authors, we tried to constrain the possible geometries of these anisotropic layers beneath the three stations. The best fitting models are plotted in Figure 3 and listed in Table S3 (see footnote 1).

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[1] GSA supplemental data item 2015006, detailed methods, data tables, and supplementary figures, is online at www.geosociety.org/pubs/ft2015.htm. You can also request a copy from GSA Today, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

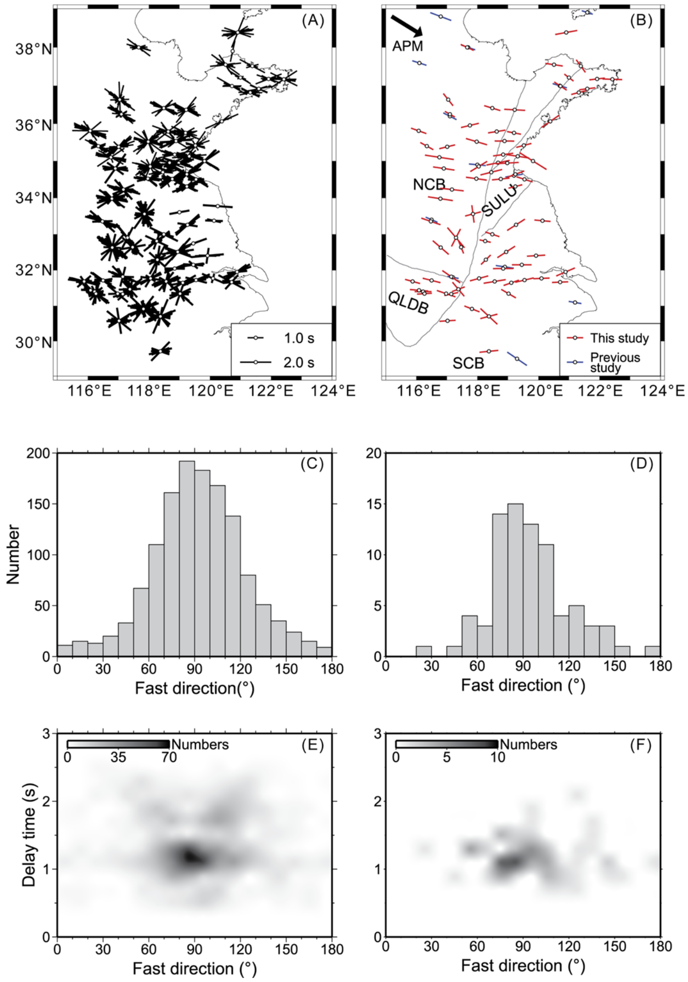

Figure 2. (A) Individual splitting measurements plotted at each station. The orientation and length of the bars correspond to the fast direction and delay time, respectively. (B) Anisotropy map of eastern China presenting the averaged splitting measurements (red bars). Previous results are plotted in blue. APM—absolute plate motion; NCB—North China block; QLDB—Qinling-Dabie orogenic belts; SCB—South China block; SULU—Sulu orogenic belt. (C) and (D) are the histograms of the fast direction for individual and station average, respectively. (E) and (F) show the splitting parameters distribution for individual and station average, respectively.

DISCUSSION

In our individual measurements (see Figs. 2A, 2C, and 2E), most results were characterized by E-W–trending fast polarization direction and delay times of 1.2 s. In addition, some measurements show ENE-WSW- or NW-SE–trending fast polarization directions. Similar features can also be found in station average values (see Figs. 2B, 2D, and 2F), with most averages having ENE-WSW- to E-W (N070°E to N110°E) trending fast polarization direction and delay times of 1.0 s. However, some averages show a NW-SE (N110°E to N150°E) trending fast polarization direction.

Previous studies (Chang et al., 2009; Zhao et al., 2007; Zhao et al., 2013; Zhao and Xue, 2010) have shown a WNW-ESE- to NW-SE–trending fast polarization direction at most stations in the eastern part of China. Based on the wide distribution of the WNW-ESE orientation in the eastern part of China and its coincidence with absolute plate motion (APM), which is assumed to be coupled with the underlying asthenosphere, these studies suggest that the WNW-ESE to NW-SE fast direction anisotropy is produced by the motion of asthenospheric flow.

In our results, some individual values and station averages show such a fast polarization direction, and two-layer model fitting also suggests a lower layer with a N120°E- to N130°E–trending fast polarization direction, which is parallel to the direction of Pacific plate subduction (Fig. 2B) calculated from HS3-Nuvel1A (Gripp and Gordon, 2002). We interpret this fast direction as the asthenospheric flow induced by the subduction of the western Pacific or Philippine plates (see Fig. 4B). Global and regional seismic tomography shows that the subducting western Pacific slab becomes stagnant in the mantle transition zone under eastern China and that there are extensive low-velocity anomalies in the upper mantle (Huang and Zhao, 2006). Mantle convection beneath the overriding plate may be induced by deep slab dehydration (Zhao et al., 2007). Both the low velocity and thinness of the lithosphere imply a hot mantle beneath eastern China (Zhao et al., 2007). The development of LPO becomes much easier under the shear flow in the upper mantle when the viscosity is reduced by high temperature (Karato et al., 2008). Several teleseismic shear wave splitting studies have shown a NW-SE–trending fast polarization direction at many stations in eastern China and have suggested that this feature is caused by the subducting Pacific or Philippine slab-induced flow (Liu et al., 2008).

The ENE-WSW- to E-W–trending fast polarization direction anisotropy in our study region has been noted at several stations in previous studies (Chang et al., 2009; Zhao et al., 2007). This study, based on dense stations and 5–6 years of data, shows this fast direction to be characteristic of most individual measurements and station average values. Two-layer model fitting in this study also suggests that the upper layer is characterized by an ENE-WSW- to E-W–trending fast polarization direction. This direction differs from the direction of plate motion and asthenospheric flow and is considered to have been generated by lithospheric deformation. From the late Mesozoic through the Cenozoic, deformation of the eastern Asian continent was dominated by WNW-ESE–trending extensional tectonics leading to the formation of Cenozoic intracontinental basins (Yin, 2010). We therefore propose that the ENE-WSW- to E-W–trending fast polarization direction represents a "fossilized" anisotropic signature preserved in the lithosphere beneath eastern China.

Continental shortening and thickening accompany the compressional tectonics associated with the convergence between continents. The vertically coherent deformation between crust and lithospheric mantle has been observed in active tectonic regions (Silver, 1996). It is well established that upper mantle minerals, especially olivine, are highly anisotropic and develop LPO in response to finite strain, where the fast direction is predominantly parallel to the strike of the orogenic belt. This has been documented from modern orogenic belts including the Zagros and Caucasus Mountains and the Alps (Silver, 1996). In ancient orogens, the anisotropic signature of deformation can remain "fossilized" in the lithospheric mantle in cases where subsequent intense deformation has not erased this record (Silver and Chan, 1991).

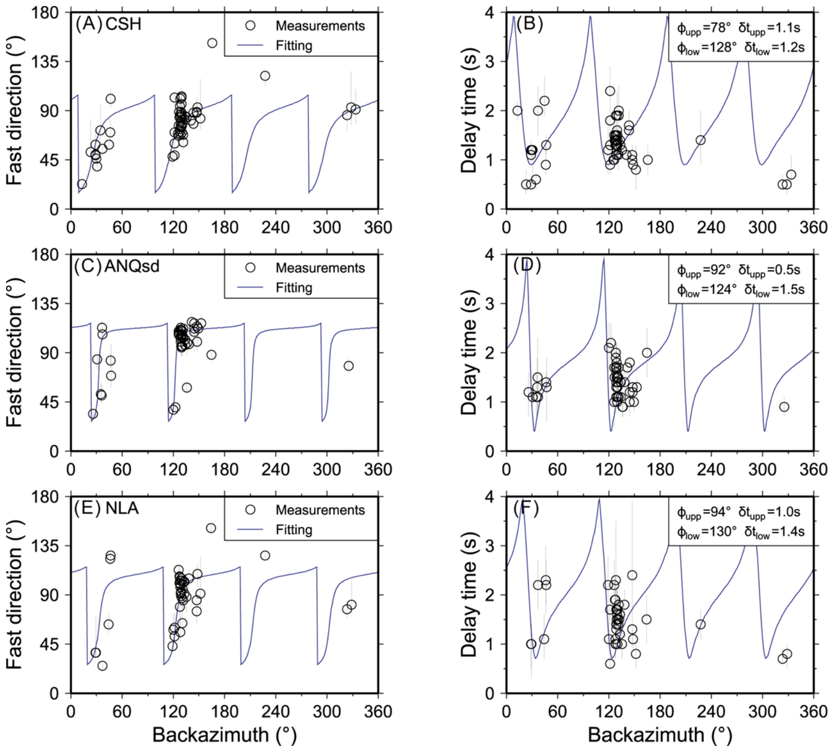

Figure 3. Two-layer anisotropy fitting. Left and right maps show apparent variations of the observed fast direction and delay time (black circle with error bar) as a function of the back-azimuth of the incoming wave, respectively. The best fitting two layer model is shown as blue line. (A) and (B) Station CSH; (C) and (D) Station ANQsd; (E) and (F) Station NLA.

Subduction of the western Pacific oceanic plate (including the Izanagi plate) under eastern China could explain the "fossilized" anisotropy in the continental lithosphere. Subduction of the western Pacific plate had started by 180 Ma (Maruyama et al., 1997). If the western Pacific plate subducted as a flat-slab in a north or north-northwest direction under eastern Asia in the Mesozoic, the overlying continental lithosphere might be expected to have undergone north-south contraction. If so, an ENE-WSW- to E-W–trending fast polarization direction anisotropy could have been produced in the deforming lithosphere. However, neither northward flat-slab subduction nor north-south contractional deformation induced by the flat-slab subduction has received support from other studies in eastern China. On the other hand, if the western Pacific plate subducted at a steep angle in a west or east-northeast direction in the Mesozoic, the asthenospheric flow resulting from slab retreat would also produce an ENE-WSW to E-W fast direction anisotropy. After cooling, the fast direction anisotropy could be preserved in the lower part of the lithosphere. However, in our study region, the lithosphere is only 70–80 km thick (Chen, 2010) and does not adequately explain the 1.0 s delay times in the lower part of the lithosphere.

It is apparent that the crust overlying the lithospheric mantle lid, which is ~30 km thick in the study area (Xu et al., 2014), has a significant effect on the observed total delay time, possibly arising from the LPO in the middle to lower crust. Foliation planes within the crust are usually horizontal, and the splitting of the teleseismic shear wave with vertical propagation is expected to be small. However, dipping foliation planes in the middle to lower crust can be created in convergent plate margins (Barruol and Mainprice, 1993). Some studies (Okaya et al., 1995; Savage et al., 1996) have indicated that an ~10 km thickness of schistose rocks

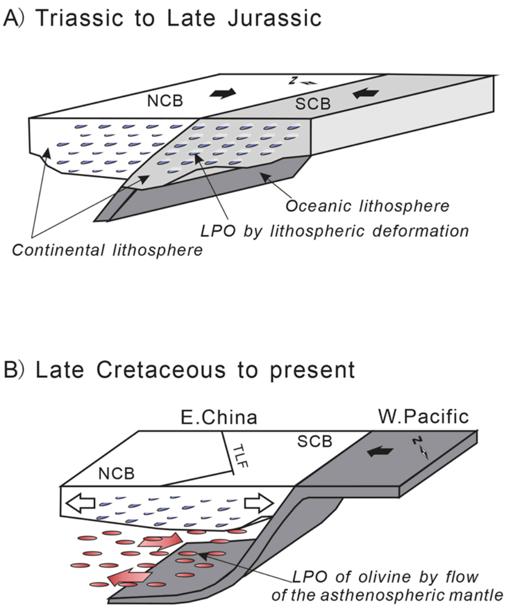

Figure 4. Cartoons illustrating a possible scenario for the origin of anisotropic layering beneath eastern China. (A) Pervasive deformation occurred in the lithosphere during the collision between the South China block (SCB) and North China block (NCB) from the Triassic to Late Jurassic. In response to the NNW-SSE convergence, the lithosphere was thickening and developing lattice preferred orientation (LPO; shown as blue fusiform), the fast direction is predominantly parallel to the strike of collision belt. The thickened and anisotropic lithosphere was destroyed during the late Mesozoic, and only the shallow part of the anisotropic lithosphere survived. (B) Since the Late Cretaceous, lithosphere extension and asthenospheric flow were induced by the Pacific plate subduction beneath eastern China. The LPO of olivine (shown as red fusiform) developed in the asthenospheric flow and trends NW-SE, parallel to the direction of the subduction. TLF—Tan-Lu fault.

with near-vertical foliation planes would be adequate to cause splitting of up to 1.0 s. On the other hand, based on relations between delay time δt, anisotropy magnitude A, and length of the anisotropic path L,

$$A = (\delta t^{*} V_s)/L$$

(Bonnin et al., 2010), where V_s is velocity of shear wave considered (here SKS), a 70–80-km-thick lithosphere with anisotropy magnitude $A = 0.05$ would produce a delay time of 1.0 s. The continent-continent collision between the North and South China blocks, one of the most important tectonic events in the Asian continent during the Mesozoic, is the potential process that produced the ENE-WSW- to E-W–trending fast polarization direction anisotropy on a whole lithosphere scale. The N-S–directed collision and crustal shortening have been reported in previous studies. Closure of the ocean between the NCB and SCB has been suggested to have occurred through subduction with northward polarity (e.g., Hsu et al., 1987). The lithofacies distribution along the southern margin of the NCB and northern margin of the SCB is consistent with the interpretation (Yin and Nie, 1993) that the southern edge of the NCB was originally a smooth, E-W–trending boundary prior to the collision, whereas the SCB had an irregular geometry with its eastern part extending some 500 km farther to the north than its western counterpart. Based on the study of regional geologic setting, Yin and Nie (1993) considered the left-lateral Tan-Lu strike-slip fault in China and the right-lateral Honam strike-slip fault in Korea to be transform faults that accommodated the northward indentation of the SCB. Triassic to Early Jurassic deformation is widespread in the NCB north of the Sulu belt, probably related to the continent-continent collision. In the northeastern NCB, E-W- to ENE-WSW–trending thrusts and folds involving Permian strata are unconformably overlain by Jurassic strata (Geologic Map of Liaoning Province, 1989), suggesting Triassic crustal shortening in a north-south direction. Triassic to Early Jurassic deformation during the Indosinian orogeny is widespread in Korea. In particular, E-W- to ENE-WSW–trending thrusts and folds developed along and north of the Imjingang belt (Um and Chun, 1984). The suture between the blocks in the region east of the Tan-Lu fault trends E-W or ENE-WSW, as inferred from the analysis of aeromagnetic anomalies (Li, 1994), and extends to the Imjingang belt in the central part of the Korean Peninsula (Yin and Nie, 1993).

As illustrated in Figure 4A, we suggest that the E-W- to ENE-WSW–trending fast polarization direction represents "frozen" anisotropy in the lithosphere produced by the collision between the NCB and SCB during the Late Paleozoic or Triassic. Thus, the convergence of the two blocks in the east is inferred to have been in a NNW-SSE direction. Subsequently, lithosphere shortening induced an LPO with an E-W or ENE-WSW orientation. This proposal is supported by the ENE-WSW fast direction reported from South Korea (Kang and Shin, 2009). During the late Mesozoic, the lithosphere of the eastern NCB lost a significant proportion of its deep mantle keel through cratonic erosion and reactivation (e.g., Griffin et al., 1998; Santosh, 2010; Guo et al., 2013). The thinning of the lithosphere may extend southward into Dabie and Sulu, as well as the northern part of SCB, as inferred from the thin lithosphere in these regions as imaged by seismic studies (Chen, 2010). Although a substantial part of the deep cratonic root has been removed, our results suggest that the "fossilized" anisotropic signature is still preserved in the remnant lithosphere beneath eastern China (Fig. 4B).

Recent studies indicate that the cratonic lithosphere in some regions on the globe has been extensively destroyed or reactivated, resulting in loss or modification of the refractory lithospheric "root." Examples include the North China Craton in East Asia, the southwestern part of the Kaapvaal Craton in South Africa, the Wyoming Craton in North America, and the Brazilian Craton in South America, among which the eastern part of the North China Craton is considered to be one of the best examples for wholesale destruction of cratonic root (Zhang et al., 2013). Following cratonization in the late Paleoproterozoic, the interior part of the North China Craton remained largely quiescent until the Mesozoic when extensive reactivation, erosion of the cratonic keel, and differential destruction of the lithosphere occurred (Zhai and Santosh, 2011, 2013). The craton was in a "superconvergent regime" (Li et al., 2013), caught up among the southward indentation of the Siberian block following the closure of the Mongol-Okhotsk Ocean, the collision between the North and South China Blocks, and the oblique subduction of the paleo-Pacific plate from the east. Our study demonstrates that despite the extensive erosion and destruction of the cratonic root beneath eastern China, a "fossilized" anisotropic signature is preserved in the lithosphere, and this has important bearing on understanding the stability and destruction of ancient cratons.

CONCLUSIONS

Because seismic waves effectively propagate and interact with the internal structure of lithosphere, they provide high-resolution data for studying the structure of the crust and upper mantle, as well as to constrain the geodynamic processes. Similar to the reconstruction of the tectonic evolution of a region based on rock records by geologists, seismologists try to understand the ancient dynamic processes by exploring the structure and rock fabric in the crust and upper mantle, which are not reset during later tectonic events. In eastern China, the collision between the NCB and SCB resulted in lithospheric compressional deformation and constructed the Qinling-Dabie-Sulu orogenic belt during the Late Paleozoic to Triassic. During the late Mesozoic, extensive cratonic reactivation and dramatic lithospheric thinning affected the eastern NCB. From the late Mesozoic through the Cenozoic, deformation of the eastern Asian continent was dominated by extensional tectonics associated with the Pacific plate subduction along the eastern margin of Asia. Whether the deformed lithosphere induced by the convergence between the SCB and NCB was destroyed or reset by these subsequent tectonic events is a topic of wide interest.

In this study, we performed teleseismic shear wave splitting measurements to investigate lithosphere and upper mantle deformation beneath eastern China. Our results show a dominant E-W or ENE-WSW fast direction and a delay time of 1.0 s. Some individual measurements, as well as the station averages, are characterized by a WNW-ESE to NW-SE fast direction. Based on fitting the fast directions and delay times as a function of the back azimuth, the two-layer anisotropic models at three stations show similar features. The fast direction of the upper layer is ENE-WSW or E-W, whereas the lower layer shows a

NW-SE fast direction. The delay times of the upper layer show a large variation from 0.5 s to 1.1 s between the three stations, whereas the delay times of the lower layer show a limited range from 1.2 s to 1.5 s.

We interpret the WNW-ESE to NW-SE fast direction, which is parallel to the direction of Pacific plate subduction, as the asthenospheric flow induced by the subduction of western Pacific or Philippine plates. The E-W to ENE-WSW fast direction was probably produced by lithospheric deformation accompanying the collision between the North and South China blocks in the Late Paleozoic or Triassic. Our results suggest the preservation of a "fossilized" anisotropic signature in the lithosphere beneath eastern China, in spite of the extensive erosion and destruction of the cratonic root during the late Mesozoic.

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