Seismic imaging of the Asian orogens and subduction zones

Dapeng Zhao\textsuperscript{a,*}, Yukio Isozaki\textsuperscript{b}, Shigenori Maruyama\textsuperscript{c}

\textsuperscript{a} Department of Geophysics, Tohoku University, Sendai 980-8578, Japan
\textsuperscript{b} Department of General System Studies, University of Tokyo, Tokyo 153-8902, Japan
\textsuperscript{c} Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo 152-8550, Japan

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\textbf{ABSTRACT}

In this article we make a review of recent findings on seismic imaging of the Asian orogens and subduction zones. High-resolution images of seismic tomography and receiver functions of the Asian region are obtained, revealing significant lateral heterogeneities in the crust and upper mantle, which are caused by active plate subductions and continental orogeny. A significant advance in the seismic imaging is tomographic inversions for three-dimensional distribution of seismic anisotropy in the crust and mantle, which provides important new information on the lithospheric deformation and mantle convection associated with the continental orogeny and plate subductions. The intraplate volcanism in Northeast Asia is caused by hot and wet upwelling flows in the big mantle wedge above the stagnant Pacific slab in the mantle transition zone (MTZ). The age distribution of the subducting Pacific slab beneath East Asia is estimated, shedding new light on the evolution of the Pacific slab, as well as the East Asian tectonics during the Late Mesozoic to the Cenozoic. The nucleation of great earthquakes, such as the 2008 Wenchuan earthquake (M 8.0), the 2011 Tohoku-oki earthquake (M 9.0) and the 2015 Nepal earthquake (M 7.9), is controlled by structural heterogeneities in and around the seismogenic fault zones. It is considered that fluids are involved in the nucleation and rupture processes of all types of earthquakes. The cause of deep earthquakes is still not very clear, though transformational faulting triggered by metastable olivine transforming to spinel in the cold, stressed core of the subducting slab is a viable mechanism, and a metastable olivine wedge is revealed within the western Pacific subducting slab at the MTZ depths. The 2015 Bonin deep earthquake (M 7.9, \textsim 670 km depth) occurred at the MTZ bottom within the vertical Pacific slab which is penetrating into the lower mantle. This very unusual deep event was caused by joint effects of several factors, including the slab’s fast deep subduction, slab tearing and thermal variation, stress changes and phase transformations in the slab, and complex interactions between the slab and the ambient mantle.

\section{1. Introduction}

The geological structures and tectonics are complex in the Asian region (Fig. 1). Many orogenic belts and active fault zones exist within the Asian continent, and active subduction occurs in its surrounding regions. In the east, the Pacific plate and the Philippine Sea plate are subducting beneath East Asia, causing the development of trench-arc-backarc systems. In the southwest, the Indian plate is subducting beneath the Eurasian plate, resulting in the formation of the Tibetan Plateau. Due to the intense interactions among the four tectonic plates, large earthquakes take place frequently in the Asian region, such as the 2008 Wenchuan earthquake (M 8.0), the 2011 Tohoku-oki earthquake (M 9.0), the 2015 Nepal earthquake (M 7.9), and the 2015 Bonin deep earthquake (M 7.9, \textsim 670 km depth), and the 2016 Kumamoto earthquake (M 7.3) (Fig. 1). There are also some active intraplate volcanoes in the Asian region, but their origin and relationship with the intraplate tectonics are still not very clear (e.g., Zhao et al., 2011a; Tian et al., 2016; Chen et al., 2017).

Seismic imaging is a powerful tool for exploring the deep structure of the orogenic belts and subduction zones, and can provide useful information on the depth extension of the surface geological features and the influence and control of mantle dynamics on the lithospheric processes. Generally speaking, seismologists basically use three kinds of physical parameters to characterize the Earth’s interior structure, i.e., seismic velocity, seismic attenuation, and seismic anisotropy (e.g., Zhao, 2015). Seismic velocity means propagating speeds of P and S waves (Vp, Vs), which can be determined using P and S wave arrival times measured from seismograms. Seismic attenuation is quantified with a dimensionless quality factor (Q) which is defined in terms of the energy (E) stored in one cycle of a seismic wave and the change in energy ($\Delta E$) over that cycle, i.e., $Q = 2\pi E/\Delta E$. Q can be determined from amplitudes of seismic waves (e.g., Liu and Zhao, 2014, 2015;...
Studying seismic anisotropy can greatly improve our understanding of the structure and dynamics of the Earth’s interior, because anisotropy provides a unique constraint on the character of past and present deformation in the lithosphere and sublithospheric mantle. Applying the three-dimensional (3-D) distribution of these parameters in the Earth’s crust and mantle, i.e., seismic velocity tomography, attenuation tomography, and anisotropy tomography (Zhao, 2015).

In the past three decades, a great number of seismological studies have been made on the 3-D structure of the crust and mantle beneath the Asian region, but most of them investigated only the seismic velocity structure. Its reason is that seismic velocity can be easily determined from P and S wave arrival times which are the most abundant seismological data, because they can be measured in high quality and great quantity by the routine processing of data from seismic networks which are installed in many areas for monitoring the local seismic activity. Zhao et al. (2011a) made a review of the seismic imaging studies made for East Asia by 2010, focusing on the results of seismic velocity tomography. In the past a few years, more advanced studies of seismic imaging have been made for the Asian region, including not only seismic velocity tomography, but also anisotropic tomography, attenuation tomography and receiver-function imaging, which shed new light on the mantle structure and dynamics beneath the Asian orogenic belts and subduction zones, seismotectonics and intraplate volcanism. In this article, we review these recent findings and discuss their implications for continental tectonics and mantle dynamics of the Asian region.

2. Seismic anisotropy, tomography and mantle dynamics

Seismic anisotropy exists widely in the Earth’s interior, from the crust and mantle to the inner core, which has been revealed by a great number of seismological observations and laboratory studies (for detailed reviews, see Silver, 1996; Fouch and Rondenay, 2006; Long, 2013; Zhao et al., 2016). The major causes of seismic anisotropy are lattice-preferred orientation (LPO) and shape-preferred orientation (SPO) of the materials constituting the Earth. Both body-wave and surface-wave data are used to study seismic anisotropy. The body-wave methods include shear-wave splitting, receiver functions, and travel-time tomography (e.g., Zhao et al., 2016).

Shear-wave splitting (SWS), also called seismic birefringence, is a phenomenon in which a shear wave splits into two polarized S waves with different velocities when traveling through an anisotropic medium. Two splitting parameters (φ, δt) can be measured from horizontal-component seismograms, which correspond to the polarization direction of the fast quasi-S phase (φ) and the delay time (δt) between the fast and slow S waves, respectively (Long and Silver, 2009). To date, the SWS measurement has been the most popular tool for characterizing (detecting) seismic anisotropy in the Earth. By using the long-period core phases, such as SKS, SKKS, SKiKS and PKS, the observed SWS is usually considered to reflect seismic anisotropy at some depth in the crust and/or the mantle under a seismograph station. Hence, the two splitting parameters can be used to study the anisotropy and deformation in the crust and/or the mantle.

So far, many researchers have made SWS measurements to study the seismic anisotropy structures in different parts of the Asian region. Huang et al. (2011) reviewed the previous SWS works in Asia and made
new SWS measurements using teleseismic waveforms recorded at 138 permanent seismic stations in China. Their results provide new insights into the anisotropic structure and mantle dynamics in and around the Chinese continent (Fig. 2). The fast directions ($\phi$) in East China, to the first order, are consistent with GPS observations (e.g., Wang et al., 2001), suggesting that the SWS reflects anisotropy in the asthenosphere or deeper areas due to mineral LPO. In NE China and North China, the subduction of the Pacific plate plays an important role in the LPO development. Beneath the orogens in the western part of East China, anisotropy in the lithosphere contributes significantly to the SWS observations, e.g., the observations in the Ordos Block may reflect fossil anisotropy frozen in the stable Archean block (Fig. 2). In SE China, the NE–SW $\phi$ is caused by anisotropy in the lithosphere due to the strong NW–SE contraction between the Eurasian and the Philippine Sea plates. The most significant feature in West China is that $\phi$ is perpendicular to the orientations of the maximum horizontal stress $\sigma_H$ (Heidbach et al., 2010) while parallel to the strikes of the orogens and major fault zones (Fig. 2). The observed spatial variations in anisotropy reflect the large-scale pattern of lithospheric deformation, accompanying a transition from simple shear in the Tibetan Plateau to pure shear in the surrounding regions. In southern Tibet, the crustal anisotropy, either due to deep crustal flow or the fault-fabric, contributes to the observed SWS. In addition, $\phi$ exhibits a good correlation with the GPS results, and many studies have revealed that the anisotropy exists widely in the asthenosphere beneath West China. These results suggest that the mountain building has caused significant deformation in the lithosphere, but has also affected the underlying asthenosphere, from the viewpoint of seismic anisotropy (Huang et al., 2011; Wei et al., 2016; Zhang et al., 2016a,b).

Although measuring SWS is popular and useful to study (detect) seismic anisotropy, it has no depth resolution, and so the interpretation of the SWS results is usually not unique. This drawback can be overcome by P-wave anisotropic tomography (PWAT). Among the methods for studying seismic anisotropy, PWAT is relatively new and has been just developed and widely applied in the past decade (see a review by Zhao et al., 2016), though Pn anisotropy tomography has a longer history (e.g., Hearn, 1996). Because Pn waves refract at the Moho discontinuity and propagate in the uppermost mantle, the Pn tomography can only estimate two-dimensional (2-D) P-wave velocity ($V_p$) variations and azimuthal anisotropy in the uppermost mantle directly beneath the Moho discontinuity. In contrast, PWAT can determine the 3-D distribution of $V_p$ anisotropy in the crust and mantle beneath a seismic network. But one potential problem of PWAT is that there could be a trade-off between velocity heterogeneity and anisotropy, in particular, when the ray path coverage is not complete in different directions. However, recent studies show that the trade-off problem can be resolved when earthquakes and seismic stations used in a tomographic inversion are densely and uniformly distributed in the study area (e.g., Wang and Zhao, 2008, 2013; Huang et al., 2015a; Zhao et al., 2016), then both the 3-D velocity heterogeneity and anisotropy can be determined reliably (Liu and Zhao, 2017a,b).

In the past decade, the PWAT method has been applied to several
areas in the Asian region, including the Japan subduction zone (e.g., Ishise and Oda, 2008; Wang and Zhao, 2008, 2013; Liu et al., 2013a; Wei et al., 2015; Niu et al., 2016; Liu and Zhao, 2017a,b; Wang et al., 2017c), the North China Craton (Tian and Zhao, 2013; Wang et al., 2013, 2014), Southwest China (Wei et al., 2013, 2016), the Tibetan Plateau (Zhang et al., 2016a,b), and Southeast Asia (Huang et al., 2015b). Huang et al. (2014a) determined the first model of 3-D Vp azimuthal anisotropy in the lithosphere (0–120 km depth) beneath China, revealing that the fast velocity directions (FVDs) are generally correlated with the surface geologic features, such as the strikes of orogenic belts, active faults, and tectonic boundaries. The FVDs in the upper crust are normal to the maximal horizontal stress ($\sigma_H$) in regions with intensive compression such as the Tibetan Plateau, whereas they are subparallel to $\sigma_H$ in strike-slip shear zones such as the western and eastern Himalayan syntax. A comparison of the FVDs of P-wave anisotropy with SKS splitting measurements (Huang et al., 2011, 2014a) indicates that beneath the Tibetan Plateau the seismic anisotropy in the lithosphere contributes significantly to the SKS splitting observations. In contrast, in East China the Vp FVDs in the lithosphere are different from the SKS splitting measurements, suggesting that the SKS splitting is mainly caused by the anisotropy in the deeper mantle, such as the asthenosphere and the mantle transition zone under East China (Huang et al., 2014a; Wei et al., 2015, 2016).

High-resolution images of Vp anisotropic tomography of the crust and mantle down to a depth of 1200 km beneath Asia are determined using a large number of arrival-time data recorded by permanent seismic networks and temporary seismic arrays (Figs. 3 and 4; Wei et al., 2015, 2016). The images provide important new insights into the
plate subductions and continental tectonics in Asia. The results show that the northern limit of the subducting Indian plate has reached the Jinsha River suture in eastern Tibet. A striking variation of Vp azimuthal anisotropy is revealed in the Indian lithosphere: the FVD is NE-SW beneath the Indian continent, whereas the FVD is arc parallel beneath the Himalaya and Tibetan Plateau, which may reflect re-orientation of minerals due to lithospheric extension, in response to the India-Eurasia collision. Multiple anisotropic layers with different FVDs are revealed in some parts of the Tibetan Plateau, which may cause the dominant null SWS measurements observed in those areas. The Vp anisotropic models of Huang et al. (2014a) and Wei et al. (2016) show a similar feature in the Tibetan lithosphere that the FVD is generally arc-normal in the crust but becomes arc-parallel in the upper mantle, though some detailed features are different between the two models. A circular pattern of FVDs is revealed around the Philippine Sea slab beneath SE China, which reflects asthenospheric strain caused by toroidal mantle flow around the edge of the subducting slab (Wei et al., 2016).

3. Receiver functions and mantle discontinuities

The receiver-function method is a way to model the Earth structure using waveforms of teleseismic events recorded at a three-component seismograph (e.g., Langston, 1979; Ammon et al., 1990). A teleseismic P-wave will generate P to S conversion at a seismic discontinuity beneath the seismograph. The travel-time difference between the PS converted wave and the first P-wave contains information on the depth to the seismic discontinuity, and if further reverberations are included, more detailed structure can be resolved. This is done by deconvolution of the incoming vertical and longitudinal components of the seismogram, which can remove the common effects to the components, i.e., the source and traveling path information. The resulting waveform is the receiver function (RF). The teleseismic RF method is particularly useful to investigate the depth, geometry and fine structure of seismic
discontinuities in the crust and mantle, such as the Moho, the lithosphere-asthenosphere boundary, the 410 and 660 km discontinuities, etc. In the past decade, this method has been widely used to study the crust and mantle structure in many areas of Asia (e.g., Shen et al., 2008; Tonegawa et al., 2008; Chen and Ai, 2009; Tian et al., 2010; Hu et al., 2013, 2015; Huang et al., 2014b, 2015; Tonegawa et al., 2014; Lee et al., 2014; Shi et al., 2015, 2016; Tian et al., 2016; Si et al., 2017; Yang et al., 2017).

Depth variations of the 410 and 660 km discontinuities (hereafter we call them d410 and d660) beneath the entire Mainland China are investigated using the teleseismic RF method (Shen et al., 2008). Clear signatures corresponding to d410 and d660 are visible at almost all of the stations. The average depth of d410 is 413 km, and the peak-to-peak topography is ∼36 km, with regional depressions that correlate with the Datong quaternary volcano in northern China. The d660 topography exhibits a peak-to-peak variation of ∼43 km, and its average depth is 669 km. The d660 depressions in northeastern, southeastern and northern China are well correlated with the past subductions around the Pacific Ocean and the Philippine Sea. The mantle transition zone thickens in the region with a deeper d660 (Shen et al., 2008).

The d410 and d660 topographies beneath the Korean Peninsula and SW Japan are also studied using the RF method (Tonegawa et al., 2008; Lee et al., 2014). Their topographic variations are roughly consistent with the low temperature of the subducting Pacific slab. However, the complex slab structure produced distinct changes of the upper mantle discontinuities, which cannot be explained by temperature variations alone. Depression of the d410 is observed in a wide region from the Korean Peninsula to Kyushu Island, which may be related to trench
rollback history. The d660 topography varies significantly with latitude. North of 38°N, the d660 depth has little change, despite the presence of the stagnant slab there, whereas a significant d660 depression appears south of 36°N, which may be caused by different angles of subduction of the Japan slab and the Izu-Bonin slab. However, different water contents in the slabs may also contribute to the topographical changes (Lee et al., 2014).

Closely-spaced RF profiles in the east-central India–Tibet collision zone reveal drastic west–east changes in the crustal and upper mantle structure (Fig. 5). West of ~91.5°E, Shi et al. (2016) revealed the Indian crust-mantle boundary (Moho) extending subhorizontally from ~50 km depth below sea level under the High Himalaya to ~90 km under the central Lhasa terrane. Further north, this boundary becomes the top of the Indian lithospheric mantle and, becoming faint but still observable, it can be tracked continuously to ~135 km depth near ~31.5°N. The top of the Indian lithospheric mantle is clearly visible beneath the Tibetan Moho that is also a conspicuous boundary, undulatory at 60–75 km depth from the central Lhasa terrane to the northern end of the profile at ~34°N. This geometry is consistent with underthrusting of the Indian lower crust and underplating of the Indian plate directly beneath southern Tibet. In contrast, east of ~91.5°E, the Indian Moho is only seen under the southernmost margin of the Tibetan plateau, and eludes imaging from ~50 km south of the Yarlung-Zangbo suture to the north. The Indian lower crust thins greatly and in places lacks a clear Moho. This is in contrast to the observation west of ~91.5°E, that the Indian lower crust thickens northwards. A clear depression of the top of the Indian lower crust is also observed along the west–east oriented profiles, centered above the region where the Indian Moho is not imaged. These observations suggest that rollback of the Indian lithospheric mantle has occurred east of ~91.5°E, likely due to delamination associated with density instabilities in eclogitized Indian lower crust, with the center of foundering beneath the southern Lhasa terrane slightly east of 91.5°E (Fig. 5).

4. Big mantle wedge (BMW) and intraplate volcanism

Several Cenozoic intraplate volcanoes exist in NE Asia (Fig. 1). Among these volcanoes, Changbai is the largest and most active one, which is located at the border between China and North Korea and ~1300 km away from the Japan Trench (Figs. 6 and 7). Different from arc volcanism resulting from the subducting slab dehydration and mantle wedge melting (e.g., Hasegawa and Zhao, 1994; Iwamori and Zhao, 2000) and hotspot volcanism fed by a deep-rooted mantle plume (e.g., Morgan, 1971; Zhao, 2004), the intraplate volcanism in NE Asia is

![Fig. 6. Vertical cross-sections of P-wave tomography along the eight profiles shown in Fig. 7. The red and blue colors denote low and high velocity perturbations, respectively, whose scale (in %) is shown at the bottom-middle. The color bar with blue colors above each cross-section shows the subducting Pacific lithosphere ages from the west (East China) to the east (near the Japan Trench), whose scale (in Ma) is shown at the bottom-left. The surface topography along each profile is shown above the lithosphere age bar. The color bar with red numbers below each cross-section shows the subduction ages of the Pacific slab, whose scale (in Ma) is shown at the bottom-right. The red and pink triangles atop each cross-section denote locations of active volcanoes and Cenozoic basalts, respectively, within a 1° width of each profile. The background seismicity and large earthquakes (M ≥ 7.0) that occurred within a 1° width of each profile are shown in white circles and red stars, respectively. The two black dashed lines denote the 410 and 660 km discontinuities. After Liu et al. (2017). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)
considered to be caused by hot and wet upwelling in the big mantle wedge (BMW) above the Pacific slab which is currently stagnant in the mantle transition zone (MTZ) beneath the Korean Peninsula and East China (e.g., Zhao, 2004; Zhao et al., 2004, 2007, 2009; Lei and Zhao, 2005; Duan et al., 2009; Richard and Iwamori, 2010; Kuritani et al., 2011; Kameyama and Nishioka, 2012; Zhao and Tian, 2013; He, 2014, 2017; Tian et al., 2016; Choi et al., 2017; Su et al., 2017). Tomographic models at regional and global scales have clearly imaged the high-velocity (high-V) stagnant slab in the MTZ and low-velocity (low-V) anomalies in the BMW beneath NE Asia (e.g., Fukao et al., 2001; Zhao, 2004; Huang and Zhao, 2006; Wei et al., 2012, 2015) (Fig. 6). Receiver-function studies have revealed localized depth variations of the d410 and d660 (e.g., Li and Yuan, 2003; Lee et al., 2014; Tian et al., 2016). SS precursors and triplicated phases associated with the MTZ discontinuities are also used to study the stagnant slab thickness and geophysical properties (e.g., Tajima et al., 2009; Ye et al., 2011; Gu et al., 2012; Li et al., 2013; Dokht et al., 2016).

In the past a few years, several seismological studies of NE Asia have been made using data recorded by a portable seismic network (NECESSArray) deployed in NE China during 2009–2011. A tomographic model obtained from teleseismic relative travel times recorded by the NECESSArray shows a low-V anomaly within the stagnant slab, which was interpreted as a slab gap (Tang et al., 2014). However, other tomographic models obtained from absolute P and S travel times show higher velocities in the slab there, and so do not support the existence of the so-called slab gap (Takeuchi et al., 2014; Wei et al., 2015; Chen et al., 2017). Teleseismic tomography using relative travel-time data is a popular and widely used tool for studying the upper-mantle structure (e.g., Aki et al., 1977; Lei and Zhao, 2005; Zhao et al., 2004, 2009; Tang et al., 2014). However, this method has an inherent limitation, that is, the background mean velocity in the study volume is removed during the computation of relative travel times. Thus, teleseismic tomography

**Fig. 7.** Tectonic settings of East Asia (Liu et al., 2017). The red triangles denote active volcanoes. The pink triangles denote locations of the Cenozoic basalts. The thin blue lines denote depth contours of the present upper boundary of the subducting Pacific slab estimated from seismicity. The thick red line shows a boundary of gravity anomaly. The thick blue line shows the western edge of the flat Pacific slab in the mantle transition zone (MTZ) estimated from the tomographic model shown in Fig. 6. The eight black lines denote locations of the vertical cross-sections shown in Fig. 6. The solid sawtooth lines and the black dashed line denote the plate boundaries. SLB, the Songliao Basin; NCC, the North China Craton; CCO, the Central China Orogen; SCC, the South China Craton; ECS, the East China Sea; PHS, the Philippine Sea. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 8. East–west vertical cross-sections of P-wave tomography along the eight profiles shown in the inset map (Chen et al., 2017). The red and blue colors denote low and high velocities, respectively. The velocity perturbation scale (in %) is shown at the bottom. The red triangles denote active volcanoes. The two white dashed lines denote the 410 and 660 km discontinuities. The white dots denote seismicity within a 30 km width of each profile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
alone is unable to recover the real shape of a network-wide feature in a given depth range beneath a local seismic network (e.g., Bastow, 2012), such as the wide and flat stagnant slab in the MTZ beneath NE Asia (Chen et al., 2017). This limitation could be compensated by a simultaneous inversion of teleseismic relative travel-time residuals and absolute arrival-time data of local earthquakes (e.g., Zhao et al., 2009) or by adding surface-wave data (e.g., Liu and Zhao, 2016).

Chen et al. (2017) investigated 3-D Vp and Vs structures of the mantle down to a depth of 800 km beneath NE Asia using a great number of arrival-time data of local earthquakes and teleseismic events recorded at 2388 stations of permanent and portable seismic networks deployed in NE China, Japan and South Korea (Fig. 8). Their results do not support the existence of a gap (or a hole) in the stagnant slab beneath the Changbai volcano. They conducted joint inversions of both local-earthquake arrival times and teleseismic relative travel-time residuals, leading to a robust tomography of the upper mantle and the MTZ beneath NE Asia (Fig. 8). Their joint inversion results reveal clearly the subducting Pacific slab beneath the Japan Islands and the Japan Sea, as well as the stagnant slab in the MTZ beneath the Korean Peninsula and NE China (Fig. 8). Localized low-V anomalies are revealed clearly in the crust and the BMW directly beneath the active Changbai and Ulleung volcanoes (Fig. 8c, g and h), indicating that the intraplate volcanism is caused by hot and wet upwelling in the BMW associated with corner flows in the BMW and deep slab dehydration as well. To the west of the Changbai volcano, the stagnant slab exhibits a slightly lower Vp than that of the surrounding parts of the slab (Figs. 6 and 8), suggesting the existence of lateral heterogeneities in the slab, which may be caused by several factors, such as changes in the slab age (Fig. 6; Liu et al., 2017), compositional variations in the slab due to the hotspot magmatism in the Paleo-Pacific Ocean like that in Hawaii, and oceanic fracture zones in the Paleo-Pacific lithosphere (Liu et al., 2017), etc.

Tian et al. (2016) investigated the detailed MTZ structure beneath the active Changbai volcano applying a RF method to teleseismic waveforms recorded at many local seismic stations deployed around the Changbai volcano. Their results reveal significant depth variations of the d410 and d660 as well as the 520 km discontinuity (d520) (Fig. 9). A broad d410 depression and a low-V anomaly are revealed beneath the Changbai volcano, which may reflect hot mantle upwelling around the d410 with a positive Clapeyron slope. The d520 is also identified clearly, and its uplift occurs above the stagnant Pacific slab. They also find a prominent depression of the d660 (Fig. 9), which is elongated along the trend of deep earthquake clusters in a range of 39°N–44°N latitude, and the depressed area has a lateral extent of ∼400 km.

![Figure 9](https://example.com/figure9.png)

**Fig. 9.** (a–e) Vertical cross-sections of P-wave tomography along the five profiles shown in the map (f). The red and blue colors denote the slow and fast velocity perturbations (in %), respectively, whose scale is shown at the bottom. The four dashed lines show the Moho, 410, 520 and 660 km discontinuities. The red solid lines represent the geometries of the 410, 520 and 660 km discontinuities obtained by a teleseismic receiver-function study. The short red line in (a–c) denote the second phase associated with the 520 km discontinuity (see the text for details). The black and red triangles denote the Changbai intraplate volcanoes. The white dots denote deep earthquakes within a 30-km width of each profile. Modified from Tian et al. (2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Because the d520 and d660 correspond to positive and negative Clapeyron slopes, respectively, the d520 uplift and the d660 depression should be caused by the cold Pacific slab. This high-resolution RF study supports the BMW model for the formation of the Changbai intraplate volcano (Tian et al., 2016). A prominent feature of the d520 is that two separate phases show up to the east of the Changbai volcano, where deep earthquakes take place actively (Fig. 9a–c). Deuss and Woodhouse (2001) obtained a similar result using SS precursors in the same area, and they suggested that the two d520 phases are related to anomalies of temperature and water content, as well as large-scale chemical heterogeneities.

5. Ages of the Pacific slab beneath East Asia

Although it is well known that the deep subduction of the Pacific plate plays a crucial role in mantle dynamics and the tectonic evolution of East Asia, the nature of the stagnant (flat) slab in the MTZ is still not well understood, such as the slab’s lithospheric age and the duration of its subduction from the Japan Trench (i.e., the slab’s subduction age), which are critical information for linking seismic tomography to plate reconstruction (e.g., Spakman and Hall, 2010; Sigloch and Mihalynuk, 2013; Zabirovic et al., 2014; Hall and Spakman, 2015; Wu et al., 2016) and time-dependent geodynamic modeling (e.g., Billen, 2008; Goes et al., 2008; Liu et al., 2008; Bower et al., 2015; Seton et al., 2015). Global plate reconstructions suggest that the Izanagi plate had subducted beneath East Asia prior to the Pacific plate (e.g., Maruyama et al., 1997; Müller et al., 2008; Seton et al., 2012). The poorly constrained ages of the subducting oceanic lithosphere lead to some key questions, such as: Is the present flat slab beneath East Asia the subducted Izanagi slab or the Pacific slab? Which slab was associated with the destruction of the North China Craton? How long has the present flat slab stayed in the MTZ?, etc.

To resolve these issues, Liu et al. (2017) attempted to map the distribution of the slab’s lithosphere age and its subduction age in the upper mantle and the MTZ beneath East Asia (Fig. 6), by reconciling a high-resolution model of regional Vp tomography (Wei et al., 2012) and the paleo-age data of ancient seafloor (Müller et al., 2008; Seton et al., 2012). Here the slab’s lithospheric age means the period from the birth of the oceanic lithosphere at the mid-ocean ridge to the present, whereas the slab’s subduction age is the time period from the plate subduction at the trench to the present.

The results of Liu et al. (2017) show that the subducting oceanic lithosphere becomes younger from the Japan Trench (~130 Ma) to the slab’s western edge (~90 Ma) beneath East China (Fig. 6). Such a feature indicates that the flat slab now in the MTZ beneath East Asia is the subducted Pacific slab rather than the Izanagi slab which should have already sunk into the lower mantle. The slab’s subduction age ranges from 0 Ma at the present-day trench to ~30 Ma at the western edge of the flat slab in the MTZ beneath East China. The stagnant duration of the flat Pacific slab in the MTZ is no more than ~10–20 million years, much shorter than the age of the BMW beneath East Asia (>110 million years; e.g., Liu et al., 2013b). It is the present Pacific slab that has contributed to the Cenozoic lithosphere destruction, extensive intraplate volcanism, and back-arc spreading in East Asia, whereas the destruction of the North China Craton during the Early Cretaceous (~140–110 Ma) was caused by the subduction of the Izanagi (or the Paleo-Pacific) plate. These results shed new light on the evolution of the Pacific slab in the upper mantle and the MTZ, as well as the East Asian tectonics during the Late Mesozoic to the Cenozoic.

6. Seismotectonics

Asia a seismically very active region where large earthquakes often strike and cause significant damages to the densely populated societies and infrastructures (Fig. 1). It is important to study these large earthquakes for not only clarifying their causal mechanisms but also the reduction of earthquake hazards. Here we introduce a few case studies of recent large earthquakes associated with the Asian orogeny and plate
subductions.

The 12 May 2008 Wenchuan earthquake (M 8.0) occurred in the Longmenshan fault zone at the eastern margin of the Tibetan Plateau and caused more than 69,000 fatalities. Lei and Zhao (2009, 2016a, 2016b) investigated the detailed 3-D velocity structure of the crust and upper mantle beneath Wenchuan and adjacent areas. They find that the crustal structure in the source area exhibits prominent low-V and high-Poisson’s ratio (high-σ) anomalies, indicating that in addition to compositional variations, fluid-filled fractured rock matrices exist in the Longmenshan fault zone, which may have influenced the nucleation of the large earthquake. Significant low-V anomalies are revealed between the main shock hypocenters of the 2008 Wenchuan earthquake and the 2013 Lushan earthquake (M 7.1), which may explain why their aftershock zones extended northward and southward, respectively. The relocated aftershocks of the 2011 Yingjiang earthquake (M 5.8) and the 2014 Ludian earthquake (M 6.5) in the same region show a conjugate-shaped distribution, which may explain why the two moderate-sized earthquakes caused heavy damage. The large earthquakes in eastern Tibet are located at boundaries of low-V and high-V anomalies in the upper mantle. The structural heterogeneities in the crust and upper mantle are associated with hot upwelling and corner flows in the BMW above the subducting Indian slab beneath eastern Tibet, as well as slab dehydration, which affect the seismogenesis in the region (Lei and Zhao, 2016b).

Detailed 3-D Vp and Vs images as well as Vp azimuthal anisotropy in the crust and uppermost mantle beneath the Helan-Liupan tectonic belt in western China are determined (Cheng et al., 2016). Significant low-V anomalies are revealed in the lower crust beneath the Qilian
Orogenic Belt and Western Qinling, which reflect a weakened zone mainly caused by water and capable of ductile flow on a geological timescale. Their Vp anisotropy results suggest that the flow direction in the lower crust is nearly parallel to the direction of the geodetic crustal motion and that of the upper mantle flow beneath the northeastern corner of the Tibetan Plateau. Most of the 26 large crustal earthquakes (M 6.0–8.5) during 1125–2016 in the region occurred in the boundary zones where Vp and Vs change drastically over a short distance. Beneath the earthquake source areas, fluid-related low-V zones exist widely in the lower crust. The fluids may result from dehydration of hydrous minerals in the deeper crust and uppermost mantle. When the fluids migrate upward to the active faults in the upper crust, the fault-zone friction is reduced and so large crustal earthquakes can be triggered (Mishra and Zhao, 2003; Huang and Zhao, 2004; Qi et al., 2006; Zhao et al., 2011a; Cheng et al., 2016).

High-resolution tomographic images of seismic velocity (Vp, Vs) and attenuation (Qp, Qs) of the NE Japan forearc are determined for investigating the 2011 Tohoku-oki earthquake (Mw 9.0) and its induced tsunami (Zhao et al., 2011b; Huang and Zhao, 2013; Liu et al., 2014; Liu and Zhao, 2017a). The results show that the Tohoku megathrust zone exhibits significant lateral variations of seismic velocity and attenuation, and most large megathrust earthquakes (M 7.0–9.0) during 1900–2011 are found to occur in high-V and high-Q areas or the boundary between high-V/high-Q and low-V/low-Q anomalies. The high-V and high-Q zones may represent high-strength asperities at the plate interface where the subducting Pacific plate and the overriding...
Okhotsk plate are strongly coupled. A shallow high-V zone with large coseismic slips near the Japan Trench may account for the 2011 main shock asperity. Because it is an isolated asperity surrounded by low-V patches, most stress on it was released in a short time and the plate interface became decoupled after the M 9.0 earthquake. Thus the overriding Okhotsk plate there was shot out toward the Japan Trench and caused the huge tsunami (Huang and Zhao, 2013).

P-wave anisotropic tomography beneath Nepal and surrounding areas is determined to study the 25 April 2015 Nepal earthquake (M 7.9) and geodynamics related to the India-Asia collision (Wei and Zhao, 2016). The results show that the 2015 Nepal earthquake and the 1833 Nepal earthquake (M 8.0) occurred in a high-V zone which coincides with the coseismic slip area of the 2015 Nepal main shock (Fig. 10). The high-V zone may reflect a strongly coupled patch (i.e., asperity) in the megathrust zone between the subducting Indian plate and the overlying Eurasian plate. This result suggests that the nucleation of the Nepal earthquakes was controlled by structural heterogeneities in the megathrust zone, similar to the 2011 Tohoku-oki earthquake (Zhao et al., 2011b). Significant variations of Vp azimuthal anisotropy are revealed across the Himalaya collision belt. The predominant FVD is NE-SW beneath northern India, whereas it becomes NW-SE beneath the Himalaya, suggesting that the fossil anisotropy in the Indian plate is overprinted by the ongoing India-Asia collision (Wei and Zhao, 2016). Recently, a change in Vp azimuthal anisotropy is revealed in the asperity of the 2011 Tohoku-oki earthquake (Liu and Zhao, 2017a). However, the Vp anisotropic tomography of the Nepal earthquake area has a much lower resolution, hence the relationship between the Vp anisotropy and the seismogenesis is still not clear, which should be investigated in future studies.

Wang et al. (2017a) determined detailed 3-D images of seismic velocity (Vp, Vs), Poisson’s ratio (σ) and seismic attenuation (Qp and Qs) in the source area of the 2016 Kumamoto earthquake (M 7.3) (Fig. 11). Their results show that the 2016 Kumamoto earthquake occurred in a high-V, high-Q and low-σ zone in the upper crust, which is surrounded and underlain by low-V, low-Q and high-σ anomalies in the lower crust and upper mantle. These results suggest that the 2016 Kumamoto earthquake took place in a brittle seismicogenic layer in the upper crust, but its rupture nucleation was affected by fluids and arc magma ascending from the mantle wedge.

Fig. 12 shows Qp and Qs images of the Japan subduction zone determined by Wang et al. (2017b). The subducting Pacific and Philippine Sea slabs are imaged clearly as dipping high-Q zones where intermediate-depth earthquakes occur actively, whereas low-Q anomalies are revealed in the crust and mantle wedge under the volcanic front and back-arc areas. Low-frequency microearthquakes are located in or around the low-Q zones in the lower crust and uppermost mantle, which are related to fluids and arc magmas ascending from the upper-mantle wedge. The Q images are very similar to the velocity images (e.g., Zhao et al., 2015; Liu and Zhao, 2016), both of which reflect very well the structural heterogeneity and subduction dynamics of the region.

7. Deep slabs and deep earthquakes

Deep earthquakes occur at the MTZ depths within the subducting slabs. However, the causal mechanism of deep earthquakes is still not well understood. Several mechanisms for deep earthquakes have been proposed (e.g., Frohlich, 2006; Houston, 2015; Ye et al., 2016), including transformational faulting triggered by metastable olivine transforming to spinel in the cold, stressed core of the subducting slab, thermal instability and run-away shear melting, and dehydration embrittlement. All of these mechanisms depend on the thermal structure of deep slabs and the deviatoric stress conditions associated with the slabs impinging on the upper-lower mantle boundary (e.g., Karato et al., 2001; Ye et al., 2016). It is challenging to distinguish between these possible mechanisms for deep earthquakes, because of the difficulty to clarify their source dimensions and rupture processes, as well as the fine slab structure in and around the source zones of deep earthquakes. Among these mechanisms, dehydration embrittlement is considered to operate for the intermediate-depth earthquakes but may not for the deep earthquakes (e.g., Kirby et al., 1996; Mishra and Zhao, 2004; Houston, 2015). The viability of transformational faulting as a mechanism for deep earthquakes depends on the presence of a sufficient amount of metastable phase. So far, a metastable olivine wedge has been detected within the subducting Pacific slab at the MTZ depths beneath SW Japan (Iida and Suetsugu, 1992; Kawakatsu and Yoshioka, 2011), Mariana (Kaneshima et al., 2007; Kudo et al., 2009), and the Japan Sea (Jiang et al., 2008, 2015), and it is considered that the generation of deep earthquakes in these regions is related to the existence of the metastable olivine wedge in the slab.

On 30 May 2015 an isolated deep earthquake (≈670 km, M 7.9) occurred to the west of the Bonin Islands (Figs. 1 and 13). This earthquake is the deepest large event occurring in and around Japan during the observational history of the Japan Meteorological Agency in the past 140 years. Globally, it is the deepest event with M ≥ 7.8 in the seismological record (Ye et al., 2016). It is an isolated event locating...
over 100 km deeper than the Wadati-Benioff zone seismicity recorded so far. Hence, this Bonin event is not part of the mainstream deep seismicity, and its relationship to the subducting Paciﬁc slab and the MTZ is unclear. To date, several studies have investigated this unusual deep earthquake but obtained controversial results on its source location relative to the subducting Paciﬁc slab (Ye et al., 2016; Takemura et al., 2016; Porritt and Yoshioka, 2016; Zhao et al., 2017).

To clarify its causal mechanism and its relationship to the subducting Pacific slab, Zhao et al. (2017) determined a detailed Vp tomography of the deep earthquake source zone using a large number of arrival-time data. Their results show that this large deep event occurred within the subducting Pacific slab which is penetrating into the lower mantle (Fig. 13). In the Izu-Bonin region, the Paciﬁc slab is split at ∼28° north latitude, i.e., slightly north of the 2015 deep event hypocenter. In the north, the slab becomes stagnant in the MTZ, whereas in the south the slab is directly penetrating into the lower mantle (Fig. 13c). Zhao et al. (2017) relocated the 2015 Bonin deep event using their 3-D Vp model. The relocated focal depth is 667.2 ± 0.5 km, and the relocated hypocenter is located within the high-V slab but close to the eastern boundary of the near-vertical slab (Fig. 13b). The slab-related high-V zone looks thicker at depths of 600–800 km (Fig. 13b), which may suggest that the slab has thickened near the MTZ bottom due to resistance at the upper-lower mantle boundary. This unusual deep earthquake was caused by joint effects of several factors, including
the Pacific slab’s fast deep subduction, slab tearing and thermal variation, stress changes and phase transformations in the slab, and complex interactions between the slab and the mantle (Zhao et al., 2017). It is not clear why the isolated deep earthquake is so large, but its large size indicates the presence of a large volume of material still in seismogenic conditions (Lundgren and Giardini, 1994; Okal, 2001). There may be very infrequent mineral transformation or volatile release processes that occur only under particularly high deviatoric stress conditions allowing large dynamic stress relaxations to take place (Ye et al., 2016).

Fig. 14 shows whole-mantle tomographic images beneath the Izu-Bonin region and the Philippine Sea determined by Zhao et al. (2017). Below the Pacific slab in the MTZ, intermittent high-V zones are visible in the lower mantle, and broad high-V anomalies exist above the core-mantle boundary, which reflect old pieces of the Pacific slab and other ancient slabs that have collapsed down to the lower mantle and reached the core-mantle boundary due to gravitational instability caused by phase transformations (e.g., Maruyama, 1994; Zhao, 2004; Zhao et al., 2017).

8. Discussion and conclusions

Future advances of seismic imaging of the Asian region mainly depend on the progress in seismic instrumentation, because the data coverage determines the first-order features of seismic images. The distribution of the existing seismic stations is very inhomogeneous in the Asian region (see, e.g., Wei et al., 2015, 2016). Most of the permanent seismic stations are installed on the Japan Islands, South Korea, and East China, whereas the other parts of Asia are poorly instrumented. There are few seismic stations in the Pacific Ocean and the marginal seas. Gradual deployment of seismometers on seafloor and in those less instrumented land areas will be the most important task for seismologists from now. Installing a dense permanent or portable OBS (ocean bottom seismometer) network in the marginal seas (e.g., the Japan Sea, the East China Sea) will be necessary to resolve important geodynamic issues, such as the fate of the subducting Pacific and PHS slabs, the fine structure and convection in the BMW, the mechanism of deep earthquakes, and the back-arc spreading and intraplate magmatism. A joint use of the OBS data and the land-based network data will result in much better tomographic images.

To have a thorough understanding of the structure and dynamics of the Asian orogens and subduction zones, updated findings of other branches of Earth sciences are needed, such as geology, geochemistry and mineral physics, which are very helpful to better interpret the seismological results. In the following, we show an example of such a multidisciplinary study. Recently, detailed tomographic images beneath NE Japan are obtained (Zhao et al., 2015), which reveal a unique domain with a prominent low-V anomaly in the crust and mantle wedge beneath the fore-arc area (Fig. 15). The low-V zone was interpreted as a water wall in the forearc mantle wedge and crust, which may reflect a column of fluids from the slab dehydration and may play an important role in the generation of large crustal earthquakes (Zhao et al., 2015). Note that the vertical cross-section in Fig. 15 does not pass through the active arc volcanoes, hence the low-V zone under the volcanic front is not obvious. The water wall (or water curtain) exists immediately beneath the non-volcanic fore-arc of NE Japan (Fig. 15). As illustrated in Fig. 16a, NE Japan clearly exhibits a double-arc system with a non-volcanic arc on the oceanic side (the Kitakami and Abukuma Mountains) and a volcanic arc (the volcanic front) along the N-S strike of Honshu Island (the Ou Mountain). These parallel-running along-arc topographic reliefs are clearly separated from each other by a narrow depression called the Kitakami Lowland, through which the Kitakami River runs in the N-S direction. In contrast to the Ou Mountain with multiple active and dormant volcanoes, the Kitakami and Abukuma Mountains are composed of relatively older supra-crustal rocks of the Cambrian to Mesozoic ages (e.g., Ehiro, 2001; Isozaki et al., 2015; Fig. 16b), without any sign of active volcanism or hydrothermal activity. The reason for the occurrence of such a non-volcanic arc in NE Japan has not been properly explained to date.

A plausible explanation for the emergence of the non-volcanic arc is the uplift of surface crust driven by an along-arc up-rising domain within the wedge mantle. The expected temperature in the fore-arc wedge mantle is too low to induce partial melting of peridotite, thus it is not related to any magmatism. Instead, the tomographic image (Fig. 15) suggests that something buoyant is rising up within the wedge mantle, e.g., water-containing rocks. A possible candidate is hydrated peridotite in the form of serpentinite, because rock volume increases and density decreases by the mineral phase transition from the olivine/pyroxene to serpentinite. In the Izu-Bonin-Mariana arc, the occurrence of serpentinite seamounts with high-P/T blueschists clasts on the modern trench inner wall was reported (e.g., Fryer et al., 1985, 1999; Maekawa et al., 2001), indicating the serpentinite formation in the fore-arc wedge mantle. But in the Kitakami Mountain, there is no extensive exposure of such well-proven fore-arc serpentinite.

Along the modern Japan Trench (Fig. 16c) as well as the Izu-Bonin Trench, active tectonic erosion (subduction erosion) has occurred since the Miocene time, as clearly demonstrated by various lines of evidence from seismic profiles and sedimentary sequences off NE Japan (e.g., von Huene and Culotta, 1989; von Huene and Scholl, 1991). This suggests that a large amount of fore-arc crust, together with sediments, have been subducted and transported into the deeper mantle through the subduction channel atop the descending Pacific plate. The massive subduction of water-containing sediments can supply water of large quantity enough to hydrate the overlying peridotite of wedge mantle.

The low-V anomaly beneath the fore-arc revealed by seismic tomography (Fig. 15) can be viewed as a domain of water-saturated peridotite with relatively high buoyancy. We speculate that the origin of the double arc in NE Japan is in the water-addition to the wedge mantle by subduction erosion. In order to check this scenario, we need to examine similar water curtain domains beneath fore-arc in other arc-trench systems, in particular, those with the double-arc feature.

Recently, it is proposed that the Hadean crustal KREEP materials may have sunk to the MTZ depths and even the core-mantle boundary, forming the second and third continents in the mantle (Kawai et al., 2009, 2013; Dohm and Maruyama, 2015; Maruyama and Ebisuzaki,
2017; Maruyama et al., 2017; Sawada et al., 2017). It is possible that these Hadean KREEP materials may have become heat sources for hot mantle upwelling, mantle plumes and super-plumes, which may be detected by seismic tomography as low-V anomalies in and around the MTZ and the deep lower mantle (e.g., Fig. 14). This will be an important research subject in future studies of seismic imaging of the deep structure beneath Asia, because a large amount of crustal materials may have been brought to the deep mantle by the active subductions occurring in this region during the past long geological history.

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Fig. 16. Topographic map (a) and geologic sketch map (b) with a profile (c) of the Tohoku district, NE Japan. adopted from Geospatial Information Authority of Japan, http://www.gsi.go.jp/tohoku/chikei.html; Isuzuki et al., 2015.
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