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"Double Door" Opening of the Japan Sea Inferred by Pn Attenuation Tomography

Geng Yang[1,2], Lian-Feng Zhao[1,3], Xiao-Bi Xie[4], Xi He[1], Yan Lü[1], and Zhen-Xing Yao[1]

[1]Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China, [3]Heilongjiang Mohe Observatory of Geophysics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [4]Institute of Geophysics and Planetary Physics, University of California, Santa Cruz, CA, USA

Key Points:

- A high-resolution broadband Pn attenuation model is obtained beneath the Japan Sea
- Hot mantle materials ascend to feed the volcanoes in NE Asia, intruding into and thickening the oceanic crust in the Japan Sea
- Divergent mantle flows likely push the fan-shaped rotational opening of the Japan Sea

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

L.-F. Zhao,
zhaolf@mail.iggcas.ac.cn

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Author Contributions:

Conceptualization: Lian-Feng Zhao, Xiao-Bi Xie
Data curation: Geng Yang, Lian-Feng Zhao, Xi He, Yan Lü
Formal analysis: Geng Yang, Lian-Feng Zhao, Xiao-Bi Xie
Funding acquisition: Lian-Feng Zhao, Zhen-Xing Yao
Investigation: Lian-Feng Zhao, Yan Lü
Methodology: Lian-Feng Zhao, Xiao-Bi Xie
Project Administration: Lian-Feng Zhao, Zhen-Xing Yao
Resources: Lian-Feng Zhao
Software: Lian-Feng Zhao, Xiao-Bi Xie
Supervision: Lian-Feng Zhao, Xiao-Bi Xie, Zhen-Xing Yao
Validation: Geng Yang, Lian-Feng Zhao, Xi He
Visualization: Geng Yang, Xi He
Writing – original draft: Geng Yang

Abstract The extension of back-arc basins and formation of marginal seas following the subduction of oceanic lithosphere are usually attributed to the rollback of subducting slabs and distorted mantle convection. However, for the Japan Sea, the largest marginal sea in the northwestern Pacific, its opening is unlikely only resulted from the subduction of the Pacific plate because of the coeval Philippine plate subduction and the arcuate arc volcanic zone. Therefore, the present-day thermal structure in the uppermost mantle, which can be directly constrained by strong Pn-wave attenuation, plays a vital role in understanding the Japan Sea opening. Here, we observe two belts of strong Pn attenuation beneath the Japan Sea; their strikes are generally consistent with local Pn anisotropy and the retreat directions of the Pacific and Philippine trenches. Hence, there seem to be two divergent mantle flows in the uppermost mantle, pushing a "double door" for the Japan Sea opening.

Plain Language Summary The western Pacific is one of the most active regions of global tectonics. For the Japan Sea, the largest marginal sea in the northwest Pacific, its formation mechanism is still controversial. The Japan Sea may have experienced a complex evolution process driven by the superposition of multiple mechanisms, and finally produced a diamond-shaped ocean. The present thermal structure in the uppermost mantle, which can be directly constrained by strong Pn-wave attenuation, plays a vital role in understanding the Japan Sea opening. In this study, we construct a high-resolution broadband Pn attenuation model for the uppermost mantle beneath the Japan Sea. Two strong Pn attenuation belts are observed in this region, with their strikes generally consistent with the local Pn velocity anisotropy and the opening directions of the Japan Sea. Therefore, two divergent mantle flows likely exist in the uppermost mantle, pushing the opening of the Japan Sea like a "double door." These mantle flows could be part of mantle convection in a big mantle wedge, where ascending hot materials from the deep mantle not only feed volcanoes in northeastern Asia but also thicken the back-arc oceanic crust.

1. Introduction

The eastern Asian and western Pacific margins, including the Japan Sea, are areas related to plate subduction and extrusion due to the collision of the Pacific, Philippine Sea, Eurasian, and Okhotsk plates during the late Mesozoic and Cenozoic (Lallemand & Jolivet, 1985; Martin, 2011) (Figure 1a). However, the opening mechanism of the Japan Sea, a representative example of a virtually intact continent-ocean back-arc system, is still unclear and under debate (Van Horne et al., 2017). In general, the formation of a marginal sea in combination with back-arc extension can be ascribed to two driving mechanisms: small-scale convection in mantle wedge induced by descending lithosphere (Toksöz & Bird, 1977) (Figure 1b) and ascending convection generated by both the foundering of the descending lithosphere and seaward migration of the trench (Uyeda & Kanamori, 1979) (Figure 1c). However, the Japan Sea may have experienced complex evolution driven by the superposition of multiple mechanisms, which finally produced a diamond-shaped ocean (Van Horne et al., 2017).

The Japanese Islands were part of the northeastern edge of the Asian continent before the Late Cretaceous (Lallemand & Jolivet, 1985). Through short-term continental breakage and seafloor spreading, the Japan Sea began to open and gradually met the Pacific and Philippine plates at a trench-trench-trench triple junction. Kawai et al. (1961) discovered the difference in the magnetization directions of the rocks collected in the southwestern and northeastern parts of the Japan Arc and suggested that this contrast may have been caused by deformation of the Japanese Islands in the late Mesozoic or early Tertiary. Otofuji et al. (1985) further proposed a

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fan-shaped rotation ("double door") opening model for the Japan Sea through the application of K-Ar dating technology to paleomagnetic data. At approximately 21–15 Ma, the southwestern and northeastern parts of the Japan Arc rotated clockwise and counterclockwise by approximately 56° and 47°, respectively, around two rotation poles (Otofuji et al., 1985). Similar paleomagnetic evidence has also been obtained with slight biases in the opening times, opening stages, or rotation angles (e.g., Hayashida et al., 1991). However, since no obvious rotation-induced surface deformation has yet been observed, other models were also suggested, for example, the Japan Sea were pulled apart purely by two dextral strike-slip faults along the margins of the Korean Peninsula and the northeastern Japan Arc during the late Oligocene-early Miocene (Lallemand & Jolivet, 1985).

Seismic velocity is affected by temperature, partial melting, magnesium content, and the garnet to olivine ratio (Boyd et al., 2004), while attenuation is mainly affected by temperature (Debayle et al., 2020), thus is more sensitive in detecting the distribution of heat sources than the velocity (e.g., L.-F. Zhao et al., 2013). As the first arrival at epicentral distances between 200 and 2,000 km, the seismic Pn wave is mainly propagating in the uppermost mantle. Considering the finite frequency and interference of multiple diving waves refracted from the underside of the Moho discontinuity (Hill, 1973; Sereno & Given, 1990; Xie & Lay, 2017), the Pn energy can penetrate to a few dozens of kilometers below the Moho. The complex opening history of the Japan Sea can be recorded by thermal heterogeneities at the top of the upper mantle. On the other hand, these heterogeneities can be effectively constrained by Pn attenuation. Therefore, we conduct the Pn attenuation tomography beneath the Japan Sea and surrounding areas, and the results are used to detect the thermal structure in the uppermost mantle. By further combining other regional observations, for example, the Pn velocity and intraplate volcanic activity, the opening mechanism of the Japan Sea is investigated.

2. Data and Methods

We collected 29,232 vertical-component waveforms from 479 seismic events recorded at 242 stations from the China National Digital Seismic Network (CNDSN), Global Seismic Network (GSN) and Full-Range Seismograph Network (F-net) (Figure S1 in Supporting Information S1). The seismic sources include both natural earthquakes and six North Korean nuclear explosions (e.g., G. Yang et al., 2021), with their focal depths all above the Moho discontinuity (Laske et al., 2013). The parameters of stations, networks, earthquakes and the North Korean explosions used in this study are listed in Tables S1 and S2 in Supporting Information S2. For example, Figure S2 in Supporting Information S1 illustrates vertical-component waveforms from the sixth North Korean nuclear explosion (NKT6) and two natural earthquakes, bandpass filtered between 0.5 and 8.0 Hz. The Pn waves propagating through the oceanic and continental paths show quite different features due to different Moho discontinuity properties and lithospheric structures. Figure S3 in Supporting Information S1 illustrates the data preprocessing procedure following L. F. Zhao et al. (2015). We sampled Pn waveforms in a 0.7 km/s group velocity window around the IASP91 first arrival time and extracted the background noise in a pre-P arrival window with the same length. Both the Pn wave and noise spectra were calculated. A signal-to-noise ratio (SNR) of 2.0 was used as a criterion for Pn data selection, and the amplitudes of the Pn signal were then obtained after removing the noise.

After batch processing the waveform data, the single-station amplitudes are obtained from the observed Pn spectra at 42 frequencies between 0.5 and 20.0 Hz. Double-station data are calculated based on the amplitude ratio between stations with similar azimuth directions. We also construct Pn geometric spreading model by fitting the actual Pn data set used in this study (Yang, 2011; X. Yang et al., 2007; L. F. Zhao et al., 2015). Constant regional Q models at individual frequencies are calculated from double-station data and used as the initial model for further inversion. Then the single- and double-station data are jointly inverted by the least squares orthogonal factorization (LSQR) method (Paige & Saunders, 1982) independently at each frequency. Finally, the Pn Q distributions are obtained after removing the influence of the source, radiation pattern and geometric spreading. For detailed methodology, refer to L. F. Zhao et al. (2015) and the Text S1 in the Supporting Information S1.

3. Results

A broadband Q_p tomographic model composed of 42 frequencies between 0.5 and 20.0 Hz is constructed for the uppermost mantle beneath the Japan Sea and surrounding areas. Figures S7a–S7d in Supporting Information S1 illustrate Q_p images at 2.0, 4.0, 5.0, and 8.0 Hz, respectively. Due to the dense ray coverage from the large data set, the resolutions can reach to 1° × 1° or higher (Figure S7f in Supporting Information S1), and strong lateral

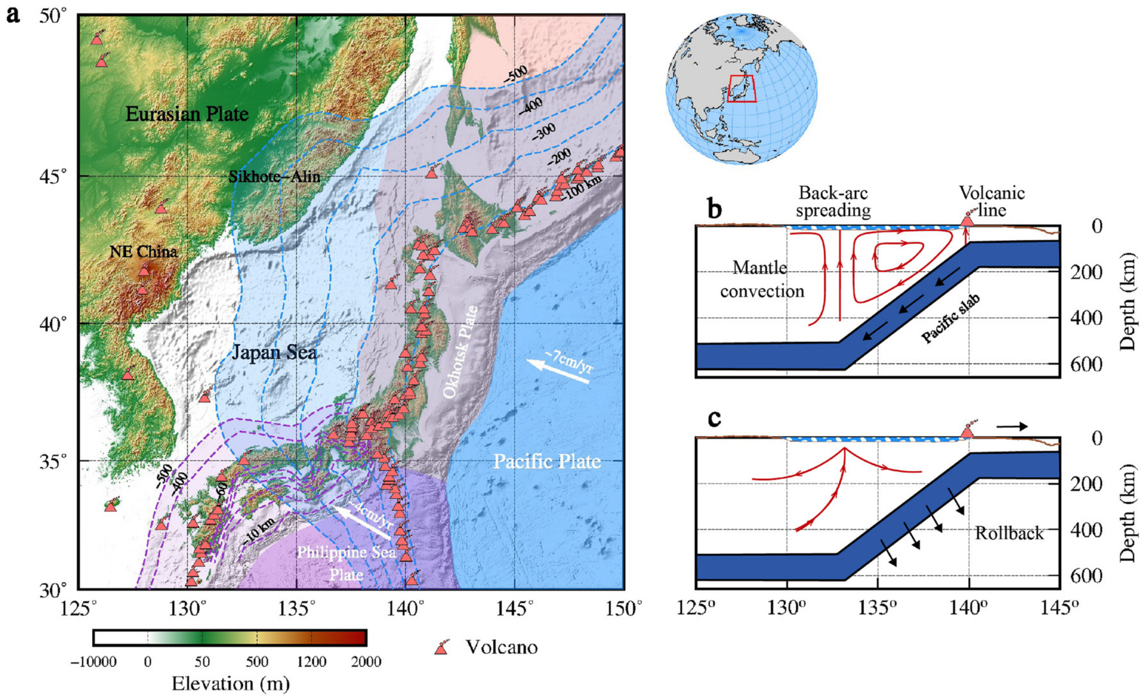

Figure 1. Map showing the study area. (a) Map showing plate positions around the Japan Sea and subduction tectonics, where the dashed lines indicate subduction depth contours (Hayes et al., 2012; Hirose et al., 2008; W. Wei et al., 2015). Possible driving mechanisms for marginal sea opening, including (b) small-scale mantle convections induced by descending lithosphere, and (c) ascending convections generated by subduction rollback. The pattern of the subducting Pacific slab is based on previous velocity tomography (e.g., D. Zhao et al., 2012).

variations in attenuation can be seen at all frequencies. As a typical case, at 2.0 Hz, 21,292 single-station and 17,210 double-station ray paths are used in the Pn attenuation tomography (Figure S7e in Supporting Information S1). The statistics of Pn Q for individual geological blocks demonstrate that, the Q values versus frequency curves can be distinguished among different blocks. Between 1.0 and 15.0 Hz, their frequency dependency are similar (Figure 2a).

Between 1.0 and 15.0 Hz, low Q_p anomalies are distributed beneath the Changbaishan, Jingpohu and Ch'uga-Ryong volcanoes in Northeast China and the Korean Peninsula (Figure 2b), where both low Pn-wave velocities (Figure 2f) (Lü et al., 2019) and reduced *S*-wave velocities (Fan et al., 2020; Tang et al., 2014) were obtained in previous studies. At lower frequencies between 1.0 and 5.0 Hz, the scattered low-Q anomalies are merged beneath Changbaishan and Jingpohu volcanoes, which may suggest these distributed magmatic activities are connected at deeper places since the low-frequency signals may penetrate slightly deeper (Figures 2c and 2f). The uppermost mantle beneath the northwestern and southwestern edges of the Japan Sea is characterized by two low Q_p zones (Figures 2b–2d), which are consistent with low phase velocities of Rayleigh waves in the 40–80 s period (Fan et al., 2020). The magmatic activities along the Japan arc exhibit strong attenuations between 1.0 and 15.0 Hz (Figure 2b), and the low-Q anomaly is even stronger within the higher frequency range between 5.0 and 15.0 Hz (Figure 2d). In contrast, the Japan Trench around the forearc is characterized by weak Pn attenuation and high Pn velocity, which should be related to the cold subducting slab (Du et al., 2022; Lü et al., 2019).

The uncertainty of the Pn attenuation tomography depends on the data coverage and inversion strategy. We inspected the inversion uncertainties from different aspects. With the inversion method used by us (L. F. Zhao et al., 2015), all Pn amplitude residuals at 42 frequencies are very close to Gaussian distributions after joint inversion for source terms, attenuations, and site responses (Figure S9 in Supporting Information S1). The uncertainty from the observations was examined by resampling the original data set using bootstrapping technique (Efron, 1983). Lower standard deviations show that the uncertainties in the data can be well suppressed by high-density raypath coverage (Figure S10 in Supporting Information S1). The reliability and robustness of the observed anomalies were further checked by using checkerboard test and synthetic model tests. 1° × 1° checkerboard can be restored well at individual frequencies (Figure S8 in Supporting Information S1). Three synthetic

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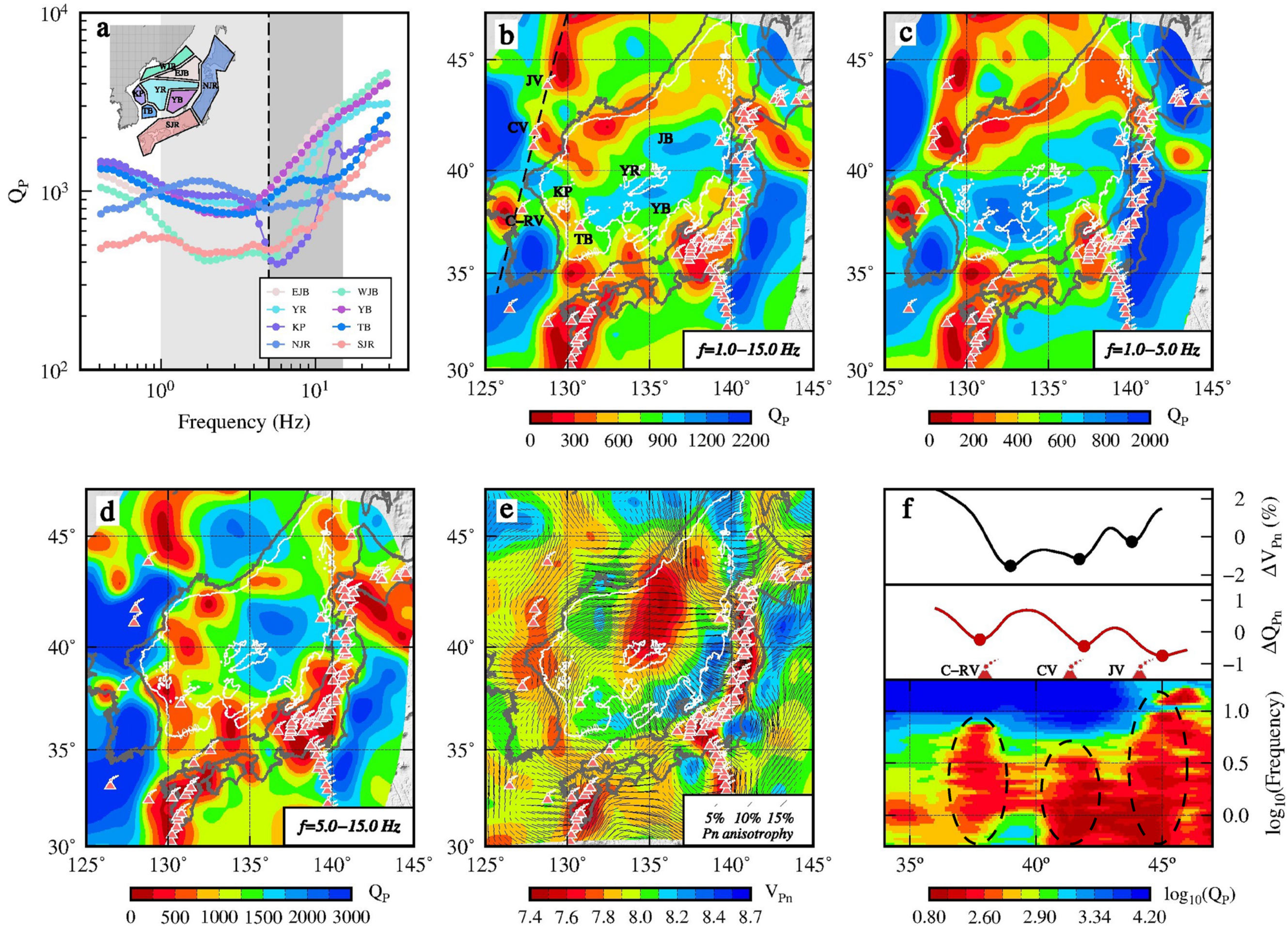

Figure 2. Tomographic images of the Pn attenuation, and Pn velocities and anisotropy in the study area. (a) Statistically averaged frequency-dependent Q values for individual geological blocks. The two shaded areas highlight the 1.0–5.0 Hz and 5.0–15.0 Hz frequency bands. (b–d) Broadband Q_p maps from 1.0 to 15.0 Hz, 1.0 to 5.0 Hz, and 5.0 to 15.0 Hz, respectively. (e) Pn velocity and its anisotropy (Lü et al., 2019). (f) A cross-section (denoted with black dotted line in Figure 2b) through intraplate volcanoes for comparing the ΔV_{Pn} (black line) (Lü et al., 2019), ΔQ_{pn} (red line), and frequency-dependent Q_P (lower panel). The minimum values of Pn velocity and attenuation are marked on these curves, respectively. The black dashed ellipses indicate the strong attenuation anomalies corresponding to three volcanic areas. JB = Japan Basin; WJB = Western Japan Basin; EJB = Eastern Japan Basin; TB = Tsushima Basin; YB = Yamato Basin; KP = Korean Plateau; YR = Yamato Bank; NJR = North Japan Arc; SJR = South Japan Arc; JV = Jingpohu volcano; CV = Changbaishan volcano; C-RV = Ch'uga-Ryong volcano.

models were constructed using anomalies similar to the real attenuation models. Shapes and magnitudes of these synthetic anomalies were also well retrieved (refer to Figure S11 and Text S2 in Supporting Information S1 for details).

4. Discussion

4.1. Intraplate Volcanoes and Mantle Flow Pattern

The low velocities revealed by seismic velocity tomography provided evidence supporting hot upwelling under Changbaishan volcano (e.g., Fan et al., 2020; Tang et al., 2014). It is suggested this back-arc volcano is related to the dehydration of the stagnant Pacific slab (D. P. Zhao et al., 2009) or to the upwelling of deep hot mantle material (Tang et al., 2014). In our Pn attenuation tomographic result, there are three separated strong attenuation anomalies under intraplate volcanoes (Figures 2a and 2f), suggested hot mantle materials may rise to the upper mantle and divide into several branches to feed Changbaishan, Jingpohu, and Ch'uga-Ryong volcanoes (Lü et al., 2019).

A big mantle wedge is observed in the western Pacific subduction area (e.g., D. P. Zhao et al., 2009). The related convection can provide hot sources to intraplate volcanoes. Hot mantle materials revealed by low Q_p values seem to flow from Northeast Asia to the northwestern and southwestern edges of the Japan Sea. Possible regional mantle flows indicated by the low-Q belts are perpendicular to the strike of the Japan Arc (Figure 2b and Figure S7c in Supporting Information S1). The directions of regional mantle flows are inferred to be parallel to the roll-back directions of the Philippine Sea and Pacific slabs based on both the fast directions of Pn velocity anisotropy (Lü et al., 2019) (Figure 2e) and the directions of shear wave splitting (Long & van der Hilst, 2005) (orange and blue bars in Figure 3a). Therefore, a laterally divergent pattern of mantle flows can be confirmed by strong Pn attenuations stretched from Northeast Asia to the Japan Arc (Figures 3b–3d). These flows may be related to the deep convections within the big mantle wedge (D. P. Zhao et al., 2009).

Late Cretaceous-Pliocene basalts outcropped in NE China date back to about 80 Ma (e.g., Liu, 1987; J. Zhou et al., 2020), and the eastern Sikhote-Alin volcanism has occurred since about 40 Ma (Matsuda et al., 1998; Nohda, 2009), while the basement basalts in the Japan Sea are relatively young, about 24–18 Ma (Tamaki et al., 1992). Therefore, the volcanic activities likely began in the Sikhote-Alin region and migrated to the northeast Japan region across the Japan Sea, accompanied by the eastward injection of asthenosphere into the mantle wedge during the Miocene (Nohda, 2009; Nohda et al., 1988; Tatsumi et al., 1989). Both the Changbaishan (4.77–0.08 Ma) and Ulleung (∼1.4 Ma–5 ka) volcanoes (Chen et al., 2021; G. B. Kim et al., 2014; H. Wei et al., 2003, 2007) developed on the opening path of the southwestern Japan Arc (Figure 3a), which likely indicates the direction of mantle flow. The age distribution of these basalts are consistent with the divergent pattern of mantle flow. Furthermore, both the Changbaishan and Ulleung volcanic activities are related to the involvement of subduction-related compositions, and may be fed by similar two-layer magma chamber structures, according to the geochemical analyses of volcanic rock compositions and crystallization temperatures (Chen et al., 2021).

4.2. Heat-Driven Reworking of the Back-Arc Crust

The upwelling hot mantle materials will inevitably rework on the overlying crust. Strong lateral variations of back-arc crustal structures in the Japan Sea can be revealed by ocean drilling data (Tamaki et al., 1992) (Figure 4). Typical oceanic crust with thickness of approximately 8.5 km is observed in the central and eastern Japan Basin. The hierarchical structure includes a sedimentary layer and two oceanic layers with their *P*-wave velocities of 3.3–6.2 and 6.6–6.8 km/s, respectively (Figure 4) (Hirata et al., 1992). The crust in the Yamato Basin, the Tsushima Basin and the western edge of the Japan Basin is significantly thicker than that in the eastern Japan Basin, although features similar layering structures (H. Kim et al., 1998; Sato et al., 2004, 2014). The thicker oceanic crust and poor magnetic lineation in the Tsushima and Yamato Basins may be caused by thermal perturbations under the lower crust during the shorter opening period (Hirata et al., 1989; Isezaki & Uyeda, 1973; H. Kim et al., 1998; Lee et al., 1999).

Both the western edge of the Japan Basin and the Tsushima Basin are characterized by strong attenuation anomalies (Figures 4 and 2b) and thicker oceanic crustal structures (H. Kim et al., 1998; Sato et al., 2014). The hot mantle flows seem to provide a large amount of molten material to form a thick igneous crust in the Tsushima Basin and on the northwestern edge of the Japan Basin during the opening of the Japan Sea. The weak Pn attenuation obtained beneath the Yamato Basin (Figure 2b) is consistent with the high-velocity anomalies observed by ocean bottom seismograph (OBS) surveys (Nakahigashi et al., 2015). The Yamato crust is thought to have been formed mainly by the extension of continental crust associated with the opening of the marginal sea (Nakahigashi et al., 2015; Tamaki et al., 1992). However, unique D-type basalts with deeper and hotter melting conditions are found in the Yamato Basin based on their incompatible trace element and Sr-Nd-Pb-Hf isotope compositions (Hirahara et al., 2015), indicating that the crustal thickening in the Yamato Basin may also be slightly influenced by the high-temperature mantle materials from the magmatic arc.

4.3. Double Door Opening of the Japan Sea

Based on paleomagnetic records, at approximately 21–15 Ma, the southwestern and northeastern parts of the Japan Arc rotated clockwise and counterclockwise, respectively, to provide space for the formation of the Japan Sea (Otofuji et al., 1985) (Figure 3a). The drag force of mantle flow may cause the overlying plate to tear and move toward the ocean (Miyashiro, 1986). However, neither single small-scale convection (Toksöz & Bird, 1977)

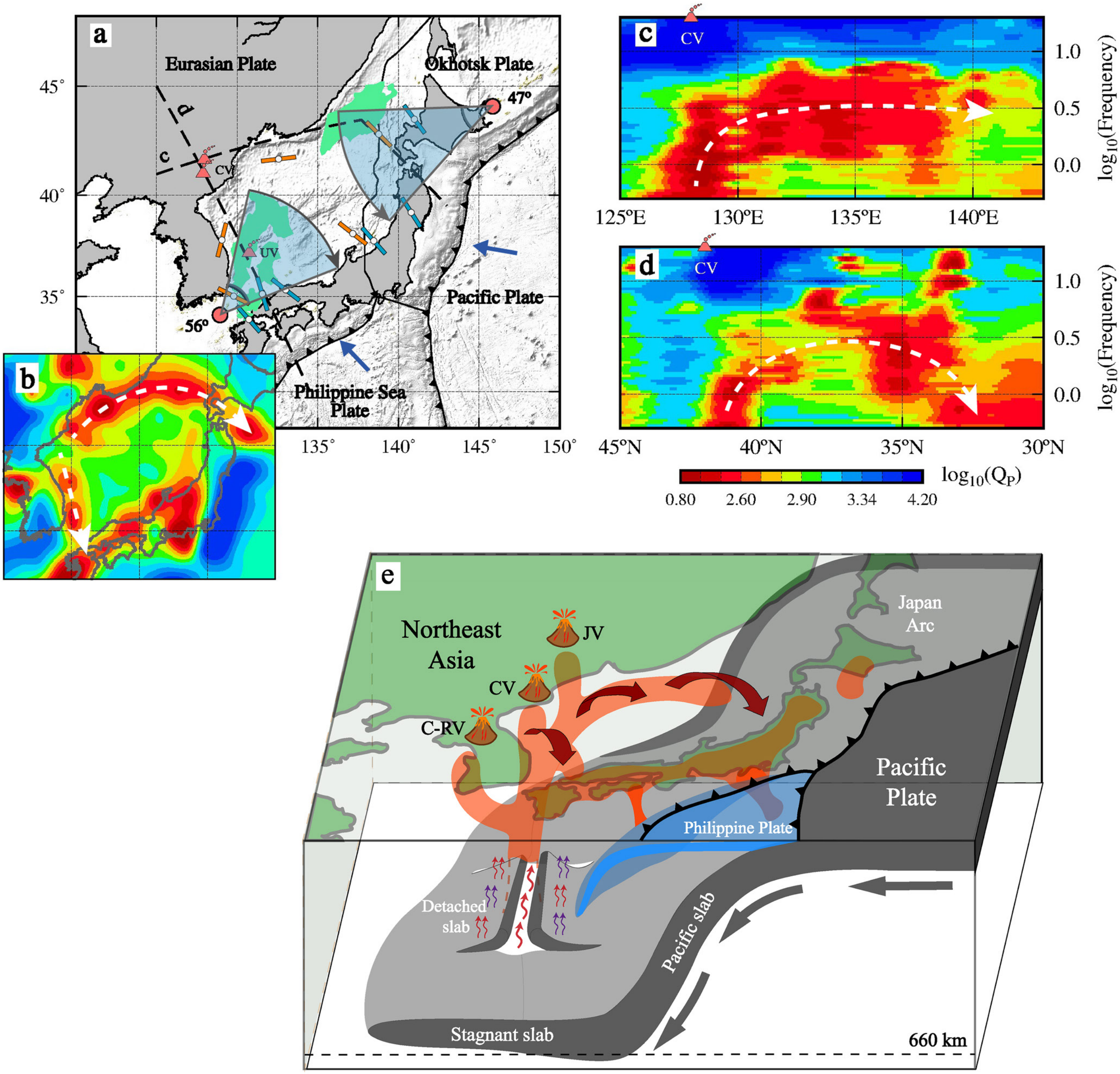

Figure 3. Possible mantle flows based on the Pn attenuation model. (a) Map showing the "double door" opening of the Japan Sea. The blue sectors indicate the old southwestern and northeastern parts of Japan (green blocks) rotated clockwise and counterclockwise approximately 56° and 47° around two rotation poles (red solid circles) (Otofuji et al., 1985). The white circles with orange and blue bars indicate the fast direction measured from previous Pn velocity anisotropy (Lü et al., 2019) and shear wave splitting studies (Long & van der Hilst, 2005). The black dashed lines represent the path of the two selected attenuation cross-sections. (b) 5.0 Hz Q_p model (Figure S7c in Supporting Information S1). (c, d) Selected Q_p cross-sections. (e) A speculative model showing the mantle dynamic processes. The red arrows indicate the directions of the estimated mantle flows. The subduction pattern of the Pacific slab is constrained by seismic receiver function studies (Wang et al., 2020) and velocity tomography (Li et al., 2008) (refer to Figure S12 in Supporting Information S1). The deep hot upwelling beneath Changbaishan may be attributed to slab dehydration (Lei et al., 2013; D. P. Zhao et al., 2009), escaped materials from below the 660 km discontinuity (Tang et al., 2014) or expelled hydrous mantle minerals from the transition zone (Yang & Faccenda, 2020).

nor ascending convection (Uyeda & Kanamori, 1979) in the mantle wedge (Figures 1b and 1c) is enough to rotationally open the Japan Sea. Two possible driving forces of rotation are the Pacific slab rollback along a curved hinge line and divergent slab pull forces from both the subducting Pacific and Philippine Sea plates (Martin, 2011). Two regional mantle flows constrained by strong Pn attenuation remarkably coincide with the counterclockwise and clockwise rotations of the two microplates of the Japan Arc, with their directions similar

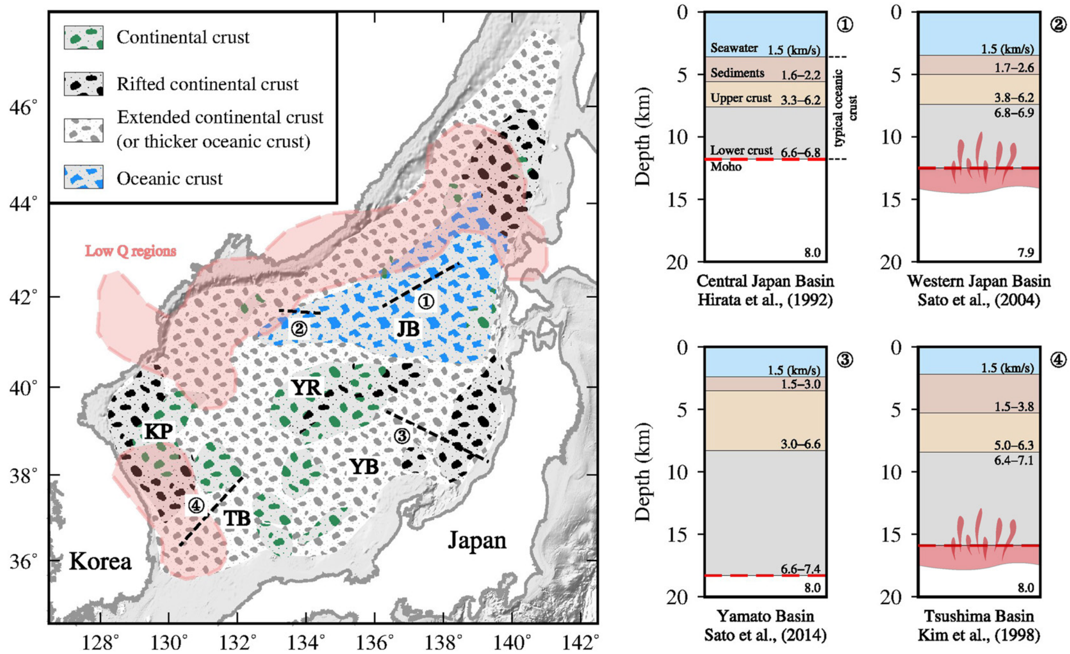

Figure 4. Crustal structures of the Japan Sea back-arc (modified from Tamaki et al. (1992)). Different crust types are indicated by green, black, gray, and blue spots. The red-shaded areas indicate strongly attenuated regions. The black-dashed lines marked with serial numbers represent previous seismic survey lines (Hirata et al., 1992; H. Kim et al., 1998; Sato et al., 2004, 2014), with their layered structures shown on the right.

to the retreats of the Philippine Sea and Pacific plates (Figures 3a and 3b). Therefore, the oceanward flow of hot mantle materials beneath Northeast Asia could be driven by the divergent rollbacks of the Philippine Sea and Pacific slabs. The Japan Sea tends to open rotationally like a double-sided door, possibly pushed by divergent mantle flows during the Miocene and Pliocene (Figure 3a). The westward migration of the Japan arc volcanoes indicates that the Japan Sea is likely in the initial stage of closure (Martin, 2011). However, the closure of the Japan Sea might not significantly change the mantle flow patterns. Thus, strong attenuation induced by regional mantle flows can still be observed clearly even at present.

5. Conclusions

Pn attenuation tomography was conducted in and around the Japan Sea. The observed strong Pn attenuation revealed the thermal structure in the uppermost mantle. Based on these findings, a mantle dynamic model was established for the opening process of the Japan Sea (Figure 3e). First, deep hot material upwelled from the Pacific stagnant slab lying in the transition zone and rose to the volcanoes in Northeast Asia (Lei et al., 2013; Tang et al., 2014; D. P. Zhao et al., 2009). Through several magmatic channels, these hot mantle materials fed intraplate volcanoes. The mantle materials flowed oceanward in separate directions, driven by the pull forces from divergent slabs of both the subducting Pacific and Philippine Sea plates. Hence, the Japan Sea opened like a double-sided door, possibly pushed by divergent mantle flows during the Miocene and Pliocene. The overlying crust that was thickened due to intrusion of hot mantle materials provides additional evidence of hot material upwelling and lateral flow driving the Japan Sea open. Double door tectonics were also observed in other regions, such as the western Mediterranean, Alboran, Tyrrhenian, and Pannonian regions (Martin, 2011).

Data Availability Statement

The broadband waveform data used in this study were collected from the China Earthquake Networks Center (CENC), the Data Management Center of the China National Seismic Network at the Institute of Geophysics, China Earthquake Administration (SEISDMC, https://doi.org/10.7914/SN/CB2010), the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC) at https://ds.iris.edu/wilber3/find_event (last

accessed July 2022), and the National Research Institute for Earth Science and Disaster Prevention (NIED) at http://www.fnet.bosai.go.jp (last accessed July 2022). Researchers can register for an account to apply for the NIED data. The global *P*-wave velocity data (Li et al., 2008) was collected at https://www.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section (last accessed July 2022). The single- and double-station Pn amplitude data used in this study can be accessed at the World Data Centre for Geophysics, Beijing (https://doi.org/10.12197/2021GA030). Certain figures were generated using Generic Mapping Tools (GMT; Wessel & Smith, 1998).

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References

Boyd, O. S., Jones, C. H., Sheehan, A. F., & Sheehan, A. F. (2004). Foundering lithosphere imaged beneath the southern Sierra Nevada, California, USA. *Science*, *305*(5684), 660–662. https://doi.org/10.1126/science.1099181

Chen, S.-S., Lee, S.-G., Simutė, S., Fichtner, A., Lee, T. J., Lee, Y.-S., et al. (2021). Geochemical and seismic tomography constraints of two-layer magma chambers beneath the bimodal volcanism: A case study of late Cenozoic volcanic rocks from Ulleung Island and Mt. Changbai (Paektu). *Chemical Geology*, *581*, 120386. https://doi.org/10.1016/j.chemgeo.2021.120386

Debayle, E., Bodin, T., Durand, S., & Ricard, Y. (2020). Seismic evidence for partial melt below tectonic plates. *Nature*, *586*(7830), 555–559. https://doi.org/10.1038/s41586-020-2809-4

Du, M., Lei, J., Zhao, D., & Lu, H. (2022). Pn anisotropic tomography of Northeast Asia: New insight into subduction dynamics and volcanism. *Journal of Geophysical Research: Solid Earth*, *127*(1), e2021JB023080. https://doi.org/10.1029/2021jb023080

Efron, B. (1983). Estimating the error rate of a prediction rule: Improvement on cross-validation. *Journal of the American Statistical Association*, *78*(382), 316–331. https://doi.org/10.1080/01621459.1983.10477973

Fan, X. L., Chen, Q. F., Legendre, C. P., & Guo, Z. (2020). Intraplate volcanism and regional geodynamics in NE Asia revealed by anisotropic Rayleigh-wave tomography. *Geophysical Research Letters*, *47*(1), e2019GL085623. https://doi.org/10.1029/2019gl085623

Hayashida, A., Fukui, T., & Torii, M. (1991). Paleomagnetism of the Early Miocene Kani Group in southwest Japan and its implication for the opening of the Japan Sea. *Geophysical Research Letters*, *18*(6), 1095–1098. https://doi.org/10.1029/91GL01349

Hayes, G. P., Wald, D. J., & Johnson, R. L. (2012). Slab1.0: A three-dimensional model of global subduction zone geometries. *Journal of Geophysical Research*, *117*(B1), B01302. https://doi.org/10.1029/2011jb008524

Hill, D. P. (1973). Critically refracted waves in a spherically symmetric radially heterogeneous earth model. *Geophysical Journal International*, *34*(2), 149–177. https://doi.org/10.1111/j.1365-246x.1973.tb02390.x

Hirahara, Y., Kimura, J. I., Senda, R., Miyazaki, T., Kawabata, H., Takahashi, T., et al. (2015). Geochemical variations in Japan Sea back-arc basin basalts formed by high-temperature adiabatic melting of mantle metasomatized by sediment subduction components. *Geochemistry, Geophysics, Geosystems*, *16*(5), 1324–1347. https://doi.org/10.1002/2015gc005720

Hirata, N., Karp, B. Y., Yamaguchi, T., Kanazawa, T., Suyehiro, K., Kasahara, J., et al. (1992). Oceanic crust in the Japan Basin of the Japan sea by the 1990 Japan-USSR expedition. *Geophysical Research Letters*, *19*(20), 2027–2030. https://doi.org/10.1029/92GL02094

Hirata, N., Tokuyama, H., & Chung, T. W. (1989). An anomalously thick layering of the crust of the Yamato Basin, southeastern Sea of Japan: The final stage of back-arc spreading. *Tectonophysics*, *165*(1–4), 303–314. https://doi.org/10.1016/0040-1951(89)90055-3

Hirose, F., Nakajima, J., & Hasegawa, A. (2008). Three-dimensional seismic velocity structure and configuration of the Philippine Sea slab in southwestern Japan estimated by double-difference tomography. *Journal of Geophysical Research*, *113*(B9), B09315. https://doi.org/10.1029/2007jb005274

Isezaki, N., & Uyeda, S. (1973). Geomagnetic anomaly pattern of the Japan Sea. *Marine Geophysical Researches*, *2*(1), 51–59. https://doi.org/10.1007/BF00451870

Kawai, N., Ito, H., & Kume, S. (1961). Deformation of the Japanese Islands as inferred from rock magnetism. *Geophysical Journal International*, *6*(1), 124–130. https://doi.org/10.1111/j.1365-246X.1961.tb02967.x

Kim, G. B., Cronin, S. J., Yoon, W. S., & Sohn, Y. K. (2014). Post 19 ka B.P. eruptive history of Ulleung Island, Korea, inferred from an intra-caldera pyroclastic sequence. *Bulletin of Volcanology*, *76*(4), 802. https://doi.org/10.1007/s00445-014-0802-1

Kim, H., Han, S., Lee, G. H., & Huh, S. (1998). Seismic study of the Ulleung Basin crust and its implications for the opening of the East Sea (Japan Sea). *Marine Geophysical Researches*, *20*(3), 219–237. https://doi.org/10.1023/A:1004573816915

Lallemand, S., & Jolivet, L. (1985). Japan Sea: A pull-apart basin? *Earth and Planetary Science Letters*, *76*(3–4), 375–389. https://doi.org/10.1016/0012-821X(86)90088-9

Laske, G., Masters, G., Ma, Z., & Pasyanos, M. (2013). Update on CRUST1.0—A 1-degree global model of Earth's crust. In *Geophysical research abstracts* (Vol. 15, No. (15), p. 2658). EGU general assembly.

Lee, G. H., Kim, H. J., Suh, M. C., & Hong, J. K. (1999). Crustal structure, volcanism, and opening mode of the Ulleung Basin, East Sea (Sea of Japan). *Tectonophysics*, *308*(4), 503–525. https://doi.org/10.1016/S0040-1951(99)00113-4

Lei, J., Xie, F., Fan, Q., & Santosh, M. (2013). Seismic imaging of the deep structure under the Chinese volcanoes: An overview. *Physics of the Earth and Planetary Interiors*, *224*, 104–123. https://doi.org/10.1016/j.pepi.2013.08.008

Li, C., van der Hilst, R. D., Engdahl, E. R., & Burdick, S. (2008). A new global model for P wave speed variations in Earth's mantle. *Geochemistry, Geophysics, Geosystems*, *9*(5), Q05018. https://doi.org/10.1029/2007gc001806

Liu, J. Q. (1987). Study on geochronology of the Cenozoic volcanic rocks in Northeast China. *Acta Petrologica Sinica*, *4*(2), 21–31.

Long, M. D., & van der Hilst, R. D. (2005). Upper mantle anisotropy beneath Japan from shear wave splitting. *Physics of the Earth and Planetary Interiors*, *151*(3–4), 206–222. https://doi.org/10.1016/j.pepi.2005.03.003

Lü, Y., Li, J., Liu, L., & Zhao, L. F. (2019). Complex uppermost mantle structure and deformation beneath the Northwest Pacific region. *Journal of Geophysical Research*, *124*(7), 6866–6879. https://doi.org/10.1029/2019jb017356

Martin, A. K. (2011). Double saloon door tectonics in the Japan Sea, Fossa magna, and the Japanese Island arc. *Tectonophysics*, *498*(1–4), 45–65. https://doi.org/10.1016/j.tecto.2010.11.016

Matsuda, T., Sakiyama, T., Enami, R., Otofuji, Y.-i., Sakhno, V. G., Matunin, A. P., et al. (1998). Fission–track ages and magnetic susceptibility of Cretaceous to Paleogene volcanic rocks in southeastern Sikhote Alin, Far East Russia. *Resource Geology*, *48*(4), 285–290. https://doi.org/10.1111/j.1751-3928.1998.tb00025.x

Miyashiro, A. (1986). Hot regions and the origin of marginal basins in the western Pacific. *Tectonophysics*, *122*(3–4), 195–216. https://doi.org/10.1016/0040-1951(86)90145-9

Nakahigashi, K., Shinohara, M., Yamada, T., Uehira, K., Sakai, S., Mochizuki, K., et al. (2015). Deep slab dehydration and large-scale upwelling flow in the upper mantle beneath the Japan Sea. *Journal of Geophysical Research: Solid Earth*, *120*(5), 3278–3292. https://doi.org/10.1002/2014jb011781

Nohda, S. (2009). Formation of the Japan Sea basin: Reassessment from Ar–Ar ages and Nd–Sr isotopic data of basement basalts of the Japan Sea and adjacent regions. *Journal of Asian Earth Sciences*, *34*(5), 599–609. https://doi.org/10.1016/j.jseaes.2008.08.003

Nohda, S., Tatsumi, Y., Otofuji, Y., Matsuda, T., & Ishizaka, K. (1988). Asthenospheric injection and back-arc opening: Isotopic evidence from Northeast Japan. *Chemical Geology*, *68*(3–4), 317–327. https://doi.org/10.1016/0009-2541(88)90029-0

Otofuji, Y. I., Matsuda, T., & Nohda, S. (1985). Opening mode of the Japan Sea inferred from the palaeomagnetism of the Japan Arc. *Nature*, *317*(6038), 603–604. https://doi.org/10.1038/317603a0

Paige, C. C., & Saunders, M. A. (1982). LSQR: An algorithm for sparse linear equations and sparse least squares. *ACM Transactions on Mathematical Software*, *8*(1), 43–71. https://doi.org/10.1145/355984.355989

Sato, T., No, T., Kodaira, S., Takahashi, N., & Kaneda, Y. (2014). Seismic constraints of the formation process on the back-arc basin in the southeastern Japan Sea. *Journal of Geophysical Research: Solid Earth*, *119*(3), 1563–1579. https://doi.org/10.1002/2013jb010643

Sato, T., Shinohara, M., Karp, B. Y., Kulinich, R., & Isezaki, N. (2004). P-wave velocity structure in the northern part of the central Japan Basin, Japan Sea with ocean bottom seismometers and airguns. *Earth Planets and Space*, *56*(5), 501–510. https://doi.org/10.1186/BF03352509

Sereno, T. J., & Given, J. W. (1990). Pn attenuation for a spherically symmetric Earth model. *Geophysical Research Letters*, *17*(8), 1141–1144. https://doi.org/10.1029/GL017i008p01141

Tamaki, K., Suyehiro, K., Allan, J., Ingle, J. J. C., & Pisciotto, K. A. (1992). Tectonic synthesis and implications of Japan Sea ODP drilling. In K. Tamaki, K. Suyehiro, J. Allan, J. J. C. Ingle, & K. A. Pisciotto (Eds.), *Proceedings of the ocean drilling program, scientific results* (pp. 1333–1348).

Tang, Y. C., Obayashi, M., Niu, F. L., Grand, S. P., Chen, Y. J., Kawakatsu, H., et al. (2014). Changbaishan volcanism in northeast China linked to subduction-induced mantle upwelling. *Nature Geoscience*, *7*(6), 470–475. https://doi.org/10.1038/ngeo2166

Tatsumi, Y., Otofuji, Y., Matsuda, T., & Nohda, S. (1989). Opening of the Sea of Japan back-arc basin by asthenospheric injection. *Tectonophysics*, *166*(4), 317–329. https://doi.org/10.1016/0040-1951(89)90283-7

Toksöz, M. N., & Bird, P. (1977). Modelling of temperatures in continental convergence zones. *Tectonophysics*, *41*(1–3), 181–193. https://doi.org/10.1016/0040-1951(77)90189-5

Uyeda, S., & Kanamori, H. (1979). Back-arc opening and the mode of subduction. *Journal of Geophysical Research*, *84*(B3), 1049. https://doi.org/10.1029/JB084iB03p01049

Van Horne, A., Sato, H., & Ishiyama, T. (2017). Evolution of the Sea of Japan back-arc and some unsolved issues. *Tectonophysics*, *710–711*, 6–20. https://doi.org/10.1016/j.tecto.2016.08.020

Wang, X., Chen, Q. F., Niu, F. L., Wei, S. J., Ning, J. Y., Li, J., et al. (2020). Distinct slab interfaces imaged within the mantle transition zone. *Nature Geoscience*, *13*(12), 822–827. https://doi.org/10.1038/s41561-020-00653-5

Wei, H., Sparks, R., Liu, R., Fan, Q., Wang, Y., Hong, H., et al. (2003). Three active volcanoes in China and their hazards. *Journal of Asian Earth Sciences*, *21*(5), 515–526. https://doi.org/10.1016/s1367-9120(02)00081-0

Wei, H., Wang, Y., Jin, J., Gao, L., Yun, S.-H., & Jin, B. (2007). Timescale and evolution of the intracontinental Tianchi volcanic shield and ignimbrite-forming eruption, Changbaishan, Northeast China. *Lithos*, *96*(1–2), 315–324. https://doi.org/10.1016/j.lithos.2006.10.004

Wei, W., Zhao, D. P., Xu, J. D., Wei, F. X., & Liu, G. M. (2015). P and S wave tomography and anisotropy in Northwest Pacific and East Asia: Constraints on stagnant slab and intraplate volcanism. *Journal of Geophysical Research: Solid Earth*, *120*(3), 1642–1666. https://doi.org/10.1002/2014jb011254

Wessel, P., & Smith, W. H. F. (1998). New, improved version of Generic Mapping Tools released. *Eos, Trans, AGU*, *79*(47), 579. https://doi.org/10.1029/98eo00426

Xie, X. B., & Lay, T. (2017). Effects of laterally varying mantle lid velocity gradient and crustal thickness on Pn geometric spreading with application to the North Korean test site. *Bulletin of the Seismological Society of America*, *107*(1), 22–33. https://doi.org/10.1785/0120160203

Yang, G., Zhao, L. F., Xie, X. B., Zhang, L., & Yao, Z. X. (2021). High-precision relocation with the burial depths of the North Korean underground nuclear explosions by combining Pn and Pg differential traveltimes. *Journal of Geophysical Research: Solid Earth*, *126*(6), e2020JB020745. https://doi.org/10.1029/2020jb020745

Yang, J. F., & Faccenda, M. (2020). Intraplate volcanism originating from upwelling hydrous mantle transition zone. *Nature*, *579*(7797), 88–91. https://doi.org/10.1038/s41586-020-2045-y

Yang, X., Lay, T., Xie, X. B., & Thorne, M. S. (2007). Geometric spreading of Pn and Sn in a spherical earth model. *Bulletin of the Seismological Society of America*, *97*(6), 2053–2065. https://doi.org/10.1785/0120070031

Yang, X. N. (2011). A Pn spreading model constrained with observed amplitudes in Asia. *Bulletin of the Seismological Society of America*, *101*(5), 2201–2211. https://doi.org/10.1785/0120100314

Zhao, D., Yanada, T., Hasegawa, A., Umino, N., & Wei, W. (2012). Imaging the subducting slabs and mantle upwelling under the Japan Islands. *Geophysical Journal International*, *190*(2), 816–828. https://doi.org/10.1111/j.1365-246X.2012.05550.x

Zhao, D. P., Tian, Y., Lei, J. S., Liu, L., & Zheng, S. (2009). Seismic image and origin of the Changbai intraplate volcano in East Asia: Role of big mantle wedge above the stagnant Pacific slab. *Physics of the Earth and Planetary Interiors*, *173*(3–4), 197–206. https://doi.org/10.1016/j.pepi.2008.11.009

Zhao, L.-F., Xie, X.-B., He, J.-K., Tian, X., & Yao, Z.-X. (2013). Crustal flow pattern beneath the Tibetan Plateau constrained by regional Lg-wave Q tomography. *Earth and Planetary Science Letters*, *383*, 113–122. https://doi.org/10.1016/j.epsl.2013.09.038

Zhao, L. F., Xie, X. B., Tian, B. F., Chen, Q. F., Hao, T. Y., & Yao, Z. X. (2015). Pn wave geometrical spreading and attenuation in Northeast China and the Korean Peninsula constrained by observations from North Korean nuclear explosions. *Journal of Geophysical Research: Solid Earth*, *120*(11), 7558–7571. https://doi.org/10.1002/2015jb012205

Zheng, X. F., Yao, Z. X., Liang, J. H., & Zheng, J. (2010). The role played and opportunities provided by IGP DMC of China National Seismic Network in Wenchuan earthquake disaster relief and researches. *Bulletin of the Seismological Society of America*, *100*(5B), 2866–2872. https://doi.org/10.1785/0120090257

Zhou, J., Dunkl, I., Liu, Y., Li, W., Wolf, A., & Eynatten, &H. (2020). Miocene age of the Huanan basalt lava flow (NE China) inferred by reset of zircon (U-Th)/He thermochronometer in the underlying sand. *Geological Journal*, *55*(11), 7443–7457. https://doi.org/10.1002/gj.3877

References From the Supporting Information

Hong, T. K. (2013). Seismic discrimination of the 2009 North Korean nuclear explosion based on regional source spectra. *Journal of Seismology*, *17*(2), 753–769. https://doi.org/10.1007/s10950-012-9352-1

Mueller, R. A., & Murphy, J. R. (1971). Seismic characteristics of underground unclear detonations. *Bulletin of the Seismological Society of America*, *61*(6), 1675–1692. https://doi.org/10.1785/bssa0610061675

Sereno, T. J., Bratt, S. R., & Bache, T. C. (1988). Simultaneous inversion of regional wave spectra for attenuation and seismic moment in Scandinavia. *Journal of Geophysical Research*, *93*(B3), 2019–2035. https://doi.org/10.1029/JB093iB03p02019

Xie, J. K. (2007). Pn attenuation beneath the Tibetan Plateau. *Bulletin of the Seismological Society of America*, *97*(6), 2040–2052. https://doi.org/10.1785/0120070016

Xie, J. K., & Patton, H. J. (1999). Regional phase excitation and propagation in the Lop Nor region of central Asia and implications for P/Lg discriminants. *Journal of Geophysical Research*, *104*(B1), 941–954. https://doi.org/10.1029/1998jb900045