Graphical Abstract

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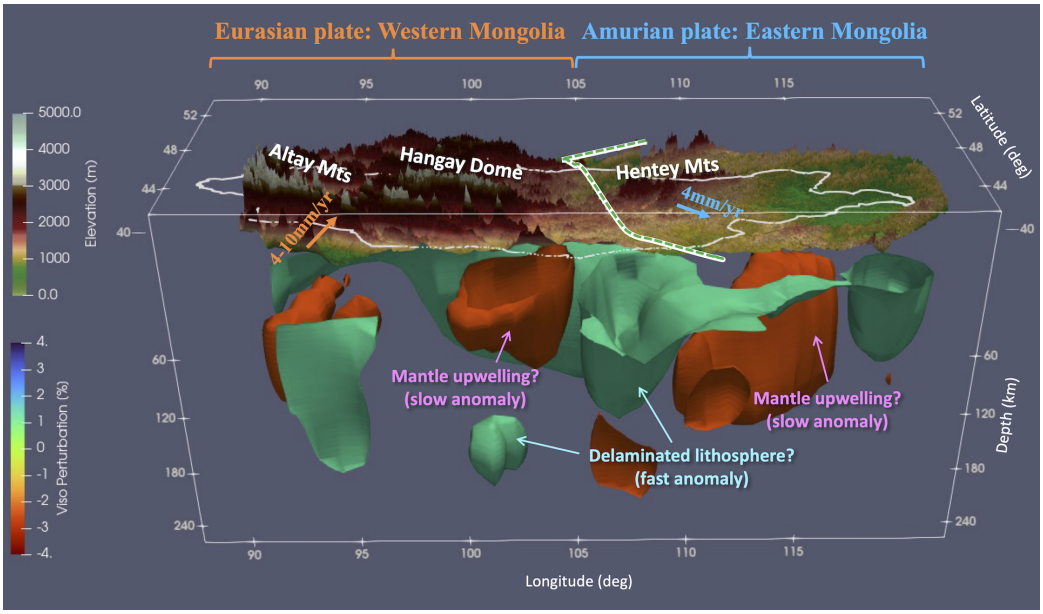

Highlights

Upper mantle structure beneath the Mongolian region from multi-mode surface waves: Implications for the western margin of Amurian plate

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- Multi-mode surface waves are used to build a new 3-D Mongolian upper mantle model.
- Significant velocity contrast is found beneath the Eurasian-Amurian plate boundary.
- Anomalous structures are found beneath the Hangay Dome uplift and the Amurian plate.

Upper mantle structure beneath the Mongolian region from multi-mode surface waves: Implications for the western margin of Amurian plate

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Abstract

Multi-mode phase speeds of surface waves are used to build a new radially anisotropic S wave model in the middle Eurasian and Mongolian regions. Our dataset includes seismic waveforms of over 2151 teleseismic events (Mw>5.8) from 2009 to 2021, recorded at permanent and temporary stations in and around Mongolia. The multi-mode dispersion curves of Love and Rayleigh waves were extracted using the nonlinear waveform fitting method for individual seismograms. Then, we retrieved phase speed maps for each mode and frequency, incorporating finite-frequency effects. Finally, localized multi-mode dispersion curves extracted from the phase speed maps were inverted for local anisotropic 1-D S-wave profiles, forming a 3-D shear wave model. Our new model exhibits significant lateral variations of S wave speeds at 70–100 km depth beneath Mongolia, i.e., slow anomalies in the tectonically active western Mongolia and fast anomalies in stable eastern Mongolia. In

the radial anisotropy model, SH waves are faster than SV waves in almost the entire Mongolian lithosphere above 100 km depth, except for the northern Altay Mountains region. The Hangay Dome region is characterized by significantly slower velocities, indicating the asthenospheric upwelling that causes the uplifting of this region. This study reveals distinct lateral variations of S wave speeds across the boundary between the Amurian and Eurasian plates, characterized by the prominent fast anomaly of the dipping lithosphere at the western edge of the Amurian plate.

Keywords: surface wave, tomography, upper mantle, lithosphere, Mongolia, Amurian plate

1. Introduction

Mongolia is located inside the East Asian continent, bounded by the Siberian craton in the north, and affected by the India-Asia collision zone in the south and by the far-field subduction zone of the Pacific plate in the east (Figure 1). The Central Asian Orogenic Belt (CAOB), a long-lasting accretionary orogen that spans much of central and eastern Asia, includes Mongolia. The CAOB, extending from North China Cratons and the northern margins of Tarim to the northern Baikal Rift region, is one of the biggest Paleozoic orogens from the Mesoproterozoic to Paleozoic, with the accretion of ophiolites, oceanic islands, accretionary wedges, island arcs, and microcontinental fragments (Windley et al., 2007). Due to the collision of the Indian and Eurasian plates as well as the subduction of the Pacific and Philippine Sea plates beneath Japan, East Asia has experienced extensive tectonic deformations during the Cenozoic (Wei et al., 2012). India has been moving

steadily northward since 55 million years ago, raised the Himalayas and Tibetan Plateau, and controls tectonics in western China and Mongolia (Molnar and Tapponnier, 1975; Hao et al., 2019). Nonetheless, the subductions of the Pacific and Philippine Sea plates have been significant contributors to the tectonic stress in Asia, producing island arcs, marginal seas, and continental rifting (Huang and Zhao, 2006; Hao et al., 2019). The creation of continental rifts and active intraplate volcanoes in Northeast China is also suggested by tomographic images to be related to the dynamic processes of the Western Pacific and East Asia because the subducted Pacific plate stagnates in the mantle transition zone beneath East China (Huang and Zhao, 2006). There are several intra-plate volcanoes in Mongolia, Korean Peninsula, and China (Global Volcanism Program, 2023). Figure 1 displays the locations of Taryatu Chulutu (TC), Khanuy Gol (KG), Bus Obo (BO), Middle Gobi (MG), and Dariganga (DG) volcanic eruption sites from the Late Cenozoic. According to Hunt et al. (2012), Mongolia's volcanism comprises several alkali-basalt cones that have been erupting for about 30 million years. Even though the greatest lava flows occur in the eastern Dariganga, the majority of modern volcanism is located near the Hangay Dome and the south of the Baikal Rift.

The Amurian plate is in northeastern Asia, covering northeast China, the Korean Peninsula, the Sea of Japan, the eastern shore of Lake Baikal in southeast Russia, and eastern Mongolia. The Amurian plate was postulated as a distinct plate from the Eurasian plate that is moving toward the southeast. The border between these two plates is thought to be confirmed by the Baikal Rift Zone (Zonenshain and Savostin, 1981). Western Mongolia belongs to the Eurasian plate, whereas Eastern Mongolia belongs to the

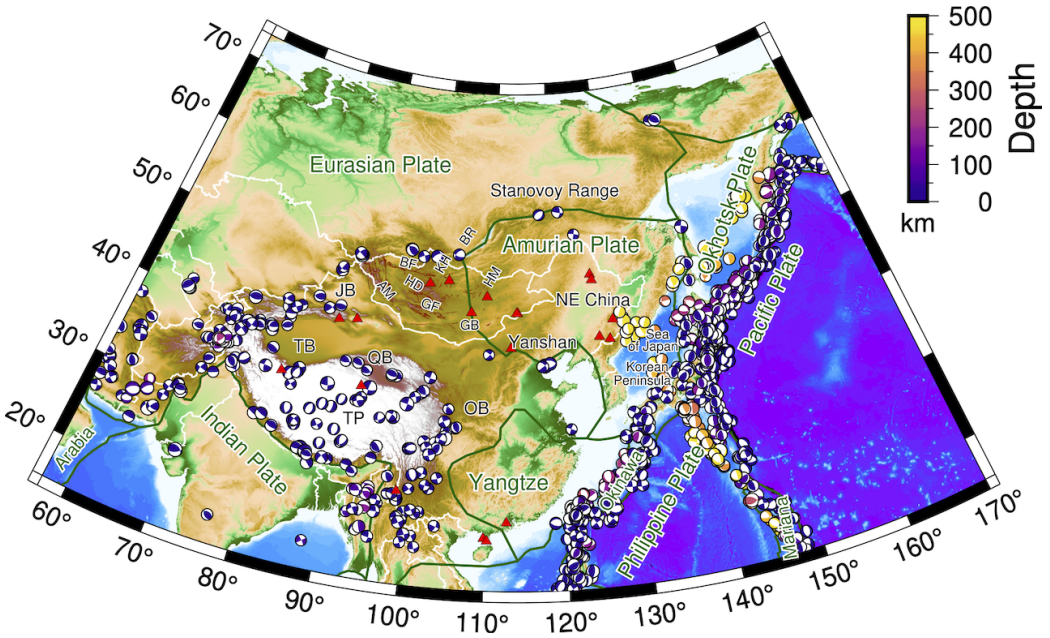

Figure 1: Dark green lines indicate plate boundaries. Triangles represent Holocene volcanoes (Global Volcanism Program, 2023). Focal mechanisms greater than Mw 6.0 from the Global CMT catalog between 1976 and 2022 (Ekström et al., 2012). Abbreviations from west to east: TB = Tarim Basin, JB = Junggar Basin, TP = Tibet Plateau, QB = Qaidam Basin, AM = Altay Mountains, BF=Bulnay Fault, HD = Hangay Dome, GF=Gobi Altay Fault, KH = Khovsgol, BR = Baikal Rift, GB = Gobi Basin, HM = Hentey Mountains, OB = Ordos Basin.

Amurian plate. The N-S compression by the convergence of the Indian plate and Tibetan Plateau affects western Mongolia, while the back-arc extension by the subduction of the Pacific plate influenced E-W oriented tectonics in eastern Mongolia (Meng et al., 2003).

GPS measurements in western Mongolia showed that northward shortening decreases from south (10 mm/year) to north (4 mm/year) in the Altay region, but central and eastern Mongolia moves eastward/southeastward mo-

tion at 4mm/year (Calais et al., 2003). This transition area dominates the Hangay Dome region, characterized by a high topography, comparatively flat plateau, and widespread Quaternary basalts. The Hangay topography is often regarded as a relatively recent formation that was elevated and formed within the past 20 – 30 million years (Walker et al., 2007), and the greatest active stage from 3 – 4 Ma until now (Barry and Kent, 1998). However, McDannell et al. (2018) indicated that this mountain environment is very old and has endured for almost 100 million years based on the geochemical and geological evidence. From geochemical and petrological investigations, Erdenesaihan et al. (2013) discussed the tectonic formation history of the Hangay region, which is considered an accretionary orogen formed through the closure of the Hangay-Hentey paleo-ocean during the early Paleozoic through early Mesozoic. Two seismically active strike-slip faults, the Bulnay Fault and the Gobi-Altay Fault, which generated gigantic ($M \geq 8.0$) intracontinental earthquakes, are situated respectively north and south of the Hangay Dome (Walker et al., 2007). Distant influences of the India-Asia convergence, Pacific plate subduction, mantle plume activity, convective mantle flow, and magmatic underplating have all been implicated in the mountainous terrain of the Mongolian plateau (Molnar and Tapponnier, 1975; Windley and Allen, 1993; Cunningham, 2001; Petit et al., 2002; Zorin et al., 2006; Petit et al., 2008). Thus, the Hangay Dome is one of Mongolia's most complex and enigmatic tectonic features that remains debated.

Previous geophysical studies present controversial models which can be categorized into two major hypotheses. One supposes high topography and intraplate volcanism are formed due to the deep-rooted mantle plume (Wind-

ley and Allen, 1993; Zorin et al., 2006). The regional heat flow measurements with 60–70 mW/m^2 in the Hentey Mountains and Hangay Dome (Khutorskoy and Yarmoluk, 1989), lithospheric thinning (Zorin et al., 1990), and late Cenozoic alkaline volcanism (Hunt et al., 2012) supported the mantle plume hypothesis. Also, Chen et al. (2015a) suggested a low-velocity zone could be caused by hot fertilized peridotite detached from the stagnant Pacific slab as it falls to the lower mantle (Zorin et al., 2006) from a large tomographic image in East Asia. Another hypothetical model is a lithospheric model, which can be explained as the dispersed locations of the potential melting zones (Cunningham, 2001; Barry et al., 2003). This scenario is consistent with a strong negative gravity model (Petit et al., 2002), the result of magnetotelluric inversions (Comeau et al., 2018), thermo-mechanical numerical modeling (Comeau et al., 2021), and recent tomography models (Feng, 2021; Wu et al., 2021; Wang et al., 2022).

Mongolia and the neighboring regions have been investigated using various seismic tomography as a part of the wider regional models covering eastern and central Asia (e.g., Tiberi et al., 2008; Chen et al., 2015b,a; He et al., 2016; Tao et al., 2018; Wu et al., 2021; Zhao et al., 2021; Witek et al., 2021; Feng, 2021; Huang and Zhao, 2022; Wang et al., 2022; Li et al., 2022). Recent local-scale investigations in western and central Mongolia, especially in Hangay Dome, indicated a thinner lithosphere (60–80 km) contrasted to the surrounding areas, while the crust was found to be as thick as about 50–55 km (Petit et al., 2008; Feng, 2021; Zhao et al., 2021). Low-velocity anomalies were seen in the upper mantle at around 70–150 km depths (Tiberi et al., 2008; Chen et al., 2015a; Comeau et al., 2018; Wu et al., 2021; Feng,

2021; Wang et al., 2022; Huang and Zhao, 2022).

In contrast to western Mongolia, eastern Mongolia has been less investigated, mainly due to poor seismic station coverage. A receiver function result of He et al. (2016) showed the crustal thickness varies between 38 and 46 km, and Rayleigh-wave phase speed maps by Yu et al. (2015); Pan et al. (2015) exhibited high-velocity anomalies in Southern Gobi and Hangay-Hentey basin while low-velocity anomalies in Middle Gobi. Using traveltime tomography, Zhang et al. (2017) found slow P and S velocities under the Hentey Mountains and areas close to the comparatively low-lying Gobi Desert. Rayleigh-wave tomography by Wang et al. (2022) suggested that consistently faster upper mantle velocities may indicate the strong lithosphere beneath the East Gobi Desert.

Although various seismological studies have been done in and near Mongolia, nationwide regional seismological images beneath the whole areas of Mongolia with uniform station coverage using seismic surface waves have not yet been obtained. Thus, the detailed 3-D structure of the entire Mongolian upper mantle, including radial anisotropy, remains still largely unknown. The aim of this study is to construct a new 3-D upper-mantle S-wave speed model including radial anisotropy beneath central Eurasia around Mongolia with multimode surface waves using many permanent and temporary broadband seismic stations inside Mongolia. Such a high-resolution 3-D model will enable us to clarify the relationship between the current Mongolian tectonics and mantle dynamics. In this study, we employ the three-stage inversion technique by Yoshizawa and Kennett (2004); Yoshizawa (2014). The 3-D distributions of SV and SH wave speeds are obtained from dispersion data

of multimode Love and Rayleigh waves recorded at the permanent and temporary Mongolian networks and neighboring GSN, PASSCAL, and NECESSArray networks. The new 3-D model provides a high-resolution image of lateral structural variations between the Eurasian and Amurian plates, indicating new seismological evidence of an enigmatic boundary at the western border of the Amurian plate.

2. Data and method of multimode phase speed measurements

2.1. Seismic stations and events

We employed three-component broadband seismograms of the permanent and temporary Mongolian networks, Global Seismograph Network (GSN), Central Mongolian Seismic Experiments (Meltzer et al., 2019) (PASSCAL network), and temporary networks in Northeast China (NECESSArray). In total, 455 broadband seismic stations (Figure 2) are used. We have analyzed 2151 teleseismic events with a moment magnitude 5.8 or higher, located at an epicentral distance longer than 1000 km (Figure 3). At first, all original waveforms are deconvolved with corresponding instrument responses. Then, the horizontal components are rotated to the radial and transverse components. Using the vertical and transverse components independently, a large number of path-average multimode phase speeds of Rayleigh and Love waves are measured for each event-station path across the target area using the single-station waveform fitting method, as described in the next section.

2.2. Multimode phase speed measurements

As the initial step for the three-stage inversion of surface wave tomography (Kennett and Yoshizawa, 2002; Yoshizawa and Kennett, 2004), we

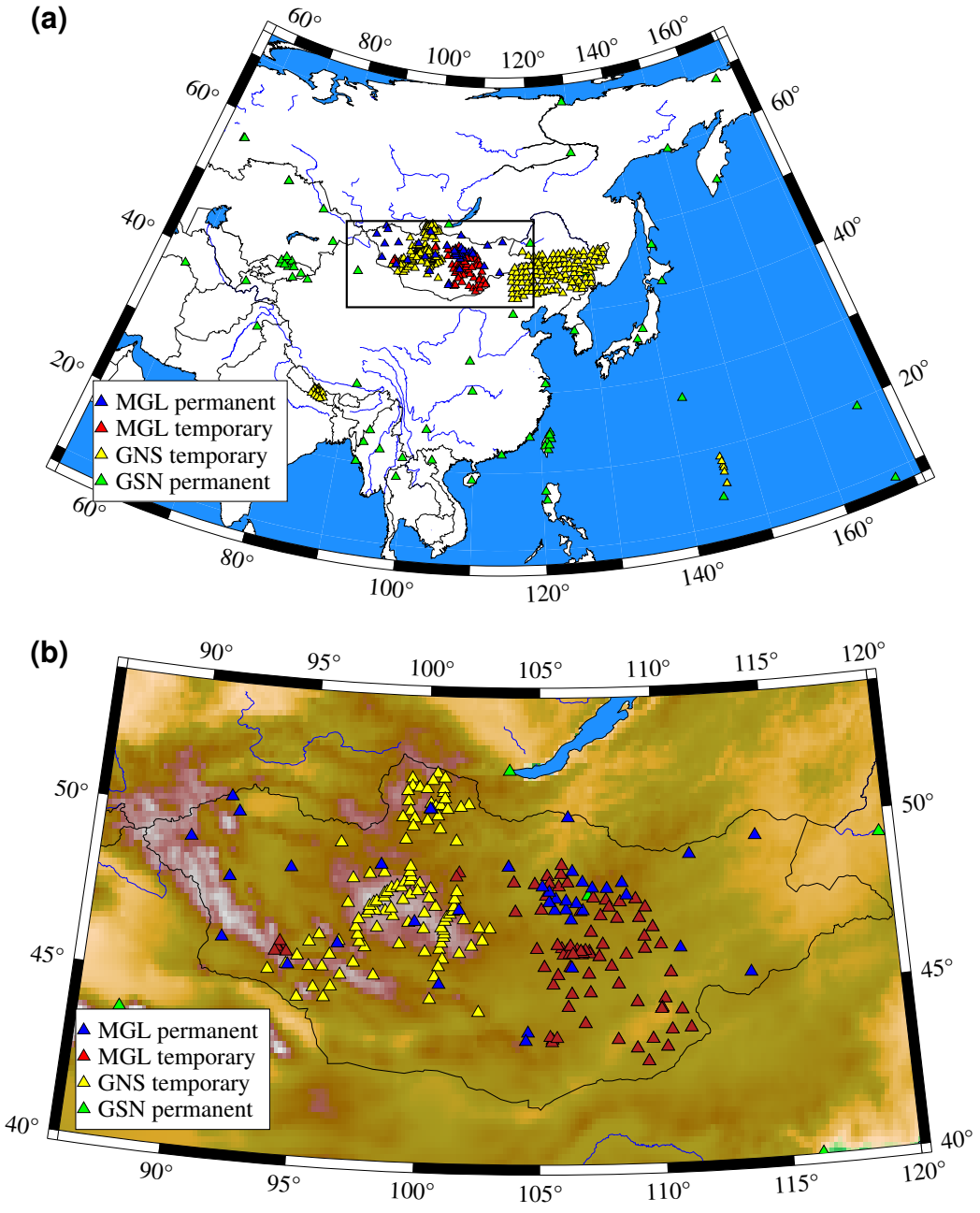

Figure 2: Seismic stations used in this study. a) All stations, b) stations in Mongolia.

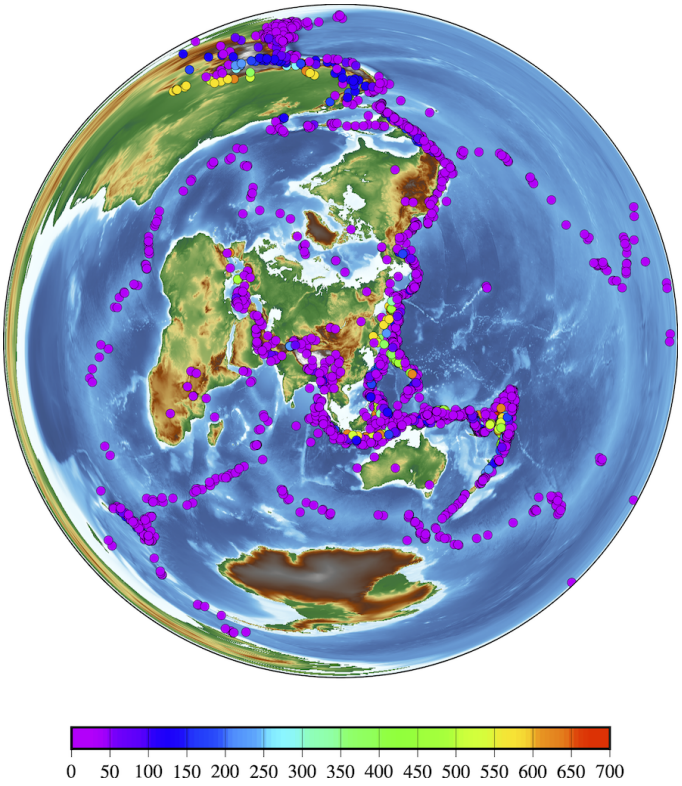

Figure 3: Employed seismic events with a moment magnitude greater than 5.8 from 2009 to 2021.

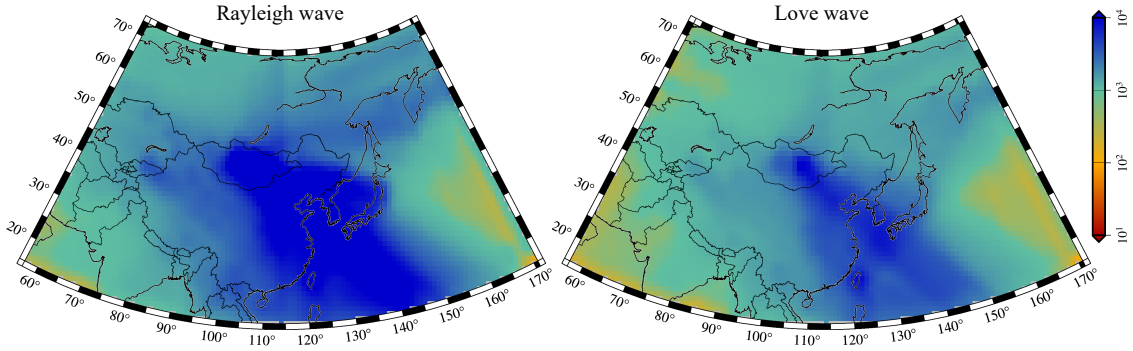

Figure 4: Ray-path density of the fundamental-mode Rayleigh and Love wave at 100 s. Ray paths count in 2x2 (degree) grids.

performed fully nonlinear waveform inversion for path-specific 1-D S-wave profiles by fitting observed and synthetic waveforms based on global optimization (Yoshizawa and Kennett, 2002b; Yoshizawa and Ekström, 2010). The details of the automated measurement procedure have been explained by Yoshizawa and Ekström (2010). Here we summarize the essence of the measurement technique briefly.

For each event-station path, more than 5000 path-specific 1-D S wave profiles are sampled using the Neighborhood Algorithms by Sambridge (1999), which is used as a global optimizer. The surface-wave WKBJ method is used to compute synthetic waveforms for all models by employing the focal mechanism from the global CMT catalog (Ekström et al., 2012). Multiple time windows are selected automatically for the fundamental and higher modes based on the predefined group-speed ranges. Waveform misfits between the synthetic and observed seismograms are assessed in these time windows with multiple bandpass filters from 5 to 30 mHz for the fundamental mode and up to 50 mHz for the higher modes. Then, the best 1-D profile, which provides the minimum waveform misfit, is selected and used to compute the path-average multimode phase speeds for each path. To evaluate the quality of measured phase speeds, we employ the frequency-dependent reliability parameter computed from the relative power of each mode and relative waveform fit as defined by Yoshizawa and Ekström (2010). In this study, we employed the same *a priori* constraints and thresholds as Yoshizawa and Ekström (2010) for selecting reliable dispersion measurements and outlier removal.

Our dataset consists of about 87,000 paths for the fundamental-mode

Rayleigh waves, about 50,000 paths for the fundamental-mode Love waves at a period of 100 s, and about 20,000–50,000 paths for higher modes of both Rayleigh and Love waves (Figure S1). An example of the ray path coverage for the fundamental-mode Rayleigh and Love waves at 100 s is displayed in Figure 4. The entire study region is covered well with the dense ray paths owing to many broadband seismic stations deployed there. We could obtain high ray-path density with good azimuthal coverage in East Asia and Mongolia. As described in the subsequent section, we reconstructed phase speed maps for each mode and frequency, for which we could gather more than 5000 paths. These multi-mode phase speed maps are employed to compute a 3-D shear wave model of the continental lithosphere and asthenosphere beneath central Eurasia around Mongolia.

3. Multimode phase speed mapping

The measured multimode phase speeds in the first step are used to retrieve phase speed maps in the second step. We used linearized tomographic inversion incorporating approximate effects of finite-frequency for surface waves around the great-circle paths (Yoshizawa and Kennett, 2002a). The procedure of phase speed mapping has been explained by Yoshizawa and Kennett (2004) and Yoshizawa (2014) in detail. Phase speed distribution is expanded in spherical B-spline functions at rectangular grids. The grid spacing of this study depends on the ray path coverage for each mode and frequency; i.e., 2.0° for the fundamental mode with more than 30,000 paths, 3.0° for more than 15,000 paths, 4.0° for more than 8,000 paths, and 5.0° for all modes with more than 5000 paths.

3.1. Resolution test

We performed checkerboard tests to clarify the lateral resolution of our tomography model. The input checkerboard models contain velocity fluctuations of around ±5 % from the reference velocity at each frequency. Various cell sizes are tested to examine the spatial resolution of phase speed models. Figure 5 displays examples of the resolution tests for the fundamental-mode Rayleigh and Love wave at 100 s with 3.0° × 3.0°.

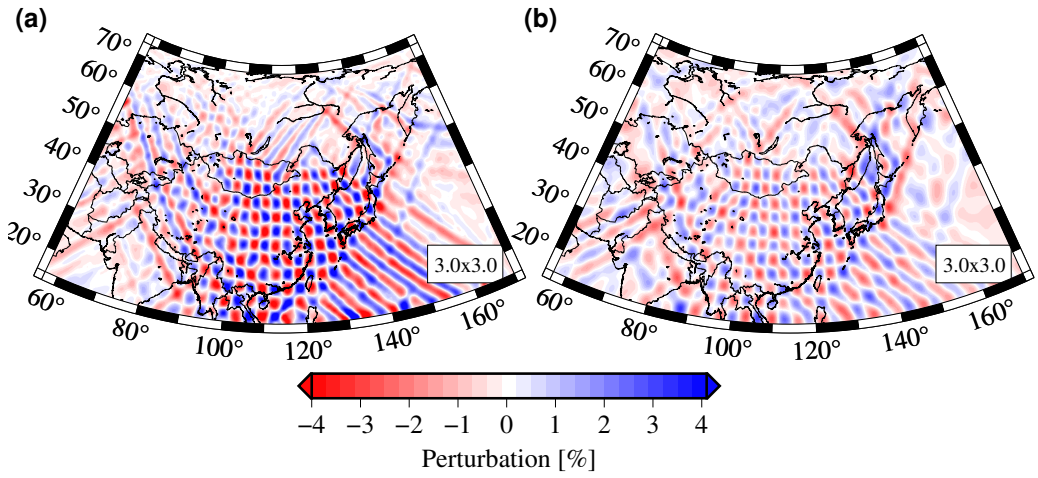

Figure 5: Outputs of checkerboard tests for the fundamental-mode Rayleigh and Love waves at 100 s with 3.0° cells.

We also show additional checkerboard tests for the fundamental- and second higher-mode Rayleigh and Love waves at 100 seconds in Figure S3 and Figure S4, respectively (in Supporting Information). The retrieved checkerboard patterns in Figure S3 suggest that our data set achieves acceptable lateral resolution with cell sizes of 2.0° × 2.0° or greater for Rayleigh-wave maps beneath Mongolia owing to many crossing paths with various direc-

tions in each cell. The checkerboard results indicate that the southern and central parts of the study regions are particularly well resolved by denser ray coverage. In contrast, the rest parts show somewhat smeared patterns due to limited numbers of crossing paths. With smaller numbers of available ray paths, the lateral resolution of higher-mode Love waves tends to be limited compared to that of Rayleigh waves, although the large-scale features greater than 3–4° can be mostly recovered.

3.2. Multimode phase speed maps

The phase speed maps are acquired in the 30–200 s period range for Rayleigh, and 33–200 s for Love waves, depending on modes. The period ranges for all modes are summarized in Table S1 (Supplementary Information). We performed jackknife resampling tests to estimate standard errors in our multimode phase speed maps. The results of the jackknife resampling tests for phase speed maps are displayed in Figure S5 (section S3 in Supporting Information). The estimated errors for the fundamental-mode Rayleigh wave at 100 s with an average phase speed of 4.13 km/s are mostly less than 0.052 km/s, while those for the second higher mode Love wave at 100 s with an average phase speed of 7.37 km/s are around 0.11 km/s. Figure 6 shows examples of phase speed maps for the fundamental- and higher-modes of Rayleigh and Love waves. Additional multimode phase speed maps for Rayleigh and Love waves are summarized in Figures S6-S9 (section 4 in Supporting Information). The average phase speed C_0 shown in each map is used as a reference for the representation of fractional phase speed perturbations. The reference phase speed is derived from the average in the whole area of this study. The large-scale features of the fundamental-mode maps show

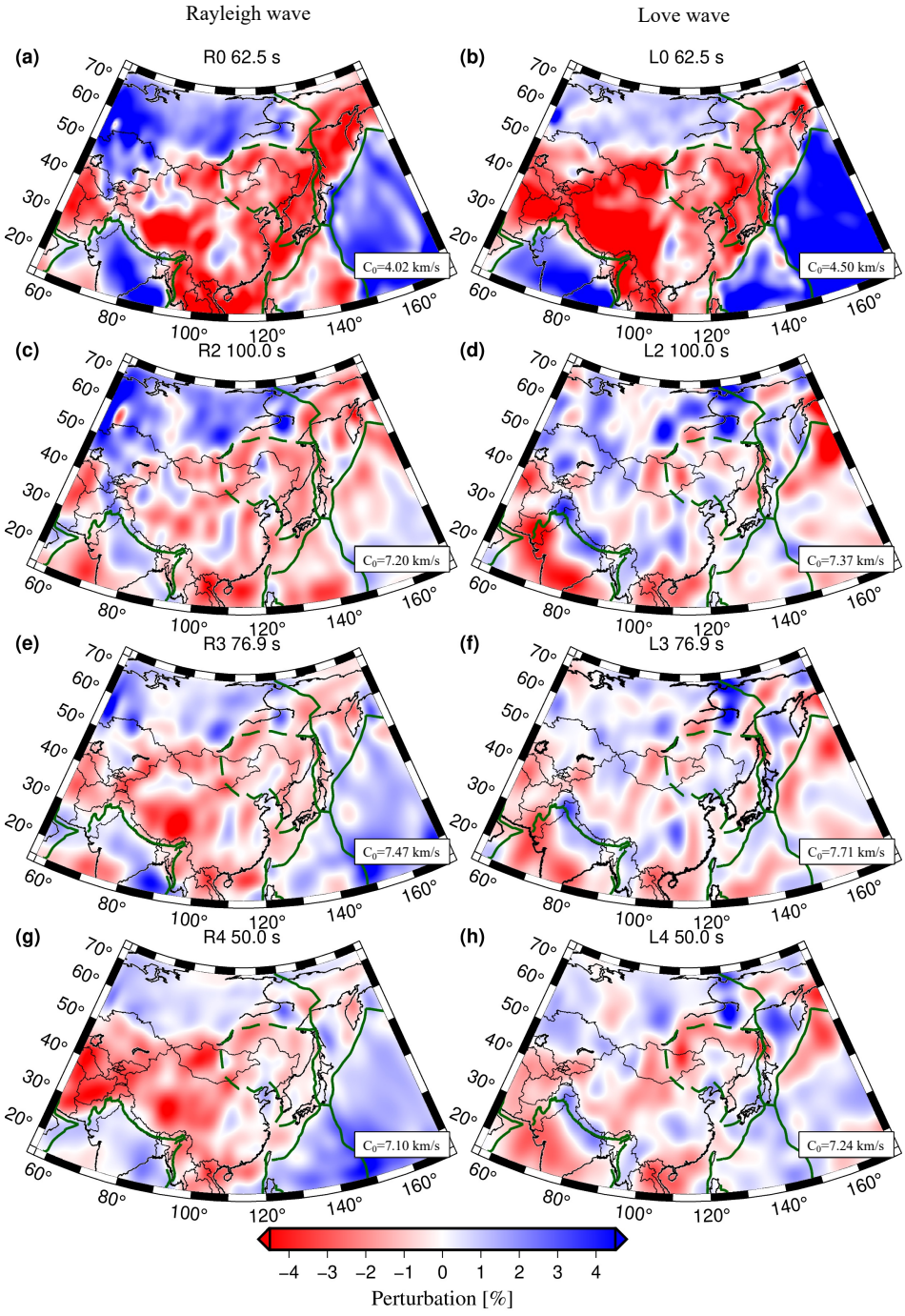

Figure 6: Phase speed maps for the fundamental- and higher-modes of the Love (L) and Rayleigh (R) waves, and the numbers indicated are mode number and period.

fast anomalies in the Siberian craton, Tarim basin, and Ordos area and slow anomalies in Tibet, Okhotsk, and western Mongolia. The overall patterns of the phase speed distribution of Rayleigh and Love waves are consistent with the global model GDM52 (Ekström, 2011). Still, our lateral resolution in this region is much higher than the global model.

4. Radially anisotropic 3-D S wave model

4.1. Inversions for radially anisotropic 1-D S wave models

Following Yoshizawa (2014), we used the generalized nonlinear least-squares inverse scheme of Tarantola and Valette (1982) to build the 3-D radially anisotropic S-wave model using the multimode phase speed maps. The detailed procedure has been described by Yoshizawa (2014). Here we consider a set of 6 independent model parameters ($\rho,\ \alpha_H, \alpha_V, \beta_H,\ \beta_V,\ \eta$), where ρ is density, α_H and α_V represent horizontally and vertically polarized P wave speeds, β_H and β_V represent horizontally and vertically polarized S wave speeds, η is a dimensionless anisotropic parameter. P wave speeds and density are considered via scaling relations for S wave speeds (e.g., Gung et al., 2003; Panning and Romanowicz, 2006) following (Montagner and Anderson, 1989). To control the amplitude of shear wave perturbations and the smoothness of the velocity model during the inversions, we employ the model covariance matrix comprising two *a priori* parameters, standard deviations σ and correlation length L (Yoshizawa and Kennett, 2004; Yoshizawa, 2014). We used the following *a priori* values, i.e., $\sigma = 0.045$ km/s and L= 10 km in the depth range between Moho and 400 km, and $L = 15$ km between 400 and 670 km. Beneath 670 km depth, σ decreases linearly to 0.025 km/s,

while L increases linearly to 30 km at 1500 km depth. The crustal velocity can be perturbed with $\sigma = 0.025$ km/s and $L = 5$ km. Thus, the crust and uppermost mantle structures change rapidly while the deeper structure changes gradually.

We performed a series of tests to examine the effects of the crustal corrections on the shear wave speed model using two reference crustal models and without the crustal correction. Figure S10 (section 5 of Supporting Information) shows the comparisons of the retrieved shear wave models with crustal corrections with 3SMAC (Nataf and Ricard, 1996) and CRUST1.0 (Laske et al., 2013), and without the crustal correction using a modified PREM (Dziewonski and Anderson, 1981) with a smoothed 220 km discontinuity. Below 150 km, the crustal correction has little impact on the deeper part of the shear wave model, although there are some variations above 150 km. In this study, we employed the local reference models combining the modified PREM (smoothed 220 km discontinuity) and the CRUST1.0 model because the crustal thickness of the CRUST1.0 model is more suited, particularly in western Mongolia. We also performed the vertical resolution tests summarized in Figure S11 (section 5 in Supporting Information), which indicate sufficient vertical resolution down to 300 km depth, despite the vertical smearing due to the long-period surface waves.

4.2. 3-D model in central Eurasia and Mongolian regions

Based on the retrieved SH (β_H) and SV (β_V) models, we consider their Voigt average as the isotropic S wave model, $\beta_{iso} = \sqrt{(2/3)\beta_V^2 + (1/3)\,\beta_H^2}$ (e.g., Panning and Romanowicz, 2006) and the radial anisotropy parameter $\xi = (\beta_H/\beta_V)^2$. Figure 7 (a-d) shows the final 3-D isotropic S wave and radial

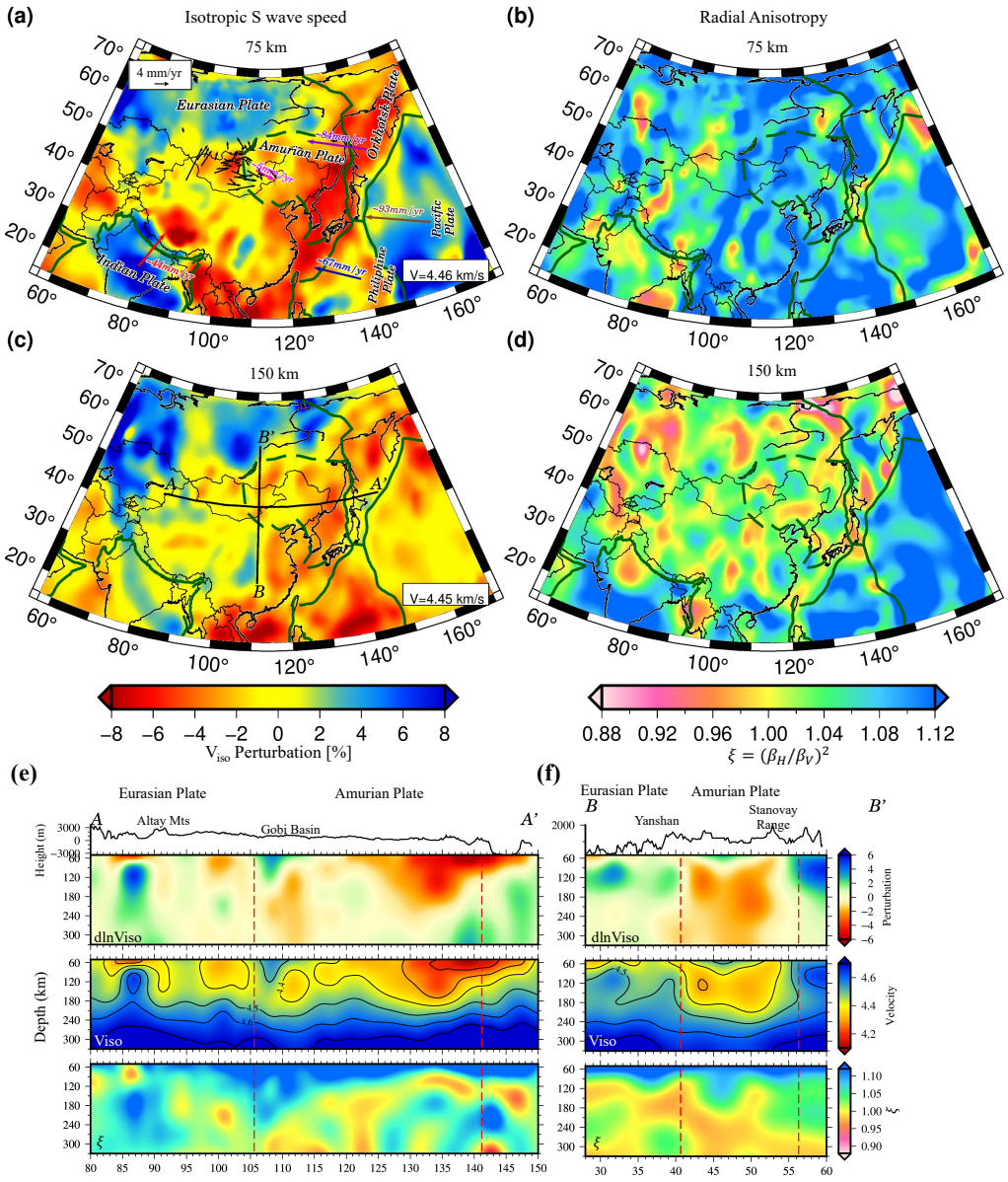

Figure 7: (a, c) 3-D isotropic S wave speed model at 75 and 150 km depths calculated as the Voigt average of retrieved SH and SV wave speeds, and (b, d) corresponding radial anisotropy parameter $\xi = (\beta_H/\beta_V)^2$. Plate boundaries (green solid lines) are taken from Bird (2003). (a) Black arrows in and around Mongolia denote the rates of crustal motion relative to Eurasia (Calais et al., 2003). The other colored arrows indicate relative plate motions based on the MORVEL plate model (DeMets et al., 2010). (e, f) Cross-sections of isotropic S wave speed perturbation (top), absolute isotropic S wave speed (middle), and radial anisotropy parameter (bottom) along the profiles A-A' and B-B' with surface topography on top. The major tectonic provinces are labeled on topography. The vertical red dashed lines show the vertical extension of the Amurian plate boundary at the surface by Bird (2003).

anisotropy models in the whole region of this study. The regionally-averaged 1-D profiles in Figure S12 ((a) Eurasian and (b) Mongolian regions) are used as local reference models for the isotropic S wave speed perturbations of our tomography models, while radial anisotropy is displayed as a deviation from isotropy ($\xi = 1$). The average 1-D profiles of the SV and SH wave speeds in the broader Eurasian region are similar to the anisotropic PREM model (Figure S12(a)), but those in the Mongolian region tend to exhibit slower shear wave speeds (Figure S12(b)). In the upper 180 km, the average radial anisotropy in Mongolia is a few percent lower than that of PREM, reflecting local tectonic features under Mongolia.

For the 3-D model plots in this study, we have applied the Gaussian filter with a standard deviation of 0.67° to smooth our 3-D velocity model laterally. In our model at 70–100 km depth, we find relatively low velocities in western Mongolia, Tibet, and in the East and South China Seas, Yellow Sea, Ryukyu Trench, Sea of Japan, and Sea of Okhotsk, while other areas in the Siberian craton, Sichuan basin (Yangtze cratons), Ordos block, Tarim basin, and eastern Mongolia exhibit higher velocities. At a depth of 150 km, the low-velocity anomalies in western Mongolia and Tibet are vanished, while the eastern marginal seas still show slower anomalies. The fast S-wave anomalies in the Tarim, Yangtze, and Sichuan basins are apparent in the isotropic S wave model down to 150 km depth. Earlier surface wave studies agree with the overall pattern of shear wave speed anomalies in the upper mantle (Ritzwoller et al., 2002; Chen et al., 2015b; Tao et al., 2018; Witek et al., 2021).

SH and SV wave speeds and radial anisotropy models are shown at various

depth slices in Figure S13 (section 5 in Supporting Information). In the radial anisotropy maps at 70–120 km depth, most regions exhibit positive radial anisotropy ($\xi > 1$ or $V_{SH} > V_{SV}$), except for a part of Tibet, northwest Mongolia, and under Japan. At the same depth range, radial anisotropy with very slow SV wave speeds can also be found in Tibet, western Mongolia (Hangay Dome), and eastern subduction regions. Below 150 km depth, the strength of radial anisotropy tends to be weaker than shallower depth in most of the region. Figures S14 to S16 (Supporting Information) summarize vertical cross-sections (E-W and N-S directions) of SH and SV wave speeds and radial anisotropy at various locations. In the following section, we will focus our discussion on the characteristic seismic structure in the Mongolian region.

5. Discussion of Mongolian Upper Mantle Structure

The lateral structural changes revealed by our new 3-D S-wave model beneath the Mongolian region suggest some intriguing geographical relations that reflect Mongolian tectonics and mantle dynamics. Here we focus on the S-wave structure in the upper mantle from 60 to 300 km depth, which has been well resolved by our surface wave dispersion data.

5.1. Entire Mongolia

Figure 8 (a-d) displays the isotropic S wave speed and radial anisotropy models at 70 and 120 km depths in the Mongolian region. Figure S17 (Supporting Information) displays various depth slices of the original SH and SV wave speed models and the radial anisotropy ξ beneath Mongolia. Figures

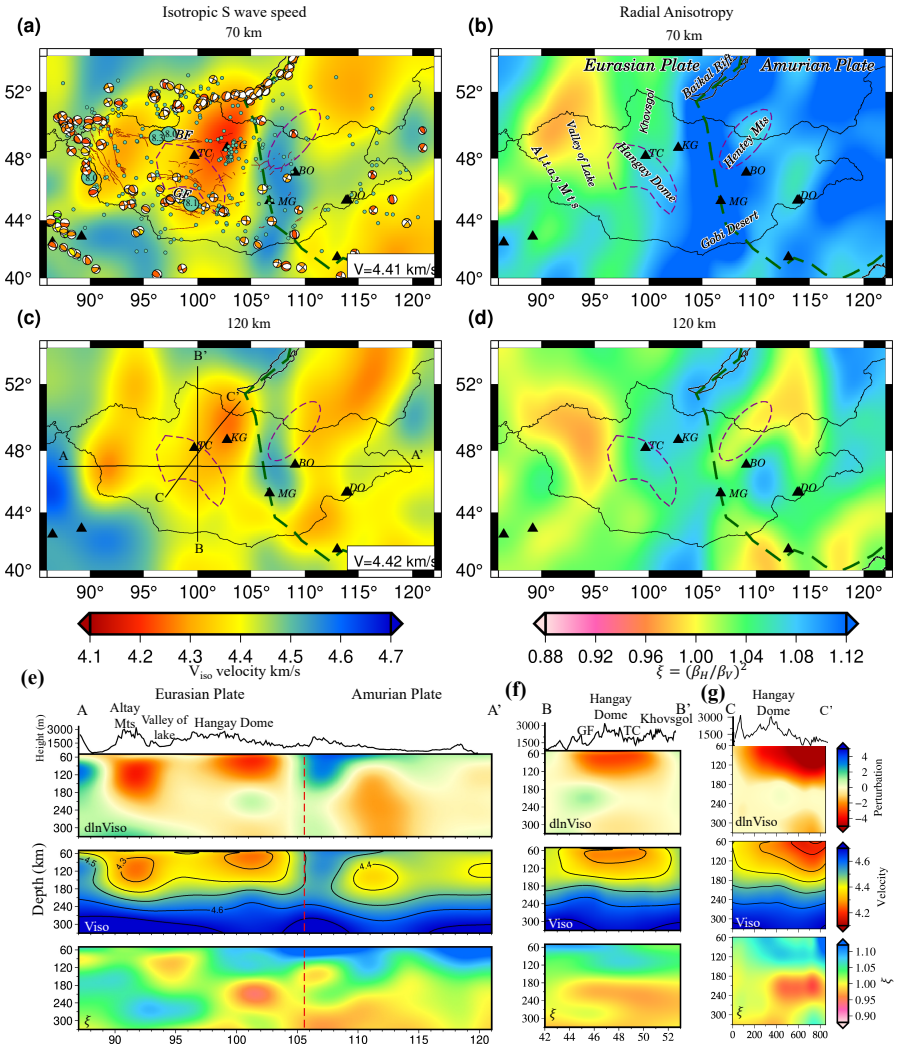

Figure 8: Isotropic S wave speed model and radial anisotropy parameter $\xi=(\beta_H/\beta_V)^2$ at 70 and 120 km depths beneath the Mongolian region. The black triangles denote the Holocene volcanoes; Taryatu Chulutu (TC), Khanuy Gol (KG), Middle Gobi (MG), Bus Obo (BO), and Dariganga (DG). (a) Isotropic S wave speed at 70 km depth with seismicity in and around Mongolia. Green circles indicate seismic events from the catalog by IAG (Institute of Astronomy and Geophysics of Mongolia) (Jan 1964- May 2023, $M_l \geq 3.5$); Some historical large earthquakes (Mw≥8.0) are labeled. Focal mechanisms greater than Mw 4.0 are taken from the Global CMT catalog between January 1976 and May 2023 (Ekström et al., 2012). Green dashed lines are the expected Amurian plate boundary by Bird (2003). (e, f, g) Cross-sections of isotropic S-wave speed perturbation, absolute isotropic S-wave speed, and radial anisotropy along profiles A-A', B-B', and C-C' with surface topography on top. Main tectonic domains are labeled on topography. A vertical red dashed line in the cross-section indicates the vertical extension of the boundary between the Eurasian and Amurian plates from Bird (2003).

S18–S20 summarize the corresponding vertical cross-sections. Figure S21 displays the 3-D views of (a, b) slow and fast shear wave speed anomalies and (c, d) radial anisotropy beneath the Mongolian region. In the shallower depth at 70–100 km beneath Mongolia, the S-wave speeds are generally slower in the tectonically active western area and become faster in the relatively stable eastern area. Slower velocities in western and central Mongolia are also seen in earlier tomography models (e.g., Ritzwoller et al., 2002; Chen et al., 2015a; Tao et al., 2018; Witek et al., 2021; Li et al., 2022).

In western Mongolia, some distinctive slow velocity anomalies are seen in the southeastern area of the Khovsgol rift zone, eastern Hangay dome, Mongol Altay, and Valley of the Lake. On the contrary, in the eastern regions at shallower depths from 70 to 100 km, the fast anomalies are observed in Southern Gobi, Hentey Mountains, and Middle Gobi. The high-velocity anomaly in Middle Gobi is still prominent even at a greater depth of around 170 km, while that in the Hentey Mountains and South Gobi has essentially disappeared by that depth. This high-velocity anomaly may indicate dipping or delaminated lithosphere, which can be affected by small-scale mantle convection, which may affect the east-to-west movement of eastern Mongolia. From the plate boundary model by Bird (2003), the Eurasian-Amurian plate border coincides well with the location where the lithosphere of eastern Mongolia dips westward, particularly in the region between the latitudes 44°N and 50°N, and between the longitudes 105°E and 110°E. We also note that a clear velocity contrast between western and eastern Mongolia extends down to 250 km depth (Figure 8 (e)), which may indicate the vertical extension of the Eurasian and Amurian boundary, as we will discuss in detail in

Section 5.3.

The radial anisotropy model exhibits a faster SH wave speed than SV in nearly the entire Mongolian lithosphere above 100 km depth, except for the northern part of the Altay Mountains, where both SH and SV wave speeds are slower than average with anomalous radial anisotropy with SV>SH (Figure S17), especially at depths of about 75–130 km. The Altay and Sayan Mountains have experienced strong convergence as a result of the northward motion of the Asian blocks (such as Junggar and Tarim Basins) due to the India-Asia collision (Huang and Zhao, 2022). The P-wave velocity model by Huang and Zhao (2022) showed low velocity down to 200 km depth beneath the Altay Mountains, suggesting that lithosphere-scale interactions may cause it. Our S-wave model also shows the low-velocity anomalies along the northern Altay Mountain border, which can persist to about 300 km depth (Figure S19).

The Hentey Mountains also show slower SH wave speed anomaly at depths between 100 and 200 km. The notable low velocity found under the Hentey Mountains agrees well with a recent tomographic study by Chen et al. (2015a) who have reported the low-velocity anomaly may stretch from the uppermost mantle to 200 km depth at least. He et al. (2019) noted that the tectonic setting and dynamic processes beneath the Hentey Mountains and Hangay Dome are distinctive. They also suggested that low-velocity anomalies beneath the Hentey Mountains could indicate partially molten or heated material in the upper mantle. Our radial anisotropy model suggests that the low-velocity anomalies with radial anisotropy of SV>SH beneath the Hentey Mountains might reflect mantle upwelling (Figure S19 (a and b) and Figure

S20 (i1)).

Figure 9 illustrates the schematic west-east cross section across Mongolia based on our tomography model, indicating the major structural features and lateral variations in the upper mantle beneath western and eastern Mongolia. Typical three-dimensional views of our model with isocontour plots are displayed in Figure S21 in Supplementary Information. In the subsequent sections, we will further discuss the major features illustrated in Figures 9 and S21, such as the uplifting Hangay Dome region with mantle upwelling in western Mongolia (Eurasian plate), and relatively thick and dipping lithosphere, which may reflect a plausible lithospheric drip or delamination in eastern Mongolia (Amurian plate). The significant structural variations between western and eastern Mongolia can be related to the differential plate motion between the Eurasian and Amurian plates.

5.2. Western Mongolia: Hangay region

The Hangay Dome in western Mongolia is considered one of the most significant tectonic units in this region. Significant earthquakes have not been recorded in the Hangay Dome itself, but some major earthquakes occurred around this area, e.g., the Mw 7.1 earthquake (1967) on the Mogod fault to the east of the Hangay Dome, Mw 8.3 earthquake (1905) on the Bolnay fault to the north, and Mw 8.1 Gobi-Altay earthquake (1957) on the Bogd faults to the south. As mentioned earlier, existing seismic tomography models showed significantly slow shear wave speeds in the upper mantle beneath the Hangay Dome and its surroundings (e.g., Tiberi et al., 2008; Chen et al., 2015a; Comeau et al., 2018; He et al., 2019; Wu et al., 2021; Feng, 2021; Wang et al., 2022; Huang and Zhao, 2022).

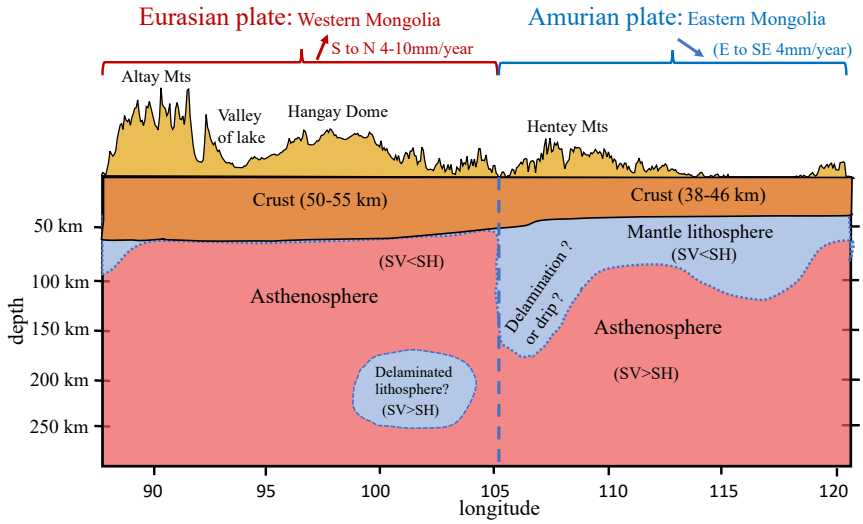

Figure 9: Schematic illustration of major structural features of our shear wave model across Mongolia (west-east cross section).

Chen et al. (2015a) found a large-scale low-speed volume in the upper mantle beneath the Hangay Dome, the Khovsgol rift system, parts of the Gobi-Altay Mountains, and the Sayan Mountains in the depth range from 50 to 90 km, although their data set lacks local seismic data in Mongolia. With low Vs (Vsv) of less than 4.2 km/s, they proposed that partial melting might spread over the area beneath the Hangay Dome and its environs. However, the recent Vs model by Feng (2021), who employed more extensive local data sets in this region, demonstrated that the partial melting zones are distributed not directly beneath the Hangay Dome. The partial melting and convective loss of the lithosphere may result in the uplift of Hangay Dome and may cause such low-speed anomalies. Recent P-wave tomography by Huang and Zhao (2022) suggested a velocity discontinuity at a depth of around 250

km, indicating that the lithosphere beneath the Hangay Dome may have been delaminated (Zhao et al., 2021).

Numerical experiments by Elkins-Tanton (2005) on continental delamination suggested the necessity of ductile mid-lithosphere to allow delamination, implying that the delamination can occur in regions that have experienced high heat flow from volcanism or mantle upwelling. Based on thermo-mechanical numerical models incorporating geological, geochemical, and geophysical data, Comeau et al. (2021) have investigated the conditions for lithospheric removal by delaminations. They have found that central Mongolia satisfied the conditions for lithospheric delamination, supported by lines of evidence such as the high surface and dome-shaped topography, thin lithosphere, and elevated temperature at the crust-mantle interface. These findings suggest that mechanical delamination or thermal processes may be to blame for the lithosphere beneath the Hangay Dome being significantly weaker than the surrounding regions (Fullea et al., 2012).

Anomalous low velocity beneath the Hangay Dome in our model is consistent with recent results by Feng (2021), showing low-velocity anomalies down to about 180 km depth, mainly beneath the northeast of the Hangay Dome, Khanuy Gol. A low-velocity region can also be seen in the upper mantle beneath the Khovsgol rift to the north. The Hangay Dome is lain by weak high-velocity anomalies around 200 km depths, which may represent the remnant of delaminated lithosphere (e.g., Comeau et al., 2021; Huang and Zhao, 2022). Our model suggests a similar high-velocity anomaly at depths of around 200 km, although its location is slightly shifted to the south, not right beneath the Hangay Dome (Figure S19 (d-f)).

The radial anisotropy maps (Figure S17) show anomalously weak regions with slower S wave speeds with significant positive radial anisotropy (SH>SV), particularly at depths of about 70–150 km, near the Hangay Dome and on the northeastern side of the Hangay Mountains, Khanuy Gol. This anomalous radial anisotropy accompanies slower SV wave speed, which can be seen beneath the Hangay Mountains down to 150 km depth. Such features may indicate the presence of finely layered or laminated heterogeneity, possibly including partially molten layers, which can generate significant positive radial anisotropy (e.g., Aki, 1968). Thus, our results may suggest that the Hangay Dome may be formed by oblique mantle upwelling from the northeast of the dome, accompanying large-scale partially molten layers in the top 150 km depth, as indicated by Chen et al. (2015a) and Feng (2021).

5.3. Eastern Mongolia: Amurian plate and its western boundary

Zonenshain and Savostin (1981) proposed the "Amurian plate" covering eastern Mongolia, north China, and southeastern Russia in the extensional areas southeast of Lake Baikal. The Amurian plate and its geometrical boundary in East Asia have been studied extensively using space geodetic observations (e.g., Takahashi et al., 1999; Heki et al., 1999; Jin, 2013), a six-plate analysis of earthquake slip vectors and NUVEL-1 data (Wei and Seno, 2011), kinematics of the active faults (Sankov et al., 2022), and topography and seismicity (e.g., Bird, 2003). The southernmost edge of the Amurian plate is unclear compared to other areas. Heki et al. (1999) suggested that the south boundary of the Amurian Plate may be the Qinling fault because it is consistent with the Euler vector and predicts left-lateral movement along its boundary with the South China block. However, Jin (2013) defined the

tectonic boundary between the North China and Amurian plates as the Yin Shan-Yan Shan Mountain belts with about 2.4 mm/yr extension. Because of the sparse and limited data, these investigations of tectonics in this region are inconclusive. Thus, the existence of the Amurian plate and its boundary geometry remains debatable.

Our anisotropic S wave model provides new insights into the local tectonic features of the eastern Mongolia region. Owing to a large number of local broadband seismic stations in Mongolia, our new 3-D model shows distinct lateral variations near the expected boundary between the Eurasian and Amurian plates (Figures 7 and 8), especially near the northern and western edges of the Amurian plate. However, the southern border of the Amurian plates in China is unclear due to the limited station coverage in the current study. The arrows in Figure 7 (a) show the relative plate motion; the Indian plate moves northward at a rate of about 44 mm/year, the Pacific, Okhotsk, and Philippine Sea plates move northeastward at about 93 mm/year, 84 mm/year and 67 mm/year, respectively, and the Amurian plate moves southeastward at about 5 mm/year, for the fixed Eurasian plate based on the MORVEL plate model (DeMets et al., 2010). The GPS measurements in Mongolia by Calais et al. (2003) are displayed with black arrows in Fig 7 (a). In western Mongolia, we can see northward shortening in the Altay area, which varies from 10 mm/year in the south to 4 mm/year in the north. However, central and eastern Mongolia moves eastward or southeastward at a rate of about 4 mm/year.

In the cross sections of Figure 7 (e, f), we can see clear velocity contrasts between the Eurasian and Amurian plates, especially at the western and

northern boundaries. The lateral variations of the S wave model at 70 km depth (Figure 8 (a)) show slow velocities in seismically active regions in western Mongolia (1964 – 2023 $M_l \geq 3.5$) and fast velocities in stable eastern Mongolia, which is likely to reflect the tectonic and structural differences between the two plates. Based on the observed velocity contrast in our model and local seismic activities, the western border of the Amurian plate in southern Mongolia may be located to the west about 2 degrees from the expected boundary by Bird (2003).

The dipping fast anomaly seen along the western border of the Amurian plate extends to about 180 km depth (Figure 8), which may manifest undergoing delamination or dripping of the lithospheric mantle (Elkins-Tanton, 2005; West et al., 2009; Bajolet et al., 2012). The slow anomaly in the asthenosphere beneath the Hentey Mountains extends wider areas in eastern Mongolia (Figures 8 and 9 and LV3 in Figure S21), which may represent the small-scale mantel convection beneath this region that may promote the lithospheric delamination in this area. Note that although our 3-D model well constrains the large-scale ($> 2^{\circ}$) upper mantle structure below 60 km depth, the shallower structure, including the crust, cannot be fully constrained due to the limited vertical resolution of the dispersion data used in this study. Also, the long-wavelength surface waves tend to blur the lithosphere images, limiting the lateral resolution of surface wave tomography. Additional seismic data, such as ambient noises and H/V ratios of Rayleigh waves, may help constrain the shallower structure. Moreover, body-wave travel times from local and teleseismic events will also help in higher-resolution images of mantle structure. Such further seismological constraints will enable us

to clarify more detailed tectonic and dynamics processes in the enigmatic western border of the Amurian plate.

6. Conclusions

We constructed a new radially anisotropic 3-D S-wave model in and around Mongolian regions from multi-mode surface waves. By combining broadband seismograms from the permanent and temporary seismic networks in Mongolia as well as neighboring GSN, PASSCAL, and NECESSArray stations, we could obtain the high-resolution S wave model under the whole areas of Mongolia, which provides new insight into large-scale tectonics of the Mongolian region, including the western border of the Amurian plate. The main conclusions of the current work can be summarized as follows.

1. S-wave speeds in the upper mantle beneath Mongolia are generally slower in the tectonically active west and faster in the stable east above 100 km depth. The significant velocity contrast between western and eastern Mongolia may reflect the boundary between the Eurasian and Amurian plates.
2. In western Mongolia, two major low-velocity anomalies are found beneath the northern Altay Mountains and the Hangay Dome. The former persists to 300 km depth, which may relate to the northward movement of Asian blocks due to the India-Asia collision. The latter continues down to 180 km depth beneath the Hangay Dome, particularly Khanuy Gol in the northeast of the Hangay area, which might reflect oblique upwelling.

3. In eastern Mongolia, located in the western Amurian plate, high velocities in the upper mantle suggest the relatively thicker lithosphere in the middle Gobi. The dipping fast anomaly along the Amurian plate boundary may indicate the delaminating or dripping lithosphere, which can be promoted by the small-scale mantle convection represented by low-velocity anomalies in the asthenosphere beneath the Hentey Mountains.
4. The new 3-D S-wave model exhibits significant velocity contrast between the Eurasian and Amurian plates and structural differences in the underlying upper mantle, implying the differential plate motions in eastern and western Mongolia can be related to such structural variations and local mantle dynamics.

Data Availability

The majority of seismograms used in this study are available from IRIS Data Management Center (`https://ds.iris.edu/ds/nodes/dmc/`). The waveform data of temporary seismic networks in eastern Mongolia can be available from the Earthquake Science Data Center at the Institute of Geophysics, China Earthquake Administration (`http://www.esdc.ac.cn`). The waveform data of the Mongolian network are available by applying to the Institute of Astronomy and Geophysics, the Mongolian Academy of Sciences (`iag@iag.ac.mn`). The seismic events displayed in Figure 3 are downloaded from the USGS database (`https://earthquake.usgs.gov/earthquakes/search/`). The 3-D S wave model used in this study is available from a repository (`http://dx.doi.org/10.13140/RG.2.2.19423.43686`).

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