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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
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Dear Tectonophysics Editor,

We would like to submit our manuscript entitled “Seismic crustal structure beneath Jeju Volcanic Island, South Korea” for publication in Tectonophysics.

In this study, we examined teleseismic receiver functions (RFs) recorded from 23 seismic stations to constrain the deep crustal seismic structure beneath Jeju Island, South Korea, and thus to clarify the crustal and magmatic plumbing system of the region. Jeju Island is an intraplate volcanic island with enigmatic origins, located on the continental shelf south of the Korean Peninsula. Computed RFs show two major seismic discontinuities beneath the island, which are the upper boundary of a mid-to-lower crustal low-velocity zone (LVZ) and the top of the crust-mantle transition zone. The imaged LVZ can be interpreted as an extensively distributed residual magma plumbing system, with magma batches stalled at various levels and at various degrees of crystallization, consistent with the chemical diversity of Jeju magmas. Variations of the Moho transition zone (24–38 km) do not mirror the surface topography of Jeju Island. In particular, shallow value exists beneath Mt. Halla, suggesting either crustal thinning associated with mantle upwelling or presence of a layered crust-mantle transition zone due to presence of mafic cumulates and partially melted mushes. Spatial variations of crustal P-to-S velocity ratio (Vp/Vs) ranging from 1.54 to 1.88 represent highly heterogeneous crustal composition, resulting from magma differentiation during the evolution of the island.

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Yours sincerely,

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Highlights

- We present deep seismic crustal model of Jeju Island using receiver functions.
- Our images show highly heterogeneous Moho and \( V_p/V_S \) structure beneath the island.
- No remarkable crustal thickening is observed below high topography of Mt. Halla.
- Low velocity zone at 9–23 km depth may delineate the top of a magma reservoir.
- Variations in \( V_p/V_S \) suggest highly heterogeneous crustal composition.
Tectonophysics

Seismic crustal structure beneath Jeju Volcanic Island, South Korea

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Keywords: Jeju Island, Intraplate volcano, Crustal seismic structure, Teleseismic receiver
function, Mid-to-lower crustal low-velocity zone, Magmatic plumbing system
1. Introduction

Jeju Island is an intraplate volcanic island located to the south of the Korean Peninsula (Fig. 1a), formed on continental crust by episodic eruptions since ~1.8 Ma. The oval-shaped island (32 km×75 km) is approximately 600 km away from the nearest plate boundary, the Nankai Trough, where the Philippine Sea Plate is subducting beneath the Eurasian plate (Fig. 1a). Mt. Halla, the highest point in South Korea (1947 m.a.s.l.), lies in the center of the island, and more than 300 eruptive centres (scoria cones and tuff rings/cones) are distributed on its flanks.

Previous petrological and geochemical studies showed complex variations in geochemical signatures and eruption patterns in Jeju Island (Brenna et al., 2010; Brenna et al., 2012a; Brenna et al., 2012b). Volcanic activity started on the submerged continental shelf and formed dispersed, small-volume (<0.01 km$^3$) alkali basaltic tuff cones/rings (Kang, 2003; Sohn and Park, 2004; Sohn et al., 2008; Sohn and Yoon, 2010). After emergence, small-scale basaltic monogenetic volcanism continued forming dispersed scoria cones and lava fields associated with the formation of trachytic lava domes in the southwestern part of the island around 700–800 ka (Koh and Park, 2010). Starting ~0.4 Ma, more voluminous (>1.0 km$^3$) lava eruptions formed a composite shield (Brenna et al., 2012a; Brenna et al., 2012b; Brenna et al., 2015; Koh et al., 2013). The depth and degree of mantle partial melting varied with time, and resulted in diverse chemical composition of magmas including high-Al alkaline, low-Al alkaline, and subalkaline suites (Brenna et al., 2012a; Tatsumi et al., 2004).

Several models on the formation of Jeju Island have been suggested. Tatsumi et al. (2004) proposed that Jeju Island was formed by mantle plume-related magmatism. However, the lack of typical plume features such as a volcanic chain with age progression and topographic swells makes the mechanism unlikely to explain the volcanic activity of the island. Shin et al.
(2012) proposed that Jeju Island was formed by decompression mantle melting due to lithospheric folding under compressional environment. Brenna et al. (2015) suggested that volcanism in Jeju Island was influenced by distal subduction tectonics at the Kyushu subduction zone, in which increased trenchward mantle flow by the greater rollback of the Philippine Sea Plate resulted in mantle upwelling and decompression melting along shear zones. A recent geochemical study by Kim et al. (2019) found evidence of recycled oceanic crust and sediment components in the mantle source of the Jeju magmas and suggested that a stagnant subducted Pacific slab in the mantle transition zone may have provided metasomatic fluids to the melting mantle.

There are few geophysical investigations of Jeju Island and most are focused on the shallow part of the crust including the volcanic basement and sedimentary cover using gravity, magnetic, electric and magnetotelluric data (Choi et al., 2007; Kim and Hong, 2012; Kwon et al., 1995; Lee et al., 1983; Lee and Kim, 1993). Several studies using seismic data reported crustal thickness beneath Jeju varying from 25 km to 35 km (Jeon et al., 2013; Kim et al., 2015; Yoo et al., 2007). However, these estimates of crustal thickness are resulted from five or less seismic stations installed on the island, and thus are limited in resolution and interpretation of overall crustal properties.

In 2013–2015, 20 temporary broadband stations were deployed in Jeju Island. It was a first attempt to operate a dense seismic array on the island to enable a series of systematic seismological surveys. Using these data, two investigations have been performed to elucidate shallow and deep structure of the crust and uppermost mantle (Lee et al., in review; Song et al., 2018). Using teleseismic traveltime data, Song et al. (2018) investigated lithospheric structures beneath Jeju Island and identified a deep low-velocity anomaly (50–60 km depth) under the summit of Mt. Halla, which separates into narrower low-velocity zones at
shallower depths (10–45 km). They interpreted the deep and shallow low-velocity anomalies as a high-temperature upper mantle structure with partial melts and a dispersed magmatic system at shallow depth, respectively, and suggested that focused decompression melting at sublithospheric depths might have induced intraplate volcanism in Jeju Island. Furthermore, using ambient noise data, Lee et al. (in review) found existence of seismic anisotropy within the upper crust (1–10 km depth) beneath Jeju Island and interpreted this as the layered dike and sill structure common in the shallow magmatic plumbing of similar volcanic systems (e.g., Keating et al., 2008; Kiyosugi et al., 2012; Muirhead et al., 2016). The goal of this study is to use the dense array data to image and better interpret the subsurface structure at the mid-to-lower crustal depth range and thus clarify the relationship with features in the upper crust and uppermost mantle.

In this study, we examine teleseismic P-to-S-converted phases (or receiver functions) to identify the deep crustal structure beneath Jeju Island. We estimate the geometry of crustal discontinuities and P-to-S velocity ratio ($V_P/V_S$) and provide constraints on the composition and seismic structure. The receiver functions are migrated following the approach by Dueker and Sheehan (1997) to enhance the continuity of the deep seismic structure at the mid-to-lower crustal depth range. In particular, using obtained $V_P/V_S$ estimates, we constrain the zone where magmas stall and evolve in the mid-to-lower crust, which explains the observed chemical range from basalt to trachyte on Jeju Island (Annen et al., 2005; Brenna et al., 2012b).

2. **Data and methods**

2.1. **Data analysis**
We used teleseismic waveform data recorded from the 20 temporary and 3 permanent broadband seismic stations deployed at Jeju Island (Fig. 1b). The seismic array covers the whole island (32 km × 75 km) on an average of 9 km intervals. We visually examined all the waveforms for earthquakes with magnitudes greater than 5.5 and within an epicentral distance of 30°–90° from the seismic array, and selected those with a clear P-wave arrival. A total of 470 earthquakes passed visual quality checks and provided sufficient back-azimuthal coverage (Fig. 2a). We note that the number of the selected earthquakes at permanent stations was much greater than that of temporary stations, and the number and record period of the selected earthquakes at individual station are presented in Table S1. Waveforms were filtered using a band-pass filter from 0.01 to 1.0 Hz, and then windowed between 10 s before and 60 s after the P-wave arrival. For the three permanent stations (JJU, JJB and HALB), we corrected misaligned seismograms by applying the orientation angle on the horizontal-component seismograms (Lim et al., 2018), which are shown in Table S2.

2.2. Teleseismic imaging

We compute teleseismic receiver function (RF) (Langston, 1979) in order to accurately define the location and magnitude of the crustal seismic discontinuities. Given the station array geometry on the island (Fig. 2a), we expect to obtain the highest resolution at the mid-to-lower crustal depths assuming 25–35 km crust for Jeju Island (Kim et al., 2015; Yoo et al., 2007). We also apply common conversion point stacking algorithms to the RFs, and this procedure reduces the effect of the wave propagation and thus effectively focuses the image (e.g., Dueker and Sheehan, 1997).

The RF calculation requires two key steps. The first step consists of coordinate rotation
for isolation and separation of incident and scattered wavefields. The second step involves
deconvolution, which removes source signature and propagation path effects for each event
used in the analysis (Ammon, 1991; Rondenay, 2009). Following these steps, three
orthogonal components of the seismograms (N–E–Z) were rotated to radial–tangential–
vertical (R–T–Z) components. The R-component seismograms were then deconvolved with
the Z-component seismogram to generate R-component RFs. We employed iterative
deconvolution in time domain (Ligorria and Ammon, 1999) with a Gaussian parameter of 2
and a maximum of 100 iterations. Although broad back-azimuthal data coverage (Fig. 2a)
allows examination of anisotropic structures from the T-component RFs using harmonic
decomposition (e.g., Bianchi et al., 2010; Kang and Kim, 2019) we only focus on imaging the
isotropic structure from the R-component RFs in this study.

2.2.1 H-κ stacking of RFs

All the reflected or converted modes exhibit a distinct moveout as a function of
source- receiver offset. By measuring these moveouts (assuming a locally flat layered
structure), it is possible to estimate local depth and average Vp/Vs between the surface and
the discontinuity associated with each mode (Zhu and Kanamori, 2000). In practice,
individual modes can be difficult to observe and identify on individual traces, so stacking
many events at similar distances and back azimuths is employed, and a search is performed
over a range of depths to the discontinuity (H) and Vp/Vs (κ). This method is denoted as H-κ
stacking.

In this stacking method, the amplitudes of RFs are summed at the predicted arrival times
of the converted phase (Pds, where ‘d’ represents the subsurface position of a P-wave
impedance contrast) and its multiples ($PpPds$ and $PpSds+PsPds$), assuming different $H$ and $\kappa$. The summation function $s(H, \kappa)$ is defined as $s(H, \kappa) = w_1r(t_1) + w_2r(t_2) - w_3r(t_3)$, where $r(t)$ is the R-RF, $t_1$, $t_2$, and $t_3$ are predicted $Pds$, $PpPds$, and $PpSds+PsPds$ arrival times at $H$ and $\kappa$, and $w_i$ are weighting factors ($w_1 + w_2 + w_3 = 1$; Zhu and Kanamori, 2000). The most reliable $H$ and $\kappa$ estimates are determined when the three phases are visibly identified and coherently stacked, and therefore produce maximum amplitude after summation over the grid search range. Uncertainty estimates on the $H$ and $\kappa$ are then estimated from the flatness of the summation function at the maximum amplitude in the $H$-$\kappa$ domain (Zhu and Kanamori, 2000).

For our dataset, we found that the range of 0.01–1.0 Hz is the best to balance the trade-off between high-frequency noise suppression and maintaining the highest resolution for the layer thickness of 25–35 km. Stacking RFs from different distances and back-azimuths suppresses the effect of lateral structural changes and yields an isotropic average crustal velocity model beneath the station. In this study, we performed grid search over a range of $H$ and $\kappa$ assuming $V_p$ of 6.3 km/s, which is an average value for the crust of the Korean Peninsula (Chang and Baag, 2006, 2007). We chose unequal weighting factors ($w_1 = 0.7$, $w_2 = 0.2$, and $w_3 = 0.1$) in stacking for $Pds$, $PpPds$ and $PpSds+PsPds$ phases, respectively.

2.2.2 Common conversion point gathering

Stacking of the RFs typically enhances coherent $Pds$ conversions while decreasing random noise. We applied common conversion point (CCP) stacking (Dueker and Sheehan, 1997) to the RFs to further effectively reduce the noise that is incoherent from station to station, and thus to sharply constrain lateral variations of crustal discontinuities beneath the array. In this analysis, the RFs are ray-traced back to their theoretical conversion points and
are migrated to depth. We back-project the RF energy using a modified ak135 global velocity model (Kennett et al., 1995), in which the crustal thickness and average Vp and Vs are replaced based on our H-κ stacking results. Accordingly, each station is assigned with its individual velocity model. The study area is gridded into bins of 0.05° by 0.05°, and a circular cap with a radius of 0.07° is used in gathering the RF amplitudes. The overlap among the caps has effects of smoothing small-wavelength topographic relief of the discontinuities less than the cap size (Liu et al., 2015). RF amplitudes of the bins within the radius are averaged to represent subsurface seismic structures. Fig. S2 shows the distribution of the P-to-S conversion points at 15 km and 30 km depths. We note that CCP stacking can average out some useful information about lateral heterogeneities and emphasize near-horizontal structures. Lastly, we applied elevation correction using the Shuttle Radar Topography Mission (SRTM3) dataset (Farr et al., 2007) to account for the difference in station elevations (less than 2 km).

3. Results and interpretations

3.1. RF images

We first present back-azimuthal stacks of RFs for three representative stations, including one permanent (JJU) and two temporary stations (SS04 and TP11) (Fig. 3). In each single-station R-RFs, we observe the largest positive-amplitude Pds arrival at 3–5 s after 0 s, indicating a downward seismic velocity jump at a seismic discontinuity (Figs. 3a–c). We interpret this discontinuity as the Moho transition zone beneath the Jeju Island. We also find a negative-amplitude Pds signal at 1–2 s, associated with downward decrease in seismic velocity (Figs. 3a–c). At station TP11, an additional positive-amplitude signal arrives at 2 s,
indicating the presence of a localized mid-crustal interface associated with an increase in seismic velocity with depth (Fig. 3c).

The R-RFs of stations JJU and SS04 show strong back-azimuthal variation in arrival time of \( P_{ms} \) (where \( 'm' \) represents Moho). The arrival time difference amounts up to \( \sim 1 \) s in those stations (Figs. 3a and b). The R-RFs of station JJU also show back-azimuthal variation in \( P_{ms} \) amplitudes (Fig. 3a). At station JJU, we observe sharp \( P_{ms} \) arrivals at 3 s and 4 s at back-azimuths of 120°–200° and 30°–60°, respectively (Fig. 3a). The converted amplitude signal becomes broadened and split into two (3–5 s) between 200° and 300°, which indicates a complex, possibly broad, Moho transition zone. These observations are consistent with previous RF study for the same station (Jeon et al., 2013). At station SS04, the \( P_{ms} \) arrival is found at 3.5 s in the range of back-azimuths 30°–60°, and at 4.5 s at other back-azimuths (Fig. 3b). On the other hand, the R-RFs of station TP11 show coherent \( P_{ms} \) arrivals at \( \sim 4 \) s regardless of back-azimuths (Fig. 3c). Strong amplitudes in T-RFs are observed at \( \sim 3–8 \) s at station JJU (Fig. 3d) and at less than \( \sim 3 \) s at station SS04 (Fig. 3e). T-RFs at station TP11 show 4-lobed back-azimuthal polarity flip of \( P_{ms} \) amplitudes at \( \sim 4 \) s (Fig. 3f).

The back-azimuthal variation of \( P_{ms} \) arrival time and amplitude observed in some stations may imply a local lateral variation in Moho depth or/and a presence of localized anisotropy. Also, scattering due to heterogeneous crustal structure including shallow low-velocity layers such as sediments (Oh et al., 2000; Kim and Hong, 2012) and volcanic layers (Kwon et al., 1993; Lee et al., 2007), and a mid-crustal low-velocity zone (associated with negative-amplitude \( P_{ds} \) signal at 1–2 s) may contribute to such variation. In this study, we concentrate on identifying the isotropic seismic structure of the crust, leaving the anisotropic structure of Jeju Island as a subject of future study.
Seismic characteristics of the Moho transition zone vary greatly between different regions in Jeju Island. Strong RF amplitudes are found at 4–5 s in the southwest (e.g., station SS08), at 3–5 s in the center (e.g., station JJU), and at 3–4 s in the southeast (e.g., station SS05), suggesting a broad Moho transition zone (Fig. S5).

3.2. Moho depth and Vp/Vs from H-κ stacking method

Fig. 4 shows examples of H-κ stacking of the RFs for two nearby stations (~17 km apart), TP13 and SS09. The estimated Moho depth for the two stations are 30.8±3.1 km and 31.5±2.5 km, respectively (Figs. 4a and d). However, Vp/Vs are found quite different at these two stations, which are 1.713±0.069 and 1.878±0.062, respectively (Figs. 4a and d). Although the output of the H-κ stackings can be nonunique partly due to nonuniform back-azimuthal distribution of event data, Vp/Vs estimates for these two stations are robust given the quality of the data and their uncertainty estimates. In addition to a very clear and coherent Moho conversion (Pms) at ~4 s in the individual traces (Figs. 4b and e), as well as in the stacked traces (Figs. 4c and f), the multiple phases from the Moho (PpPms and PpSms+PsPms) are also clear (Fig. 4b, c, e and f).

The H-κ stacking results for all stations are displayed in Table 1 and Fig. S1. The stacking outputs discontinuity depths for the Moho transition zone between 24.2 km and 38 km with an average depth of 31.3 km (Fig. 5a). The Moho transition zone is sharp and deepest (maximum 38 km) in the southwest part of the Jeju Island (Figs. 5a and S3a, see SS08 in Fig. S5). Stations in central (JJU) and southeastern Jeju (SS05 and TP10) show complex H-κ contour diagrams (Fig. S1), and these stations show strong amplitude signals at 24.2–27.9 km depth (minimum 24.2 km) (Table 1).
Crustal $V_p/V_S$ for all stations ranges from 1.54 to 1.88 with an average crustal $V_p/V_S$ of 1.73 (Fig. 5b). We excluded results from two stations (TP03 and SS06) for lack of data (less than 15 RF traces, thus leading to large uncertainties in $H$-$\kappa$ stacking). In particular, the crustal thickness estimates for two permanent stations JIU and JJB are 29.1±2.5 km and 32.3±3.6 km, respectively, and $V_p/V_S$ are 1.63±0.08 and 1.77±0.11, respectively (Table 1; Fig. S1). Our estimates on the Moho depth for those two stations agree well with previous estimates by Jeon et al. (2013), which are 29 km and 33 km for stations JIU and JJB, respectively.

Variations in $V_p/V_S$ are quite high throughout the island without any particular observable pattern. High $V_p/V_S$ are identified in the southwest (1.88 at station SS09, 1.85 at station SS04) and northeast (1.87 at station TP01). Low $V_p/V_S$ occur in central (1.63 at station JIU, 1.68 at station SS10), northwestern (1.62 at station TP04), and northeastern (1.54 at station SS07) parts in Jeju Island (Figs. 5b and S3b). As also shown in Fig. 4, the $V_p/V_S$ ratios are highly variable even at adjacent stations.

3.3. CCP images

The CCP images along eight profiles depict clear lateral variations in crustal structure (Figs. 2b and 6). Fig. S2 shows the event distribution of the $Pds$ conversion points at 15 km and 30 km depths beneath Jeju Island. Our images show two distinct discontinuities, one at ~10–20 km depth and the other at 20–40 km depth (Fig. 6).

The shallow discontinuity delineated by negative RF amplitudes marks the upper boundary of the seismic low-velocity zone (LVZ). Average depth to the top interface of the LVZ is 15.7 km. The LVZ is found deep (maximum 23 km depth) in the southwest part of
Jeju and is shallow (minimum 9 km depth) in the northeast (Fig. 7a). To explain the negative RF peak amplitudes, we require a 2.5–15 km thick LVZ with $V_S$ of $\sim 1.1–2.6$ km/s, which is much slower compared with typical lower continental-crust velocity ($3.51–4.15$ km/s; Rudnick and Fountain, 1995). In the RF modelling, we assumed a 500 m near-surface layer with $V_S$ of 1.0 km/s, which was reported in previous studies (Oh et al. 2000, Kim and Hong, 2012). We note that $V_S$ of the near-surface structure can influence the $V_S$ estimates of the LVZ, and we discuss this in Section 4.3.

The deep discontinuity delineated by positive RF amplitudes is the Moho transition zone. Average crustal thickness is 31 km. The strong amplitudes are found at maximum 37 km beneath the southwestern part of Jeju and shallow (25–29 km) beneath the central and southeastern parts (Fig. 7b). The observed amplitude variations do not mirror the surface topography of Jeju Island (Fig. 7b; see images for profiles BB’ (Fig. 6b), EE’ (Fig. 6e), GG’ (Fig. 6g) and HH’ (Fig. 6h)). Beneath the summit of Mt. Halla, the crustal thickness is 28 km (Fig. 7b). The crustal thickness is found to be the thinnest beneath the southeastern part of Jeju Island, at 25 km (Fig. 7b).

In addition to observed complex topography for Moho transition zone and top of LVZ, the amplitudes of the $Pds$ phase also vary spatially. The converted phase amplitudes indicate impedance contrast across the discontinuity, and more critically the change in $V_S$ across the discontinuity (Kim et al., 2010; Kim et al., 2012; Kim et al., 2013; Kim and Clayton, 2015). Therefore, such amplitude information can provide useful constraints on lithology. However, the interpretation may not be straightforward since the amplitudes depend on the back-azimuthal distribution of the earthquakes used in the analysis, sharpness of the discontinuity and interference with reverberations from the near-surface structure. We assume that amplitude variations due to azimuthal coverage can be suppressed as we use the average
amplitudes taken from the CCP stacks of the RFs for interpretation.

The map of amplitude variations for the top of LVZ shows relatively large values concentrated near the coastal region of the island (Fig. 7c). In particular, the largest negative values can be identified in three regions: southeastern, western, and northwestern coast of the island (Fig. 7c, yellow dashed ellipse). The anomaly in the western part correlates well with the region with recently erupted volcanoes (Biyangdo, Suwolbong and Songaksan in Fig. 1b; Ahn, 2016). On the other hand, large positive amplitude anomalies are observed in the following regions: central Jeju beneath Mt. Halla, and western and southeastern coastlines (Fig. 7d, yellow dashed ellipse).

4. Discussion

4.1. Complex Moho transition zone topography

The results of $H$-κ and CCP stacking show a complex topography of the Moho transition zone under Jeju Island (Figs. 5a and 7b). The two stacking results show similar characteristics of deep seismic discontinuity in the southwest (37–38 km) and shallow discontinuity in the southeast (24–25 km), but its depth below Mt. Halla in central Jeju is found ~3 km shallower in the CCP results. Although the $H$-κ stacking is generally useful for estimating the average Moho depth below a station, in our study it mostly reflects the structure in the south and southeast because teleseismic earthquake locations are predominantly distributed in those backazimuths. The CCP stacking can provide better spatial resolution than the $H$-κ stacking for our study because station separation distance (9 km in average in this study) is much smaller than the lateral conversion offset (~20 km) at the Moho depth (Rondenay, 2009). We note that the observed discrepancy of Moho depth (up to 4.5 km at station SS08) result from
the different spatial resolution capacity of the two methods (Fig. S8).

The observed complex Moho topography can be inferred from back-azimuthal difference in the arrival times of $P_{ms}$ phase shown in individual RF traces (Figs. 3 and 8a). For example, in station SS04, the converted waves sampling north-northeast (back-azimuth range of $0^\circ$–$45^\circ$) arrive much earlier (~3 s) than those sampling southeast and southwest (~5 s) (Fig. 8b). Such observed $P_{ds}$ arrival time difference can either be attributed to both lateral variations in seismic velocity structure or discontinuity depth or both (e.g., Janiszewski et al., 2020).

Based on following evidences, we interpret the observed variation in the $P_{ms}$ arrival time as mainly resulting from Moho topography, rather than lateral variation of the crustal velocity structure. First, if the Moho depth is uniform throughout the island, the expected seismic velocity structure from the RF results does not correspond to the local 3D velocity model (Song et al., 2018). Assuming a uniform Moho depth of 30 km, the observed $P_{ms}$ arrival time can be explained when there is a fast average crustal velocity in central Jeju and a slow velocity in southern Jeju (Fig. 8b). However, this is contrary to the tomography result that show opposite trend of $V_s$ structure beneath central Jeju at less than 30 km depth (Song et al., 2018). Second, although the mid-to-lower crustal LVZ beneath the island appears to be widely distributed throughout the island (Fig. 6b), amplitudes of the converted phases at the LVZ (thus $V_s$ reduction; Fig. 7c) do not show clear relationship with the observed variations of Moho depth (Fig. 7b).

We note that another potential LVZ at the base of the crust may also have an effect on the Moho depth estimates, which will be further discussed in Section 4.2. We also note that errors in estimating Moho depths may rise from complex near-surface structure such as presence of sediments and volcanic rocks. Our observation of the delayed arrival of the direct $P$ wave in
the single-station RFs (Figs. 3 and 4) is generally considered to imply scattering from the near-surface low-velocity structures (Schulte- Pelkum et al., 2017; Sheehan et al., 1995), consistent with the presence of low-velocity volcanic rocks (Vs of 1.4-2.0 km/s; Lee et al., 2007) and sediments (Vs < 1 km/s; Kim and Hong, 2012) in Jeju Island (Kang, 2003; Koh, 1997; Sohn and Park, 2004). Localized variation in the thickness or velocity of such slow layers can lead to mischaracterization of the depth of deep crustal seismic discontinuities (e.g., Yeck et al., 2013). Thickness of volcanic rocks and sediments are reported to be several hundred meters in well logging data (Oh et al., 2000). In addition, the presence of shallow anisotropic layers observed by ambient noise analysis (Lee et al., in review) may also increase the uncertainty in Moho depth estimates. Another potential source of errors in this study may include insufficient number of events and incomplete event back-azimuthal coverage for several temporary seismic stations due to their short operation period (Table S1).

4.2. Seismic crustal structure beneath Mt. Halla

In typical volcanic zones, a thick crustal root is often observed and is attributed to a magmatic addition at the crust beneath the volcano (Thybo and Artemieva, 2013). Beneath Mt. Baekdu (also known as Changbaishan), one of the Cenozoic intraplate volcanoes in northeast Asia, a thick crust (~40 km) is reported resulting from mafic underplating at the bottom of the crust (Kim et al., 2017). In Jeju Island, xenoliths of mafic cumulates are found in lavas (Yang, 2004; Yang et al., 2012b), consistent with observations of mafic cumulates in other volcanic regions. However, as our teleseismic images show (Figs. 6b, 6e and 7b), the strong amplitude signals are found below the summit of Mt. Halla and in southeastern Jeju, ranging 24–29 km, which is much thinner than the surroundings (Fig. 7b). The depth to the
top of the Moho transition zone is 24–25 km beneath southeastern Jeju (Fig. 7b), and is only 27–29 km below the central part of the island and Mt. Halla (1,947 m.a.s.l.) (Fig. 7b).

If the strong seismic signals at 24–29 km depth are from sharp Moho discontinuities, crustal thinning by 12–14 km (~1/3 of the crust) would imply a tectonic setting such as a rift, and there is no evidence of that in the continental shelf where Jeju Island is located. It is possible that the magma plumbing system causes large variations in the observed crustal thickness. Therefore, a potential source of the lower crustal LVZ is mushy hot zones near the base of the crust, which can be closely associated with the voluminous magma supply that built Mt. Halla in the centre of the island. In this case, the presence of mafic cumulates represents the crust-mantle transition zone (e.g. Ding et al., 2019), and this mafic layer may contribute to large velocity contrast with the crust above but small velocity contrast with upper mantle beneath central Jeju.

Teleseismic travel-time data suggests a sub-lithospheric magmatic structure below the summit of Mt. Halla (Song et al., 2018). Based on their velocity model, a focused decompression melting at sub-lithospheric depths and complex magma interactions within the lithosphere explain intraplate magmatic activities of Jeju Island (Song et al., 2018). This suggests that hot and buoyant mantle can support the high elevations of Mt. Halla. Such a thin crust being supported by hot asthenospheric material is also reported in the Central Alborz mountains in western Asia (Sodoudi et al., 2009). Lastly, the strong amplitude of $P_{ds}$ beneath Mt. Halla may be related to residual heat or fluids from the recent (25 ka) episode of trachyte volcanism that formed the top of Jeju (Brenna et al., 2015).

4.3 Mid-to-lower crustal low-velocity zone
Using ambient noise data, Lee et al. (in review) imaged upper crustal (1–10 km) radially anisotropic structures beneath Jeju Island. Their images indicate dyke swarms (at depths 1–2 km and 5–10 km) covering top and bottom of sill structures (at depths of 2–5 km). Such structures were interpreted as pathways supplying magmas to the shallow crust from deeper reservoirs.

In this study, we observe a coherent negative-amplitude signal at 1–3 s, implying existence of a LVZ in the mid-to-lower crust (at 9–23 km depth). Previous RF study using two permanent stations (JJU and JJB) have also reported LVZ (with $V_s$ of $3.0\pm0.5$ km/s for JJU and $3.2\pm0.6$ km/s for JJB) at mid-crustal depth (at 14 km) beneath central Jeju Island (Jeon et al., 2013). In this study, the $V_s$ estimates of LVZ are in the range of 1.1–2.6 km/s, which are slower than the previous study by Jeon et al. (2013). Variable $V_s$ values for individual station indicates different melting or crystallization condition. On the other hand, the velocity contrast across the top of the LVZ may have been overestimated locally by the amplitude amplification by multiples generated by near-surface low-velocity structures.

Several stations in northeastern Jeju (e.g., station TP11; Fig. 3c) show a series of negative-positive amplitude signals at 1–3 s, which are considered to be the converted signal at the top and bottom interfaces of the LVZ (Fig. S4), whereas at other stations single negative-amplitude signals at 1–3 s are observed (Fig. S5). The mid-crustal discontinuity indicating the bottom of the LVZ is also seen clearly in the CCP cross-sections along the profiles CC’, FF’ and GG’ (Figs. 6c, f and g, respectively). The velocity transition from the top of LVZ to Moho might be gradual in stations that show only negative-amplitude signals at 1–3 s. Most stations that show a series of negative-positive amplitude signals at 1–3 s are distributed in the eastern part of Jeju (Fig. S6). The difference in seismic signals can be attributed to the different geologic structure of the basement in eastern and western Jeju, with
Cretaceous ignimbrite in the east as opposed to granite in the west (Sohn, 1996). The bottom interface of the low-velocity ignimbrite layer in the east may be shown as a mid-crustal discontinuity, whereas the impedance contrast across the boundary between LVZ and lower crust can be gradual in western Jeju. We also note that seismic multiples from shallow low-velocity structures (i.e., sediments) could interfere with primary conversion from mid-to-lower crustal LVZs, leading to reduction of converted signals from the bottom interfaces of the LVZ in western Jeju.

Several previous studies have revealed a LVZ in the middle or lower crust beneath or near volcanoes in both intraplate and plate boundary settings. The presence of a LVZ beneath Mt. Baekdu, an intraplate volcano, was characterized by studies using RFs (Hetland et al., 2004; Song et al., 2017), ambient noise (Kim et al., 2017), joint inversion of RFs and ambient noise (Zhu et al., 2019), and 3-D deep seismic sounding (Zhang et al., 2002). LVZs are also found in arc volcanoes such as Mt. Fuji by RFs (Kinoshita et al., 2015) and seismic tomography (Nakamichi et al., 2007), and the Aleutian Islands by RFs (Janiszewski et al., 2013). The low-velocity zone is typically interpreted to represent magmatic reservoirs consisting of mechanically weak materials, such as partial melts/crystal mushes and/or aqueous fluids (Abe et al., 2010; Sudo and Kong, 2001).

Our imaged LVZ may imply presence of a series of magma reservoirs connecting the deep sub-lithospheric magma source region with the shallow (<10 km depth) plumbing system of Jeju Island, as proposed by previous geochemical and petrological work (Brenna et al., 2012b; Yang et al., 2012a). The spatially distributed depth-profile of the LVZ supports a dispersed plumbing system feeding the >300 eruptive vents on Jeju rather than a focused central plumbing system beneath Mt. Halla (Brenna et al., 2012b). The variation in RF amplitudes associated with the LVZ (Fig. 7c) may indicate different degrees of melt present...
in partly crystallized dyke networks.

4.4 Variations of crustal $V_p/V_S$

Laboratory experiments have shown that mineralogical composition and melting condition of crustal rocks are the main determining factors for the bulk crustal Poisson’s ratio or $V_p/V_S$ (e.g., Christensen, 1996; Christensen and Mooney, 1995). Our $H$-$\kappa$ analysis shows that crustal $V_p/V_S$ beneath Jeju varies widely (1.54–1.88) with an average crustal $V_p/V_S$ of 1.73 (Fig. 5b). This average estimate is lower than the average continental value of 1.78 (Zandt and Ammon, 1995), and may not properly represent a volcanic region since the presence of partial melt and/or fluids generally increase $V_p/V_S$ (Kim et al., 2010; Kim et al., 2012; Kim et al., 2013; Kim and Clayton, 2015). Thus, $V_p/V_S$ estimate for individual station is more meaningful for interpretation of spatial variations rather than the average. We note that estimate of $\kappa$ (and $H$ to a lesser degree) can be largely biased in the presence of anisotropy (Kaviani and Rümpker, 2015).

Typically, $V_p/V_S$ values are inversely related to the silica content of the medium (Zandt and Ammon, 1995). Basalts to trachytes erupted on Jeju Island have a wide range of silica content, 44–66% (Brenna et al., 2012b). Such diverse lithologies associated to volcanism, as well as the granitic basement, may explain our observed $V_p/V_S$ range. As Fig. 5b shows, we find that distribution of the $V_p/V_S$ estimates varies significantly from station to station. Such distribution of $V_p/V_S$ may be related to dispersed eruption of small-volume magmas distributed below the island, which may be closely linked to different degree of magma evolution.
We observe that high $V_p/V_s$ are found in the southwest where the older trachytes (700–800 ka) are located (Sanbangsan region; S3), whereas the relatively lower $V_p/V_s$ are found in central and eastern parts of the island (Fig. 5b). We interpret that an older (700–800 ka) solidified plumbing system with mafic cumulates and plutonic rocks beneath the Sanbangsan region may contribute to the higher $V_p/V_s$ in the southwest, whereas the younger plumbing system associated to the Halla trachytes is still warm and partly mushy, hence resulting in the lower $V_p/V_s$ in the center.

Based on travel-time analysis, Jo and Hong (2013) suggested high upper crustal $V_p/V_s$ in western Jeju Island (1.76–1.91), and lower $V_p/V_s$ in eastern part of the island. Although the distribution of our $V_p/V_s$ estimates is somewhat sporadic, we can also draw similar findings that the crustal $V_p/V_s$ is the highest in the localized western region of Jeju Island (1.85–1.88) and the lowest in the east (1.54). The effect of the mafic volcanic component of the upper crust is reflected in $V_p/V_s$ of the entire crust.

5. Conclusions

We investigate the deep crustal seismic structure beneath the Jeju Island intraplate volcanic field formed by Pleistocene to Holocene eruptions, from teleseismic receiver functions (RFs). To improve imaging of the Moho geometry, RFs are migrated to 0–70 km depth by the common conversion point (CCP) stacking approach. We also use a grid-search scheme to constrain the seismic discontinuity depth and $V_p/V_s$ by stacking the RF amplitudes at predicted arrival times for the $P$-to-$S$ converted phase and its multiples for different values of layer thickness and $V_p/V_s$. Our teleseismic images reveal two prominent seismic discontinuities beneath Jeju Island, which are mid-to-lower crustal LVZ and Moho transition
zone. Depths to the two discontinuities are highly variable (LVZ at 9–23 km depth and deeper crustal interface at 24–38 km depth) over a short distance (less than 75 km). The observed topography of the Moho transition zone suggests crustal thinning below the Mt. Halla. This could either be associated with mantle upwelling imaged by teleseismic travel-time tomography (Song et al., 2018), or, considering the tectonic setting of Jeju Island on the continental shelf, be indicative of a layered crust-mantle transition zone composed of mafic cumulates and partially molten mushes. Diversity of crustal $V_p/V_S$ (1.54–1.88) indicates heterogeneous crustal compositions beneath the island. We link our imaged LVZ with an extensively distributed magma plumbing system, with magma batches stalling and evolving in the lower crust resulting in the chemical diversity of magmas observed on Jeju Island.
Table 1. Results of $H$-κ stacking analysis. Crustal thickness ($H$) and $V_p/V_S$ (κ) are estimated assuming mean crustal $P$ velocity of 6.3 km/s and weighting factors of 0.7, 0.2 and 0.1 for $P_{ms}$, $P_{ppms}$ and $P_{sms}+P_{psms}$, respectively. The $1\sigma$ uncertainties are estimated from the flatness of the summation function at the maximum, using the method of Zhu and Kanamori (2000).

<table>
<thead>
<tr>
<th>Station</th>
<th>Crustal thickness ($H$ in km)</th>
<th>Crustal $V_p/V_S$ (κ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK01</td>
<td>31.2 ± 2.4</td>
<td>1.78 ± 0.086</td>
</tr>
<tr>
<td>SS01</td>
<td>31.2 ± 2.1</td>
<td>1.755 ± 0.062</td>
</tr>
<tr>
<td>SS02</td>
<td>32.3 ± 2.9</td>
<td>1.765 ± 0.059</td>
</tr>
<tr>
<td>SS04</td>
<td>31.8 ± 2.3</td>
<td>1.848 ± 0.086</td>
</tr>
<tr>
<td>SS05</td>
<td>24.2 ± 2.1</td>
<td>1.73 ± 0.057</td>
</tr>
<tr>
<td>SS07</td>
<td>30.9 ± 2.8</td>
<td>1.538 ± 0.048</td>
</tr>
<tr>
<td>SS08</td>
<td>38 ± 2.1</td>
<td>1.703 ± 0.039</td>
</tr>
<tr>
<td>SS09</td>
<td>31.5 ± 2.5</td>
<td>1.878 ± 0.062</td>
</tr>
<tr>
<td>SS10</td>
<td>31.9 ± 3.6</td>
<td>1.68 ± 0.084</td>
</tr>
<tr>
<td>TP01</td>
<td>30.2 ± 2.1</td>
<td>1.865 ± 0.049</td>
</tr>
<tr>
<td>TP02</td>
<td>30.4 ± 2</td>
<td>1.728 ± 0.051</td>
</tr>
<tr>
<td>TP04</td>
<td>32.8 ± 3.4</td>
<td>1.62 ± 0.078</td>
</tr>
<tr>
<td>TP07</td>
<td>33.3 ± 2</td>
<td>1.713 ± 0.036</td>
</tr>
<tr>
<td>TP08</td>
<td>33 ± 2.4</td>
<td>1.745 ± 0.061</td>
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<tr>
<td>TP09</td>
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<td>TP11</td>
<td>32.5 ± 2.3</td>
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<td>TP13</td>
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<tr>
<td>JJU</td>
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<td>JJB</td>
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<tr>
<td>HALB</td>
<td>28.9 ± 3.2</td>
<td>1.743 ± 0.171</td>
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</table>
Figure 1. Maps showing tectonic setting of Jeju Island and location of seismic stations in the island. (a) Tectonic setting of Jeju Island in northeast Asia. The red box indicates the location of Jeju Island. Black triangles indicate location of Pleistocene-Holocene volcanoes in northeast Asia (Venzke, 2013). Convergent plate boundaries (Bird, 2003) are shown with white saw-toothed lines. (b) A map showing the location of seismic stations. 20 temporary broadband stations and 3 permanent broadband stations are shown as black and red squares, respectively. The temporary stations were operated during October 2013–November 2015. Two permanent stations (JJU and HALB) belong to network of the Korea Meteorological Administration (KMA) and one (JJB) belong to network of the Korea Institute of Geoscience and Mineral Resources (KIGAM). Location of the central shield volcano, Mt. Halla, is shown as a black triangle. Locations of recently erupted (age less than 25 ka) small-scale volcanoes (B: Biyangdo, S1: Songaksan, S2: Suwolbong, I: Ilchulbong, U: Udo, G1: Gunsan, G2: Gapado; Ahn, 2016) are shown as white triangles and denoted by their abbreviations. Location of trachyte volcano Sanbangsan (S3) is shown as a white star.
Figure 2. Maps showing distribution of teleseismic earthquakes, stations, and profile locations for teleseismic imaging. (a) Earthquake locations shown as red circles. Epicentral distances of 30° and 90° from a central point of the seismic array are marked as dashed lines. (b) Profile locations. Eight profiles (AA’, BB’, CC’, DD’, EE’, FF’, GG’ and HH’) are shown for the CCP cross-sectional images in Fig. 6.
Figure 3. Single-station radial (R) and tangential (T) RFs calculated for three representative stations, including one (a, d) permanent (JJU) and two temporary stations (SS04 (b, e) and TP11 (c, f)). The RFs are stacked by non-overlapping 10° back-azimuth bins. Positive amplitudes (red) indicate that the impedance increases with depth, and negative amplitudes (blue) indicate that the impedance decreases with depth.
Figure 4. Examples of $H$-$\kappa$ stacking result for two stations, TP13 and SS09. (a, d) Contour map of the optimal $H$ and $\kappa$ determined for stations (a) TP13 and (d) SS09. Weighting factors for $Pms$ and its multiples ($PpPms$, $PsPms+PpSms$) are 0.7, 0.2, and 0.1, respectively. The black cross represents the 1σ uncertainty of the optimal $H$ and $\kappa$. (b, e) RFs of stations (b) TP13 and (e) SS09, sorted according to the ray parameter ($p$). Predicted arrival times of $Pms$ and its multiples ($PpPms$, $PsPms+PpSms$) are indicated by black dashed lines. (c, f) Stacked RF traces are shown as black lines, and averaged predicted arrival times of $Pms$, $PpPms$ and $PsPms+PpSms$ of the stations (c) TP13 and (f) SS09 are indicated by black dashed lines. The individual RFs are normalized before stacking. Gray shading indicates one standard deviation of the RF stacks.
Figure 5. Moho depth (a) and crustal $V_p/V_s$ (b) determined by $H$-$\kappa$ stacking of RFs for individual station. The $1\sigma$ uncertainties of the optimal $H$ and $\kappa$ for individual station (Table 1) is shown as a black cross, with its size proportional to its magnitude. Results from the $H$-$\kappa$ stacking method are interpolated using weights inversely proportional to the square of the uncertainty estimates and the distance from the stations, respectively. Only the grids with more than 15 piercing points are presented (Fig. S2). $H$-$\kappa$ results for stations with less than 15 RF traces are excluded to avoid uncertainties resulting from limited number of RFs. Symbols are as in Figure 1b. See Figure S3 for the non-interpolated version.
Figure 6. CCP images along eight profiles: (a) AA’, (b) BB’, (c) CC’, (d) DD’, (e) EE’, (f) FF’, and (g) GG’ (Fig. 2b). Red color indicates impedance increase with depth whereas blue color indicates impedance decrease with depth. Top panel of each figure shows surface topography with station locations.
Figure 7. Variation in discontinuity depths and amplitudes of CCP stacks. (a) Topography of the top of the LVZ obtained from the CCP stacks. (b) Moho topography. (c) Normalized amplitudes at the top of the LVZ. (d) Normalized amplitudes at Moho. Only bins with more than 15 piercing points are shown in the figure. See Figure S7 for the results using different minimum number of piercing points within a bin (20, 30, and 40). Yellow dashed ellipse in panel (c) and (d) encloses high amplitude signals. Symbols are as in Figure 1b.
Figure 8. (a) Single-station RF traces for station SS04, sorted by back-azimuth. (b) Variation in the $Pms$ arrival time, plotted at 30 km piercing point of each individual rays. (c) Average crustal Vs near station SS04, assuming a uniform Moho depth of 30 km. Three different back-azimuthal groups (G1, G2 and G3) are highlighted in the figure.
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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version.
References


Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Shaffer, S., Shimada, J.,


Koh, G.-W., Park, J.-B., 2010. The Study on Geology and Volcanism in Jeju Island (III): Early Lava Effusion Records in Jeju Island on the Basis of $^{40}$Ar/$^{39}$Ar Absolute Ages of Lava Samples. Economic and Environmental Geology 43, 163-176.


Lee, S.-J., Kim, S., Rhie, J., Kang, T.-S., Kim, Y., in review. Isotropic and anisotropic upper crustal magma structures beneath Jeju Island volcanoes.


Schulte-Pelkum, V., Mahan, K.H., Shen, W., Stachnik, J.C., 2017. The distribution and
composition of high-velocity lower crust across the continental US: Comparison of seismic and xenolith data and implications for lithospheric dynamics and history.

Tectonics 36, 1455-1496.


analysis with teleseismic wavefield reconstruction: Application to South China.

Tectonophysics 718, 118-131.


Yoo, H., Herrmann, R., Cho, K., Lee, K., 2007. Imaging the three-dimensional crust of the Korean Peninsula by joint inversion of surface-wave dispersion and teleseismic


Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: