Episodes
Crustal velocity model of the southern Korean Peninsula along the Ganghwa–Yeongdeok seismic profile
--Manuscript Draft--

<table>
<thead>
<tr>
<th>Manuscript Number:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

| Full Title: | Crustal velocity model of the southern Korean Peninsula along the Ganghwa–Yeongdeok seismic profile |
| Article Type: | Article |
| Manuscript Classifications: | 240: Geophysics; 420: Seismology |
| Corresponding Author: | Junkee Rhie, Ph.D.  Seoul National University  Seoul, Korea, Republic of KOREA, REPUBLIC OF |
| Corresponding Author's Institution: | Seoul National University |
| Corresponding Author E-Mail: | rhie@snu.ac.kr |
| First Author: | Mikyung Choi |
| Order of Authors: | Mikyung Choi  Junkee Rhie, Ph.D.  Hyun-Moo Cho  Jung Mo Lee  Chang-Eob Baag  KI Young Kim  Heeok Jung |

| Abstract: | We herein present results of a seismic experiment conducted along with the KCRT2008 profile, a 300-km-long NW–SE-trending transect, which was the third crustal-scale seismic experiment across the southern Korean Peninsula. Two-dimensional P- and S-wave velocity models beneath the profile were determined from seismic data acquired during the KCRT2008 experiment. The P-wave velocity in the crust ranged between 4.40 and 6.85 km/s, with an average of 6.27 km/s. The S-wave velocity varied from 2.51 to 3.88 km/s, with an average of 3.61 km/s. The depths to the Mohorovicic discontinuity were 30.00–34.00 km, and the crustal thickness becomes shallower toward both ends of the profile. The Vp/Vs ratio in the crust ranged from 1.71 to 1.77 and increased with depth. The average Vp/Vs ratio along the profile was 1.74. The Vp/Vs ratios and P-wave velocity values suggest that the upper and middle crust is composed of felsic rocks, while the lower crust is intermediate in composition. These results are consistent with the findings of a previous experiment (KCRT2004). The depth changes of the Moho by isostasy coincide with the Moho depth determined by the seismic surveys. |

| Suggested Reviewers: | Tae-seob Kang, Ph. D.  taeseob.kang@gmail.com  Seongryong Kim, Ph. D.  srkim24@gmail.com  Dong-Hoon Sheen, Ph. D.  dhsheen@jnu.ac.kr |

<table>
<thead>
<tr>
<th>Opposed Reviewers:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Additional Information:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Crustal velocity model of the southern Korean Peninsula along the Ganghwa–Yeongdeok seismic profile

Mikyung Choi¹, Junkee Rhie¹*, Hyun-Moo Cho², Jung Mo Lee³, Chang-Eob Baag¹, Ki Young Kim⁴, Heeok Jung⁵

¹School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea
²Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, Daejeon, South Korea
³Department of Geology, Kyungpook National University, Daegu, South Korea
⁴Department of Geophysics, Kangwon National University, Chuncheon, South Korea
⁵Department of Coastal Construction Engineering, Kunsan National University, Gunsan, South Korea

*Corresponding author: rhie@snu.ac.kr
Abstract

We herein present results of a seismic experiment conducted along with the KCRT2008 profile, a 300-km-long NW–SE-trending transect, which was the third crustal-scale seismic experiment across the southern Korean Peninsula. Two-dimensional P- and S-wave velocity models beneath the profile were determined from seismic data acquired during the KCRT2008 experiment. The P-wave velocity in the crust ranged between 4.40 and 6.85 km/s, with an average of 6.27 km/s. The S-wave velocity varied from 2.51 to 3.88 km/s, with an average of 3.61 km/s. The depths to the Mohorovicic discontinuity were 30.00–34.00 km, and the crustal thickness becomes shallower toward both ends of the profile. The $V_p/V_s$ ratio in the crust ranged from 1.71 to 1.77 and increased with depth. The $V_p/V_s$ ratio in the Gyeonggi massif, located in the northwestern part of the profile, was found to be lower than in the tectonic units to the north and south. The average $V_p/V_s$ ratio along the profile was 1.74. The $V_p/V_s$ ratios and P-wave velocity values suggest that the upper and middle crust is composed of felsic rocks, while the lower crust is intermediate in composition. These results are consistent with the findings of a previous experiment (KCRT2004). The depth changes of the Moho by isostasy coincide with the Moho depth determined by the seismic surveys.

Keywords: 2-D crustal velocity structure, Southern Korean Peninsula, $V_p/V_s$ ratio

1. Introduction
An accurate characterization of the Earth’s crustal seismic velocity structure is important for many applications such as earthquake location and seismic hazard analysis. In addition, a velocity structure model, along with other geophysical observations, can provide valuable information for interpreting the tectonic evolution of the region. The Korean Peninsula has a very complex geological structure, yet a detailed history of its evolution has not been determined. The southern part of the Korean Peninsula (hereafter referred to as S. Korea) consists of the following tectonic units, from north to south: the Imjingang belt, the Gyeonggi massif, the Okcheon fold belt, the Yeonganam massif, and the Gyeongsang basin. Many previous studies have argued that the construction of the Korean Peninsula is somehow related to the collision between the South and North China blocks, and various tectonic models have been suggested that are based mainly on surface geology data (Cluzel et al., 1991; Yin and Nie, 1993; Zhang, 1997; Ernst and Liu, 1995; Chough et al., 2000; Ree et al., 2001; Oh, 2006; Ishiwatari and Tsujimori, 2003; Zhai et al., 2007). However, no clear conclusions have yet been reached. To understand the crustal structure of S. Korea, a number of geophysical investigations have been carried out on different scales. Early studies generated one-dimensional (1-D) regional models constrained mostly by the arrival times of local earthquakes (Kim and Kim, 1983; Kim, 1995) and gravity measurements (Choi and Shin, 1996). More recently, the development of various techniques, as well as the expansion of the seismic observation network in S. Korea, has enabled more detailed studies of the regional crustal structure. Consequently, a number of velocity models have been published in the last decade based on receiver functions (Chang and Baag, 2005; Chang and Baag, 2007; Yoo et al., 2007), ambient noise tomography (Kang and Shin, 2006; Cho et al., 2007; Choi et al., 2009), and waveform modeling (Kim et al., 2011). Seismic reflection/refraction experiments are superior to other geophysical methods for determining the velocity structure characteristics and details regarding the crust and underlying Mohorovicic discontinuity
(hereafter referred to as the Moho), and have been widely used in North America, Europe, China, and other countries (Prodehl et al., 2013). The P- and S-wave velocity models produced from these studies have been used to accurately characterize the composition and physical properties of crustal materials (Mooney and Brocher, 1987; Holbrook et al., 1988; Christensen and Mooney, 1995; Musacchio et al., 1997; Hammer et al., 2000). Christensen and Mooney (1995) inferred variations in crustal composition with depth by comparing seismic velocities obtained from field experiments with compositions obtained through laboratory analyses. In addition, similar studies have compared the $V_p/V_s$ ratios obtained from field and laboratory experiments to estimate crustal compositions (Holbrook et al., 1988; Zandt and Ammon, 1995; Christensen, 1996; Musacchio et al., 1997).

Three large-scale seismic refraction surveys in S. Korea have been carried out to characterize crustal structures across different profiles and to infer crustal composition. The first survey (KCRT2002; Cho et al., 2006) was conducted in 2002 along a 300 km NW–SE-trending transect (Figure 1). This survey line crossed major tectonic boundaries, as illustrated in Figure 1. In 2004, a second survey (KCRT2004; Cho et al., 2013) was conducted along a 340 km NNW–SSE-trending transect (Figure 1). The conclusions derived from these two surveys can be summarized as follows: (1) Thicker crust underlying the Okcheon fold belt was observed along with the KCRT2002 profile, which can be explained by accretion due to a collision between the Gyeonggi and Yeongnam massifs (Cho et al., 2006). However, the results from the KCRT2004 survey showed that the southern part of the profile, which contains the Yeongnam massif, had a thicker crust than the Okcheon fold belt does along with the same profile. These contradictory observations infer that variations in crustal thickness in S. Korea cannot be explained only by the collision of the two massifs; (2) The average $V_p/V_s$ ratio along the KCRT2004 survey was much lower than the average value for the continental crust. This observation is consistent with results obtained from East China, and can be
interpreted as the absence of the lowermost mafic section of the crust due to delamination (Chen et al., 2010); (3) Variations in the Vp/Vs ratio along a second survey profile support the hypothesis that the Gyeonggi and Yeongnam massifs are tectonically related to the North and South China Blocks, respectively (Cho et al., 2013). Although crustal characteristics were revealed by the two surveys, it is difficult to say that the observations reflect representative crustal characteristics in S. Korea because the sampling regions of both surveys were very limited. To fill this gap, a third survey (KCRT2008) was conducted in 2008 along a 300 km NW–SE-trending transect between Ganghwa and Yeongdeok (Figure 1). In order to improve the resolution of the velocity model, especially for the Moho depth and the Vp/Vs ratio, more geophones and shots were used than in the previous two surveys. A previous study used the KCRT2008 data to generate a two-dimensional (2-D) P-wave velocity model along the profile using first arrival travel time inversions (Kim et al., 2010). In this study, we present 2-D P- and S-wave velocity models and a Vp/Vs model based on data from the KCRT2008 experiment. Based on results from all three surveys, we then discuss the origin of the variations in the Moho depth, the composition of the crust, and the relationships between tectonic units in S. Korea and East China. (Figure 1 is about here)

2. Local geology and tectonic characteristics

The Korean Peninsula is located on the eastern margin of the Eurasian Plate and is divided into several tectonic units that span from Archean to Cretaceous periods. Figure 1 illustrates the main geological features of the peninsula and the location of the KCRT2008 transect, along with the locations of the KCRT2002 and KCRT2004 transects for reference. The KCRT2008 transect intersects four main geological features. From north to south, these features are as follows: 1) the Gyeonggi massif, containing Precambrian metamorphic rocks and Mesozoic granitoids and meta-sedimentary rocks that include granitic gneiss and
amphibolites (Lee et al., 2003); 2) the Okcheon fold belt, which trends NE–SW, containing metasedimentary rocks and metavolcanic rocks; 3) the Yeongnam massif, containing Precambrian metamorphic rocks; and 4) the Gyeongsang basin, which contains a 9 km-thick sequence of Cretaceous non-marine sedimentary facies and volcanic deposits that partially overlay the Yeongnam massif. These basin deposits were formed in an arc environment that was initiated by the subduction of the Izanagi Plate during the early Cretaceous (Chough and Sohn, 2010).

3. Seismic survey and data processing

The KCRT2008 survey was conducted in November 2008 along a 300 km transect from Ganghwa to Yeongdeok on the southern part of the Korean Peninsula (Figure 1). Seismic waves were generated by detonating eight shots (S1 to S8) along the survey line. Shot spacing was set at 20 to 30 km, except between S1 and S2, which were spaced 114 km apart because of proximity to the city. Each shot was fired at the bottom of a drilled hole, where hole depths ranged from 50 and 100 m. Charge sizes were 1500 kg for S1 and S8, 1000 kg for S2 and S5, and 250 kg for all other shots (S3, S4, S6, and S7). The positions and elevations of all shot points were recorded using the Global Positioning System (GPS). A total of 593 portable seismographs (Reftek-125) equipped with 4.5 Hz geophones to measure vertical components were deployed at 500 m intervals along the profile, and their locations were recorded using a portable GPS.

Seismic record sections were generated from each shot, then were amplitude-normalized and bandpass-filtered (from 4 to 15 Hz), as shown in Figure 2 with a reduction velocity of 8 km/s. For most of the seismic record sections, good quality Pg (direct P-waves propagating through the crust) and PmP (Moho reflected P-waves) phases were observed (Figure 2). The
Pg phase observed in the southeastern part of most of the record sections was clearly the first arrival phase at offset distances greater than 100 km. The PmP phases were distinctly observed on most record sections, even at offset distances greater than 140 km. However, in the northwestern parts of the S3 and S4 record sections, the Pg and PmP phases were identifiable at smaller offset distances and with small amplitudes due to the high background noise. The Pn phase, which are P-waves refracted from the uppermost mantle, was only identified in the S1 record section. Intra-crustal reflected phases (Pi1P and Pi2P) were also identified in the record sections. The Pi1P reflection between the upper and middle crust was observed in the northwestern part of the S3 record section. The Pi2P reflection from the boundary between the middle and lower crust was observed in the S4, S5, S6, S7, and S8 record sections. The PmS phase, which is an S-wave converted from a P-wave at the Moho, observed in the S1 and S8 record sections, and is clearly visible when a 2–7 Hz bandpass filter was applied instead of a 4–15 Hz filter. In addition, some phases, which are likely Pn or PmP multiples, were observed in the S1 record section at an offset distance greater than 200 km (Figure 2a). (Figure 2 is about here)

S-wave phases were observed on all seismic record sections after applying a bandpass filter of 2–9 Hz. In an ideal scenario, the explosive sources used to initiate seismic waves would not generate S-waves. However, S-waves can be produced by mode conversion of shock waves at the cavity wall and by micro- and macro-cracking (Liu and Ahrens, 2001). Thus, the S-wave phases with lower frequency contents than P-wave phases produce waveforms with more ringing and noise than the P-wave phase waveforms. The Sg (direct S-waves propagating through the crust) and SmS (Moho reflected S-waves) phases were observed in all seismic record sections. Sg phases were only detected at short offset distances, whereas SmS phases were clear in almost all the sections. We did not observe Sn phases in any of the record sections.
4. Crustal velocity model

The 2-D velocity structure of the crust and uppermost mantle along the KCRT2008 profile was determined using the RAYINVR program (Zelt and Smith, 1992), which calculates the misfit between observed and synthetic travel times of pre-defined seismic phases. Arrival times of all observed seismic phases (e.g., Pg, PmP, Pn, Sg, SmS) were identified from the seismic record sections, as previously discussed (Figure 2). A variety of bandpass filters and reduction velocities were tested to facilitate phase identification. The maximum depth of the model was set to 40 km to consider all the main crustal features, including the crust, Moho, and uppermost mantle. The model was composed of six laterally-inhomogeneous layers, based on variations in Pg phase travel times and the presence of PiP phases in the record sections. The inter-layer boundaries were designated as B1 to B5, in the order of increasing depth. The initial P-wave velocity structure was generated based on the 1-D velocity model obtained from the receiver function analyses of Chang and Baag (2006). The resulting 2-D velocity model was systematically updated for velocities from the top to bottom layer in order to reduce misfit, which is defined as the root-mean-square (RMS) of the residuals between observed and calculated travel times.

The 2-D P- and S-wave velocity models for the KCRT2008 profile are shown in Figure 3a and 3b, respectively. The layer boundary depths of B1–B4 in the final velocity model were 0.45–1.10 km, 6.00 km, 15.00 km, and 19.30–19.50 km, respectively (Table 1). The Moho (B5) depth along the profile varied from 30.00 to 34.00 km. The boundary depth determined from P-wave data was also applied to the S-velocity model. The observed and synthetic travel times calculated for the final P-wave model are also plotted in Figure 4 for comparison. Figure 4 shows the agreement between observed and predicted data (e.g., Pg, PmP, Pn, and...
In the P-wave model, the velocity structure from the surface to a depth of 10–15 km was constrained mainly by the Pg travel time. The travel times of the reflected (PiP and PmP) and Moho refracted (Pn) phases were used to determine the middle and lower crustal structures and the uppermost mantle structure, respectively. The velocity range for the top layer (from the surface to B1) was estimated to be 4.40–5.45 km/s. The top layer was the thinnest at the center of the profile (offset distance of 150 to 170 km from the S1 shot), whereas it was the thickest at the SE end of the profile in the Gyeongsang basin (Figure 1). Boundary B2 was constrained using refracted wave phases (Pg and Sg). A change in slope of the Pg travel time curve was observed at an offset distance of approximately 100 km in the S1 record section. We assumed that B2 is a boundary representing a change in the vertical velocity gradient, however the velocity itself is continuous across the boundary. The depth of B2 was set at 6 km and the velocity range for the layer between B1 and B2 was 5.70–6.17 km/s. The depth of boundary B3 was determined to be 15 km using the arrival times of the Pi₁P phases observed in the S3 record section. The velocity range for the layer between B2 and B3 was 6.03–6.32 km/s. The depth of B4 varied between 19.3 and 19.6 km along the transect and was constrained using the arrival times of Pi₂P phases measured in the S3, S4, S5, S6, S7 and S8 record sections. The lateral extent of the discontinuous B4 boundary was predicted to be over 100 km on the southeastern side of the profile. The velocity of the layer between B3 and B4 was 6.25–6.43 km/s. The Moho (B5) was the deepest (34 km) at an offset distance of 140 to 170 km from S1. The depths of the Moho at the NW and SE ends of the profile were 30.00 km and 30.75 km, respectively. The velocity of the layer between B4 and B5 was 6.35–6.85 km/s. The velocity range of the uppermost mantle beneath the Moho was 7.82–7.88 km/s, and was determined using the arrival times of Pn phases measured in the S1 seismic record section. The resulting average P-wave velocity of the crust determined by this survey was
6.27 km/s.

The initial S-wave model was constructed from the final P-wave model by assuming a Poisson solid, which means that the $V_p/V_s$ ratio is 1.73 and the S-wave model geometry is consistent with that of the P-wave model. The boundary depths (B1-B5) were held constant and the S-wave velocities within the layers were changed by reducing the misfit between the observed and synthetic travel times of the Sg and SmS phases. The S-wave velocity range between the surface and B1 was 2.45–3.09 km/s, with the slowest velocity located beneath S8 in the Gyeongsang basin. This indicates that the shallow crustal S-wave velocity beneath the Gyeongsang basin is slower than velocities within the Okcheon fold belt and the Yeongnam massif. The velocity range between B1 and B2 was 3.24–3.58 km/s, with higher values in the SE section of the profile than in the NW section. The velocity range was 3.50–3.66 km/s between B2 and B3, 3.61–3.71 km/s between B3 and B4, and, based on the arrival times of the SmS phase, 3.67–3.88 km/s between B4 and the Moho (B5). The average crustal S-wave velocity of the final model was 3.61 km/s (Figure 3b).

To verify the 2-D P-wave model, we performed a sensitivity analysis by separately altering the P-wave velocity by ±0.1 km/s and the Moho depth by ±1 km from the 2-D P-wave model values. The synthetic travel times of the Pg and PmP phases were calculated using the 2-D P-wave model with altered P-wave velocities and Moho depths, respectively. A comparison between the observed and synthetic travel times of the Pg and PmP phases showed that all observed travel times fell between the maximum and minimum synthetic travel times (Figure 5). This demonstrates that the uncertainties of the P-wave velocities and Moho depths are below 0.1 km/s and 1 km, respectively. (Figure 5 is about here)

The $V_p$ and $V_s$ models were converted into a model of the $V_p/V_s$ ratio, which is shown in Figure 3c. This model shows that the crustal material under the KCRT2008 profile has a $V_p/V_s$ ratio of 1.73 for most parts of the crust. $V_p/V_s$ ratios ranged from 1.71–1.77, with an
average value of 1.74. The \( V_p/V_s \) ratio model shows low values (1.71-1.72) at depths of 5–10 km in the Gyeonggi massif to the NE of the profile. For the Yeongnam massif and Gyeongsang basin in the shallow upper crust, the ratio increased to values of 1.73-1.75. The \( V_p/V_s \) ratio also increased with depth in the crust, as observed by previous studies (Rudnick and Fountain, 1995; Zandt and Ammon, 1995; Christensen, 1996).

5. Discussion

5.1 Comparison of the P-wave crustal velocity models

The average P-wave crustal velocity determined along the KCRT2008 profile is estimated to be 6.27 km/s. This velocity is lower than the average continental crustal velocity (6.45 ± 0.21 km/s) in general (Christensen and Mooney, 1995). The average P-wave velocities of the tectonic units in the region range from 6.23–6.34 km/s (Table 1) and have increasing velocities in the following order: Gyeonggi massif, Gyeongsang basin, Okcheon fold belt, and Yeongnam massif. This order is similar to that of average P-wave velocities (6.10-6.22 km/s) for three tectonic units (Gyeonggi massif, Gyeongsang basin, and Okcheon fold belt) based on waveform modeling of the southern Korean Peninsula (Kim et al., 2011).

The Pn phase velocity (7.82–7.88 km/s) is lower than the average Pn phase velocity (7.95 ± 0.03 km/s) determined using Pn tomography in Korea, the East Sea, and Japan (Hong and Kang, 2009). While a direct comparison of Pn phase velocities in these different locations is difficult, the trend observed along the profile in this study is similar to the trend observed using Pn tomography by Hong and Kang (2009), even though the average value obtained in this study was slightly lower.

Two intra-crustal discontinuities were defined along boundaries B3 and B4, based on observations of the \( P_{i1}P \) and \( P_{i2}P \) phases in our model. The strength of the B3 discontinuity is distinct in the northwestern part of the profile, but the B4 discontinuity is not distinct in the...
southeastern part of the profile. The B4 layer boundary is likely the same intra-crustal boundary that was observed during a tomographic study using the first arriving P-waves along the KCRT2008 profile (Kim et al., 2010), as well as the boundary suggested by a ground motion study by He and Hong (2010). However, Kim et al. (2010) also reported another intra-crustal discontinuity at a depth of 11–13 km in the southern part of the same profile that was not observed in this study.

In order to further characterize the tectonic units identified in this study, we compared the P-wave velocity models derived from KCRT2002 (Cho et al., 2006) and KCRT2004 (Cho et al., 2013), with the models developed in this study from KCRT2008 (Figure 6). Comparisons of the 1-D P-wave velocity models at three points in each tectonic unit determined using the three surveys are plotted in Figure 6c to f. The 1-D models were selected at arbitrary points along the portion of the profile that belong to a given tectonic unit. While the shallow structures show the largest variations, the velocities from all three models are similar with depth. (Figure 6 is about here)

P-wave velocities were the lowest beneath the Gyeongsang basin in the KCRT2002 and KCRT2008 profiles. However, the KCRT2008 profile intersects the Gyeongsang basin to a lesser extent than the KCRT2002 profile and the apparent extent of the resulting low velocity zone is correspondingly narrower. The P-wave velocity of the upper crust (<10 km) beneath the Okcheon fold belt in the KCRT2002 profile was lower than that of the Gyeonggi and Yeongnam massifs. While the velocity beneath the Gyeonggi massif in the KCRT2008 profile was lower than that of the Okcheon fold belt and Yeongnam massif, the velocity increased towards the southern end of the profile. This velocity pattern is like that observed along the KCRT2004 profile. The P-wave velocity of the Gyeonggi massif along the KCRT2004 profile was lower than the other tectonic units. However, the low velocity zone extended deeper beneath the Gyeonggi massif in the KCRT2004 profile that it did in the KCRT2008 profile.
The KCRT2004 profile is oriented in a NNW–SSE direction and intersects the KCRT2008 profile at 37.33°N, 127.36°E, enabling a direct comparison of model parameters at this location (Figure 1 and Figure 6). The two 1-D P-velocity models at the intersection of the KCRT2004 and KCRT2008 profiles showed similar discontinuity depths, including Moho depth, and similar trends of velocity changes with depth (Figure 6b). These similarities between the two independent models confirm their ability to predict P-wave patterns. The average crustal P-wave velocities obtained from the KCRT2004 (6.26 km/s) and KCRT2008 (6.27 km/s) profiles are also comparable, although differences exist among the phase velocities of individual tectonic units (Table 2). (Table 2 is about here)

The average crustal P-wave velocities of individual tectonic units obtained from the KCRT surveys did not show large differences overall. The average P-wave velocity of the Gyeonggi massif is commonly lower than that of the other tectonic units. The P-wave velocity of the Gyeongsang basin differs depending on the survey line.

5.2 Comparison of Vp/Vs ratios

The Vp/Vs ratio is directly affected by rock composition, mineral alteration due to metamorphic processes, and SiO₂ content (Christensen, 1996). Therefore, estimating Vp/Vs is important for characterizing the composition and physical properties of rocks (Zandt and Ammon, 1995; Christensen, 1996; Musacchio et al., 1997). Anomalously low P-wave velocities and low Vp/Vs ratios are present in the Gyeonggi massif within the upper crust. A low Vp/Vs ratio in the Gyeonggi massif was also reported in the findings of KCRT2004 (Cho et al., 2013), teleseismic receiver function analyses (Chang and Baag, 2007), and waveform modeling studies of local earthquakes (Kim et al., 2011). P-wave velocities and Vp/Vs ratios in the upper crust of the Yeongnam massif are high, which were are also reported in the findings of KCRT2004 (Cho et al., 2013).
The $V_p/V_s$ ratio is mostly controlled by rock composition at depths greater than 3–4 km, although it can be influenced by many factors (Christensen, 1996). In order to quantitatively determine $V_p/V_s$ ratios with depth for each tectonic unit along the KCRT2008 profile, the $V_p/V_s$ ratios determined in this study were compared with those measured in laboratory experiments carried out by Musacchio et al. (1997). Musacchio et al. (1997) distinguished three different areas based on the $V_p/V_s$ ratios. Figure 7 shows $V_p/V_s$ ratios plotted as a function of P-wave velocity for different tectonic units and reference crustal rocks for the (a) upper, (b) middle, and (c) lower crust. The shaded areas indicate groups of rocks that have similar compositions, as well as similar seismic properties determined from rock samples. In Figure 7, the felsic area refers to rocks in which intermediate–high silica content results in low P-wave velocities (less than 6.7 km/s). The anorthosite area refers to rocks in which high plagioclase content produces relatively low P-wave velocities (6.6–7.1 km/s) and high $V_p/V_s$ ratios (greater than 1.85). The mafic area refers to rocks in which low silica content results in high P-wave velocities (greater than 6.7 km/s) and high $V_p/V_s$ ratios (up to 1.86). The ranges of $V_p/V_s$ ratio versus P-wave velocity obtained from the KCRT2008 profile are plotted as solid cyan, yellow, magenta, and black lines that represent the extent of $V_p/V_s$ versus $V_p$ for each tectonic unit along the KCRT2008 profile: the Gyeonggi massif, Okcheon fold belt, Yeongnam massif, and Gyeongsang basin, respectively. The crustal composition of these four tectonic units (Figure 7) in the upper and middle crust is felsic (Figure 7a, 7b), but is intermediate (between felsic and mafic) in the lower crust (Figure 7c). Rocks located less than 14 km deep were categorized as felsic, while rock compositions at depths greater than 14 km range from felsic to mafic. Two Precambrian massifs, the Gyeonggi and Yeongnam massifs, have different distributions in the $V_p/V_s$ ratio vs. $V_p$ plot in the upper and middle crust at 4–8 km and 10–14 km depths, respectively (Figure 7a and 7b). The Gyeonggi massif consists of Precambrian schists and gneisses. Similar rock units are distributed in the
Yeongnam massif in the SE part of the KCRT2008 profile. These two Precambrian massifs have different $V_p/V_s$ ratios and it seems that they might have different origins and independent evolutions. Chang and Baag (2007) estimated the crustal $V_p/V_s$ ratio in southern Korea using receiver functions and H-k methods and inferred tectonic relationships between southern Korea and China. They concluded that the Yeongnam massif, with a high $V_p/V_s$ ratio (1.78-1.82), is related to the Sino-Korean craton, whereas the Gyeonggi massif (1.71-1.76 $V_p/V_s$ ratio) is related to the Yangtze craton. The $V_p/V_s$ ratios obtained from the KCRT2008 profile also produce different $V_p/V_s$ ratios for these two massifs and supports the tectonic relationships proposed by Chang and Baag (2007). (Figure 7 is about here)

The average crustal $V_p/V_s$ ratios (Table 2) obtained from the KCRT2008 profile are lower than the typical value for continental crust (1.768) determined by Christensen (1996). The composition along the KCRT2008 profile is intermediate rather than mafic in the lower crust. An intermediate lower crustal composition was also reported by Cho et al. (2013) from findings of the KCRT2004 experiment. The absence of mafic rocks in the lower crust has also been reported in China (Gao et al., 1998; Chen et al., 2010; Liu et al., 2006).

5.3 Interpretation of variations in the Moho depth

The changes in Moho depth along the KCRT2008 profile are consistent with the results from previous studies in this region based on receiver functions and PmP analyses (Park et al., 2003; Chang and Baag, 2005; Chang and Baag 2007; Yoo et al., 2007). The KCRT2008 and KCRT2002 profiles are characterized by similar Moho depths (KCRT2002: 28–34 km [Cho et al., 2006]), with the thickest crust located beneath the central regions of the profiles and the thinnest crust located beneath the southeastern part of the profiles. The Moho depth is variable along the KCRT2004 profile (29.0–34.9 km) and the associated crustal thickness increases gradually to the south (Cho et al., 2013). This result was not obtained in either
KCRT2002 or KCRT2008. This difference is shown by the 1-D model selected at arbitrary points (Figure 6c-f). The Moho depth estimates did not vary largely for the tectonic units, except for the Yeongnam massif. This discrepancy could be explained by some factors.

First, collision of the Gyeonggi and Yeongnam massifs from the late Paleozoic to early Mesozoic (Chough et al., 2000) could explain changes in the Moho depth. Previous studies (Cho et al., 2006; Yoo et al., 2007 Kim et al., 2013) have also suggested that crustal thickening in the Okcheon fold belt is related to accretion resulting from oblique collision between the two massifs. This collision is an indentation type (Yin and Nie, 1993; Chough et al., 2000; Ree et al., 2001), not an ordinary collision such as those that form a folded mountain range. Secondly, magmatism such as intrusions and underplating could have increased the Moho depth. Plutonic activity occurred from the Paleozoic to Cenozoic, and these plutonic rocks are dominated by granitoid rocks. Finally, changes in the Moho depth could be explained by isostasy related to the presence of a mountain range. The variation in the Moho depth is like the topographic characteristics of S. Korea. The topography of the Korean Peninsula formed due to the collision between the two massifs then experienced deformation, such as changes in stress state around the peninsula, uplift, and denudation. The present distribution of Moho depths can be interpreted as related to isostatic equilibrium affected by topographic changes. The similarities between the distribution of Moho depths and regional topography have also been shown by studies of Moho undulation using gravity inversion (Choi et al., 1996; Shin et al., 2006; Shin, 2006) and crustal thicknesses calculated from travel time residuals using the PmP phases (Park et al., 2003). The crustal thickening in the Okcheon fold belt is considered to influence topographic characteristic affected by isostatic state.

There is also a relative difference in Moho depth between the Gyeongsang basin and the other tectonic units. The crust is thinnest below the Gyeongsang basin, as shown in the
profile along KCRT2008, and the profile of Moho depths along KCRT2002 show a similar
feature (Cho et al., 2006). The Gyeongsang basin was formed during the Cretaceous by
oblique subduction of the Izanagi plate under the Asian continent (Chough et al., 2000;
Chough and Sohn, 2010). Due to the influence of extensional stresses caused by this oblique
subduction, the crust under the Gyeongsang basin would have thinned and the crust under the
Okcheon fold belt and Yeongnam massif became would have thickened.

Several factors might have affected changes in Moho depth in the region studied by the
three seismic surveys, namely, the collision of the Gyeonggi and Yeongnam massifs, plutonic
activity such as intrusion and underplating, thinning due to extensional stress during the
formation of the Gyeongsang Basin, and isostatic changes due to topography. Moho depth
changes due to isostasy, coincide with Moho depths determined by seismic surveys, whereas
the other factors do not produce consistent results with the Moho depth determined by
seismic surveys. Therefore, the Moho depth observed below the Okcheon fold belt can be
interpreted as an effect of isostasy due to topographic changes.

6. Conclusions

The data obtained during the seismic experiments along the KCRT2008 transect were used
to efficiently characterize the P-and S-wave velocity structures observed throughout the
southern Korean Peninsula. Two-dimensional P- and S-wave velocity models, along with a
model for Vp/Vs ratio, were generated along the survey line using the travel times of various
wave phases measured during the survey.

The P-wave velocities in the crust ranged from 4.40–6.85 km/s, with an average of 6.27 km/s.
This average velocity is lower than the average crustal velocity of 6.4 km/s (Christensen and
Mooney, 1995). The S-wave velocities in the crust ranged from 2.54–3.88 km/s, with an
average of 3.61 km/s. The $V_p/V_s$ ratio in the crust ranged between 1.71–1.77 and the average
crustal $V_p/V_s$ ratio (1.744) from the KCRT2008 profile was lower than the typical value for
continental crust (1.768) determined by Christensen (1996). The upper and middle crustal
compositions are felsic, but change to intermediate in the lower crust. The average $V_p/V_s$
ratio in the crust was lowest in the Gyeonggi massif and highest in the Yeongnam massif. The
Gyeonggi and Yeongnam massifs consist of Precambrian schists and gneisses, however the
massifs have different $V_p/V_s$ ratios. This indicates that the two massifs have different origins.
The P-wave velocities and $V_p/V_s$ ratios of tectonic units from the KCRT surveys do not show
large differences overall. The $V_p$ and $V_p/V_s$ ratio of the Gyeonggi massif are lower than other
units that have similar compositions.
The Moho depth was greatest (34.00 km) beneath the central part of the profile and shallows
towards both ends of the KCRT2008 profile. The average Moho depth was 31.78 km. The
average thicknesses and velocities along the KCRT2008 profile are similar to crust in an
extensional tectonic regime (Christensen and Mooney, 1995). Christensen and Mooney (1995)
estimated that this type of crust has an average thickness of 30.5 km and an average crustal
velocity of 6.2 km/s. We also compared the Moho depths along the KCRT2008 profile with
those obtained from the previous two seismic surveys (KCRT2002 and KCRT2004). Several
factors likely affect changes in the Moho depth estimated by the three seismic surveys. We
conclude that variations in the Moho depth observed by these seismic experiments can be
explained by isostasy or crustal thinning beneath the Gyeongsang basin due to extensional
stress from the subduction of the Izanagi plate.

Acknowledgments
This work was funded by the Korea Meteorological Institute under Grant KMI 2019-00110

References


Choi, J., Kang, T.-S., Baag, C.-E., 2009, Three-dimensional surface wave tomography for the
upper crustal velocity structure of southern Korea using seismic noise correlations.


Holbrook, W. S., Gajewski, D., Krammer, A., Prodehl, C., 1988, An interpretation of wide-
angle compressional and shear wave data in southwest Germany: Poisson’s ratio and petrological implications. J. Geophys. Res., v. 93, pp. 12,081-12,106.


Kim, S.J., Kim, S.G., 1983, A study on the crustal structure of South Korea by using seismic


Shin Y. H., 2006, Implications of gravity anomalies in the tectonic provinces of the southern


Table 1. P- and S-wave velocities from KCRT2008
<table>
<thead>
<tr>
<th>Layer-boundary</th>
<th>Depth (km)</th>
<th>P-wave velocity (km/s)</th>
<th>S-wave velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.45–1.10</td>
<td>4.40–5.45</td>
<td>2.45–3.09</td>
</tr>
<tr>
<td>B2</td>
<td>6.00</td>
<td>5.70–6.17</td>
<td>3.24–3.58</td>
</tr>
<tr>
<td>B3</td>
<td>15.00</td>
<td>6.03–6.32</td>
<td>3.50–3.66</td>
</tr>
<tr>
<td>B4</td>
<td>19.30–19.50</td>
<td>6.25–6.43</td>
<td>3.61–3.71</td>
</tr>
<tr>
<td>B5</td>
<td>30.00–34.00</td>
<td>6.35–6.85</td>
<td>3.67–3.88</td>
</tr>
</tbody>
</table>

Table 2. Average P- and S-wave velocities and average Vp/Vs ratios from KCRT2008 and KCRT2004 (Cho et al., 2013).
<table>
<thead>
<tr>
<th></th>
<th>KCRT2008</th>
<th></th>
<th>KCRT2004</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vp(km/s)</td>
<td>Vs (km/s)</td>
<td>Vp/Vs</td>
<td>Vp(km/s)</td>
</tr>
<tr>
<td>Gyeonggi massif</td>
<td>6.23</td>
<td>3.60</td>
<td>1.727</td>
<td>6.20</td>
</tr>
<tr>
<td>Okcheon Fold Belt</td>
<td>6.33</td>
<td>3.64</td>
<td>1.736</td>
<td>6.30</td>
</tr>
<tr>
<td>Yeongnam massif</td>
<td>6.34</td>
<td>3.64</td>
<td>1.740</td>
<td>6.32</td>
</tr>
<tr>
<td>Gyeongsang basin</td>
<td>6.27</td>
<td>3.60</td>
<td>1.742</td>
<td>6.22</td>
</tr>
<tr>
<td>Whole average</td>
<td>6.27</td>
<td>3.61</td>
<td>1.744</td>
<td>6.26</td>
</tr>
</tbody>
</table>

List of Figures
Figure 1. Locations of the crustal-scale seismic profile KCRT2008, from Ganghwa to Yeongdeok on the S. Korean Peninsula. Locations of previous experiments, KCRT2002 (Cho et al., 2006 and KCRT2004 (Cho et al., 2013), are also shown. The eight shot locations (S1-S8) along the KCRT2008 profile are indicated by red stars, and the 593 receiver locations are indicated by solid black circles. NM= Nanglim massif, GM=Gyeonggi massif, OFB=Ockcheon fold belt, YM=Yeongnam massif, GB=Gyeongsang basin, ob=Ockcheon basin, tb=Taebaek basin.

Figure 2. Seismic record sections for shots at (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, (f) S6, (g) S7, and (h) S8. Shot locations are shown in 1. Each section was bandpass-filtered at 4-15 Hz and plotted after being trace-normalized with a reduction velocity of 8.0 km/s. P- and S-wave phases are identified and labeled as: Pg and Sg are direct and refractions through the upper crust; PmP and SmS are reflections from the Moho; Pi1P and Pi2P are reflections from intracrustal boundaries; Pn is refraction from the Moho.

Figure 3. 2-D layered velocity model for the KCRT2008 profile. (a) P-wave velocity model. Major tectonic boundaries are indicated at the top of the model. (b) S-wave velocity model. (c) Vp/Vs ratios calculated from the P- and S-wave velocities.

Figure 4. Plots of ray trajectories and synthetic travel times in the final velocity model for shots at (a) S1, (b) S3, (c) S5, and (e) S8. Upper part of each plot: ray trajectories for P-waves are indicated by solid lines, and boundaries (B1, B2, B3, B4, and B5) between the layers are indicated by dashed lines. Lower part of each plot: black lines and colored circles (Pg=red dots, PmP=green dots, Pn=blue dots, PiP phases = magenta and sky blue
dots) represent theoretical travel times in the final velocity model and the observed travel times of P-wave phases, respectively.

Figure 5. Observed seismic sections with the synthetic arrival time curves of Pg and PmP phases used for checking velocity and depth uncertainties of the model. The plots are from five shots at (a) S1, (b) S2, (c) S5, and (d) S8. Two synthetic curves of Pg arrival times were calculated using two perturbed velocity models with P-wave velocity changes ±0.1 km/s from the final velocity model. The PmP arrival times were calculated using Moho depth changes of ±1 km from the final velocity model.

Figure 6. (a) Map showing the KCRT2008 profile, as well as the previous experiment profiles (KCRT2002 and KCRT2004). (b) Comparison of P-wave velocity (Vp) profiles at the intersection of the KCRT2008 and KCRT2004 profiles. Comparisons of Vp profiles at three different locations on three seismic profiles from each tectonic region: (c) GM, (d) OFB, (e) YM, and (f) GB. The intersection of the KCRT2008 and KCRT2004 profiles is noted by a red star. Blue, green, and red solid circles represent the locations of 1-D velocity models along KCRT2008 and the other two profiles (KCRT2002 and KCRT2004).

Figure 7. Vp/Vs ratio versus P-wave velocity (Vp) at different pressure ranges corresponding to different depths of (a) 4–8 km, (b) 10–14 km, and (c) 31–35 km. Solid symbols (red, green, and blue) indicate anorthosite, mafic, and felsic compositions, as derived from laboratory measurements of rock samples (Musacchio et al., 1997). Solid colored lines
(cyan, yellow, magenta, and black) represent the results from this study.
07 April 2020

*Episodes: Journal of International Geoscience*

Dear Editor:

I wish to submit an original article for publication in *Episodes: Journal of International Geoscience*, titled “Crustal velocity model of the southern Korean Peninsula along the Ganhwa–Yeongdeok seismic profile.” The paper was coauthored by Mikyung Choi, Hyun-Moo Cho, Tae-Seob Kang, Jung Mo Lee, Chang-Eob Baag, Ki Young Kim, and Heeok Jung.

This study used seismic modeling to investigate the crustal structure across the southern Korean peninsula and found that variations in the depth to the Mohorovicic discontinuity were consistent with isostatic variations due to regional topography. We believe that our study makes a significant contribution to the literature because the model generated herein intersects and agrees with a previous model developed on another seismic transect across the peninsula, thus showing the validity of both models.

Further, we believe that this paper will be of interest to the readership of your journal because its broad readership will find our study of crustal-scale seismic properties of this region relevant for hazard monitoring and for further understanding of the overall geology of the Korean peninsula.

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal’s policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

Thank you for your consideration. I look forward to hearing from you.

Sincerely,

Junkee Rhie
School of Earth and Environmental Sciences
Seoul National University
1 Gwanak-ro, Gwanak-gu, Seoul 08826
+82-2-880-6731
rhie@snu.ac.kr
Figure 1. Locations of the crustal-scale seismic profile KCRT2008, from Ganghwa to Yeongdeok on the S. Korean Peninsula. Locations of previous experiments, KCRT2002 (Cho et al., 2006 and KCRT2004 (Cho et al., 2013), are also shown. The eight shot locations (S1-S8) along the KCRT2008 profile are indicated by red stars, and the 593
receiver locations are indicated by solid black circles. NM= Nanglim massif, GM=Gyeonggi massif, OFB=Ockcheon fold belt, YM=Yeongnam massif, GB=Gyeongsang basin, ob=Ockcheon basin, tb=Taebaek basin.
Figure 2. Seismic record sections for shots at (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, (f) S6, (g) S7, and (h) S8. Shot locations are shown in 1. Each section was bandpass-filtered at 4-15 Hz and plotted after being trace-normalized with a reduction velocity of 8.0 km/s. P- and S-wave phases are identified and labeled as: Pg and Sg are direct and refractions through the upper crust; PmP and SmS are reflections from the Moho; P11P and P12P are reflections from intracrustal boundaries; Pn is refraction from the Moho.
Figure 2. (continued)
Figure 2. (continued)
Figure 3. 2-D layered velocity model for the KCRT2008 profile. (a) P-wave velocity model. Major tectonic boundaries are indicated at the top of the model. (b) S-wave velocity
model. (c) \( V_p/V_s \) ratios calculated from the P- and S-wave velocities.
Figure 4. Plots of ray trajectories and synthetic travel times in the final velocity model for shots at (a) S1, (b) S3, (c) S5, and (e) S8. Upper part of each plot: ray trajectories for P-waves are indicated by solid lines, and boundaries (B1, B2, B3, B4, and B5) between the layers are indicated by dashed lines. Lower part of each plot: black lines and colored circles (Pg=red dots, PmP=green dots, Pn=blue dots, PiP phases = magenta and sky blue dots) represent theoretical travel times in the final velocity model and the observed travel times of P-wave phases, respectively.
Figure 4. (continued).
Figure 4. (continued).
Figure 4. (continued).
Figure 5. Observed seismic sections with the synthetic arrival time curves of Pg and PmP phases used for checking velocity and depth uncertainties of the model. The plots are from five shots at (a) S1, (b) S2, (c) S5, and (d) S8. Two synthetic curves of Pg arrival times were calculated using two perturbed velocity models with P-wave velocity changes ±0.1 km/s from the final velocity model. The PmP arrival times were calculated using Moho depth changes of ±1 km from the final velocity model.
Figure 6. (a) Map showing the KCRT2008 profile, as well as the previous experiment profiles (KCRT2002 and KCRT2004). (b) Comparison of P-wave velocity ($V_p$) profiles at the intersection of the KCRT2008 and KCRT2004 profiles. Comparisons of $V_p$ profiles at three different locations on three seismic profiles from each tectonic region: (c) GM, (d) OFB, (e) YM, and (f) GB. The intersection of the KCRT2008 and KCRT2004 profiles is noted by a red star. Blue, green, and red solid circles represent the locations of 1-D velocity models along KCRT2008 and the other two profiles (KCRT2002 and KCRT2004).
Figure 6. (continued).
Figure 7. $V_p/V_s$ ratio versus P-wave velocity ($V_p$) at different pressure ranges corresponding to different depths of (a) 4–8 km, (b) 10–14 km, and (c) 31–35 km. Solid symbols (red, green, and blue) indicate anorthosite, mafic, and felsic compositions, as derived from laboratory measurements of rock samples (Musacchio et al., 1997). Solid colored lines (cyan, yellow, magenta, and black) represent the results from this study.