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Crustal structure of the continental margin of Korea in the East Sea (Japan Sea) from deep seismic sounding data: evidence for rifting affected by the hotter than normal mantle

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Abstract

Despite the various opening models of the southwestern part of the East Sea (Japan Sea) between the Korean Peninsula and the Japan Arc, the continental margin of the Korean Peninsula remains unknown in crustal structure. As a result, continental rifting and subsequent seafloor spreading processes to explain the opening of the East Sea have not been adequately addressed. We investigated crustal and sedimentary velocity structures across the Korean margin into the adjacent Ulleung Basin from multichannel seismic (MCS) reflection and ocean bottom seismometer (OBS) data. The Ulleung Basin shows crustal velocity structure typical of oceanic although its crustal thickness of about 10 km is greater than normal. The continental margin documents rapid transition from continental to oceanic crust, exhibiting a remarkable decrease in crustal thickness accompanied by shallowing of Moho over a distance of about 50 km. The crustal model of the margin is characterized by a high-velocity (up to 7.4 km/s) lower crustal (HVLC) layer that is thicker than 10 km under the slope base and pinches out seawards. The HVLC layer is interpreted as magmatic underplating emplaced during continental rifting in response to high upper mantle temperature. The acoustic basement of the slope base shows an igneous stratigraphy developed by massive volcanic eruption. These features suggest that the evolution of the Korean margin can be explained by the processes occurring at volcanic rifted margins. Global earthquake tomography supports our interpretation by defining the abnormally hot upper mantle across the Korean margin and in the Ulleung Basin.

Keywords: Korean margin; Deep seismic sounding; Tomography; Crustal structure; Magmatic underplating

1. Introduction

The East Sea (Japan Sea) behind the Japan Arc is a back-arc area, which is comprised of three major basins: Japan, Yamato, and Ulleung Basins (Fig. 1). The radiometric $^{40}Ar-^{39}Ar$ technique dated the oldest

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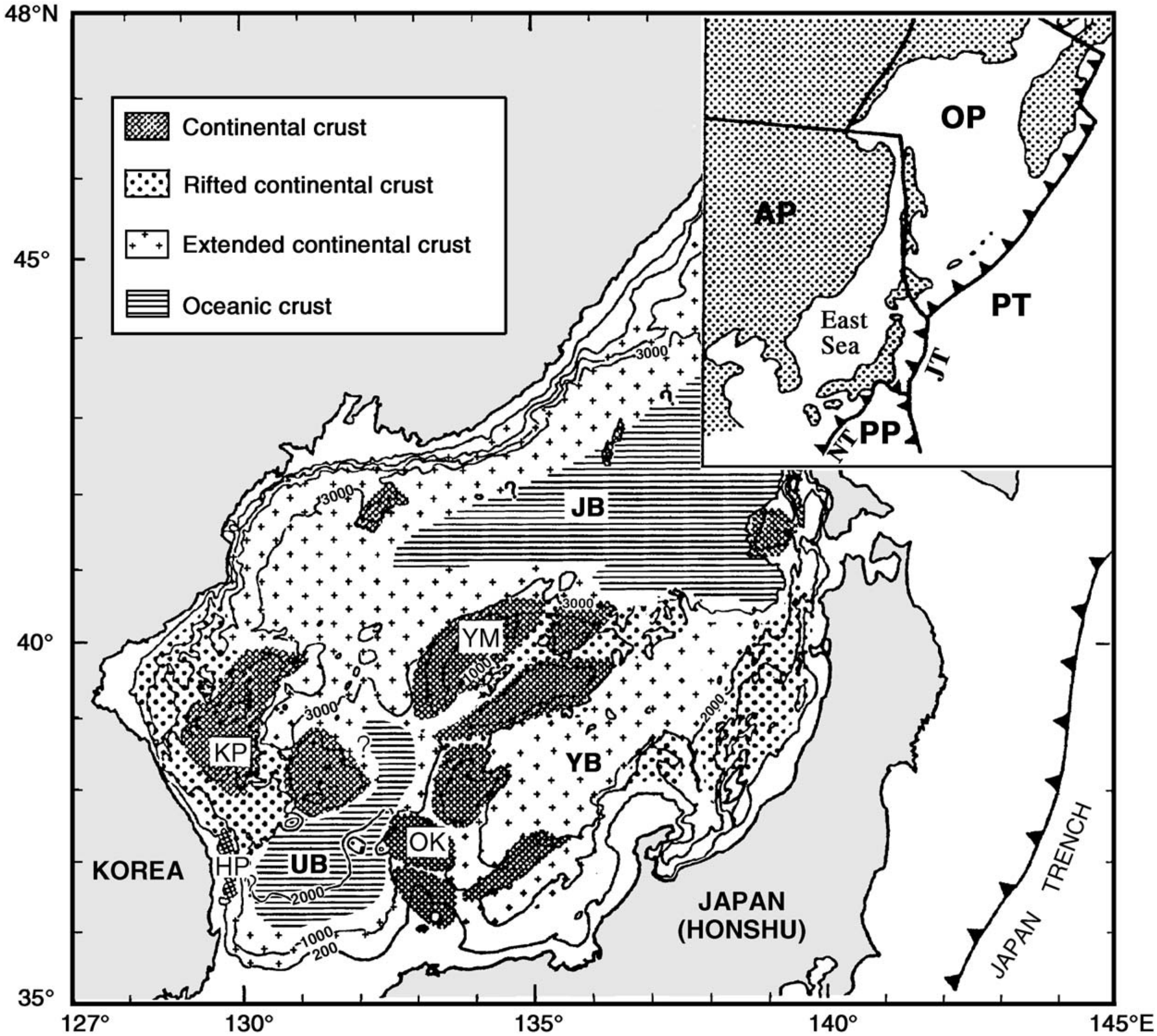


Fig. 1. Physiographic map of the East Sea (Japan Sea) showing the discrimination of crustal type (from Tamaki et al., 1992; Kim et al., 1998); JB, YB, and UB = Japan, Yamato, and Ulleung Basins, respectively; KP = Korea Plateau; YM, OK, and HP = Yamato, Oki, and Hupo Banks. Inset shows the plate configuration; OP, PT, PP, and AP = Okhotsk, Pacific, Philippine, and Amurian Plates; NT and JT = Nankai Trough and Japan Trench. Note the Ulleung Basin is floored by thicker than normal oceanic crust.

oceanic basalts drilled at the eastern margin of the Japan Basin during Ocean Drilling Program (ODP) Leg 127 as 24 Ma (Tamaki et al., 1992). This age falls in the opening period of the East Sea (32–10 Ma) deduced from the pattern of basin subsidence (Ingle, 1992). Accordingly, there is an agreement that continental rifting and subsequent opening of the East Sea took place from Late Oligocene to Middle Miocene times.

In the East Sea, the southwestern (SW) part between the Korean Peninsula and the SW Japan Arc is distinguished by complex morphology. Although the major central area of this part is occupied by the Ulleung Basin with the smooth seafloor, the surrounding continental margins of the two land masses are embossed with structural highs such as the Hupo and Oki Banks, respectively. The Korea Plateau, another structural high, is situated to the north of the Ulleung

Basin, that is interpreted as a remnant continental fragment separated from the Korean margin concurrently with the opening of the East Sea (Fig. 1). During the last two decades, a variety of opening models of the SW East Sea have been put forward. At present, they close in on the two most frequently cited models: (1) southward drift of the Japan Arc induced by north–south pull-apart crustal extension (Jolivet et al., 1994) and (2) clockwise rotation of SW Japan away the Korean Peninsula associated with the subduction of the Pacific Plate under the Japan Arc (Otofuji, 1996). However, because these models were proposed without any knowledge of correct structure and nature of the underlying crust, they are subject to verification on the basis of convincing evidence. Recently, from a deep seismic sounding (DSS) experiment using ocean bottom seismometers (OBSs), Kim et al. (1998) established that the Ulleung Basin crust is thicker than normal (10 km thick) but essentially oceanic in nature. They suggested that seafloor spreading in the Ulleung Basin took place in a region of hotter than normal mantle temperature, resulting in the formation of thicker than normal oceanic crust. This points to the need of better understanding of continental rifting and subsequent ocean spreading processes on the Korean margin.

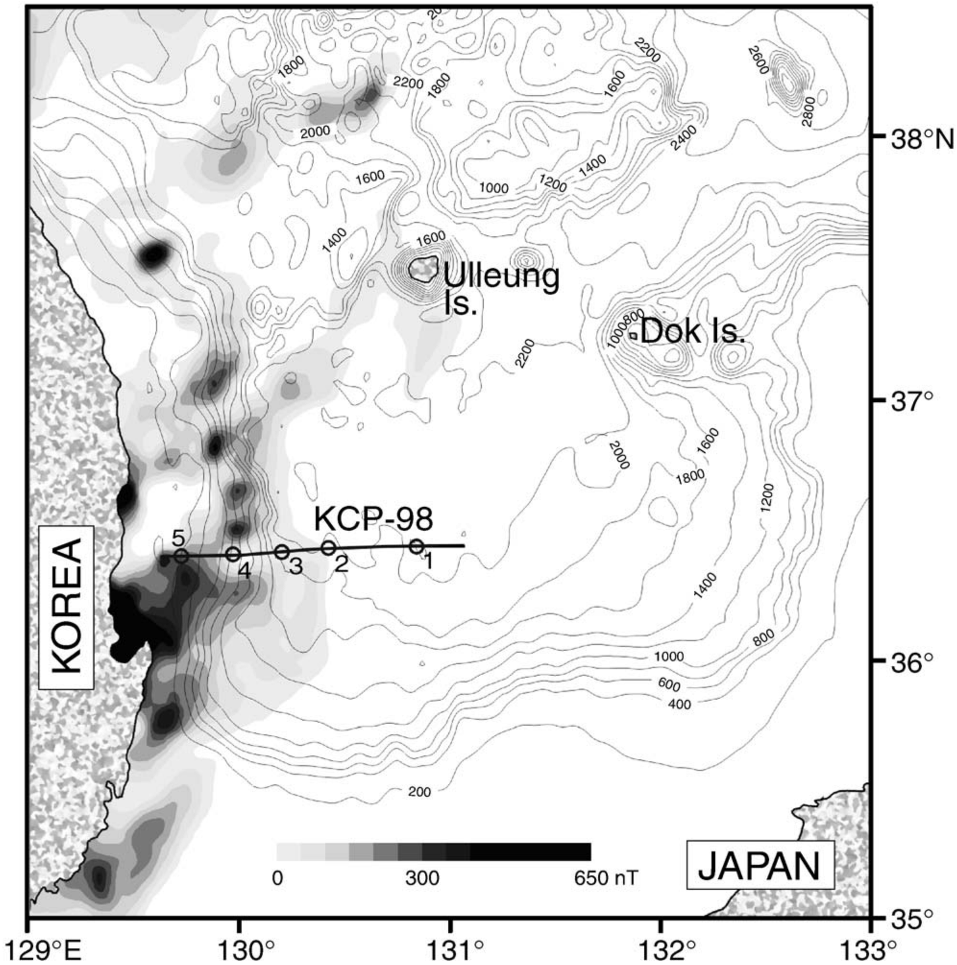


Fig. 2. Location of deep seismic sounding line KCP-98 with the positive magnetic anomaly of the Korean margin. Numbered discs indicate OBS positions. Bathymetric contours are in meters. The magnetic anomaly is from Kim et al. (1999).

In this paper, we investigate the crustal structure of the Korean margin using multichannel seismic (MCS) and OBS data. Because continental rifting above the thermally anomalous mantle would create volcanic passive margins (Goldschmidt-Rokita et al., 1994), our primary objective is to examine if there are any features that pertain to volcanic rifted margins. Volcanic rifted margins such as the Vøring and Hatton Bank margins (Eldholm and Grue, 1994) are characterized by extensive extrusive and intrusive magmatism in the form of seaward dipping basaltic flows and a thick prism of underplated material with seismic velocity in excess of 7.2 km/s. Consequently, discussions are given to the following specific questions: (1) How does crustal structure vary across the transition from the continental shelf to the oceanic Ulleung Basin? (2) Does a high-velocity lower crustal (HVLC) body exist that might indicate magmatic underplating emplaced during continental rifting? Further, we imaged mantle velocity structure across the Korean margin and the East Sea with global tomography to examine the presence and dimension of a thermal anomaly in the upper mantle.

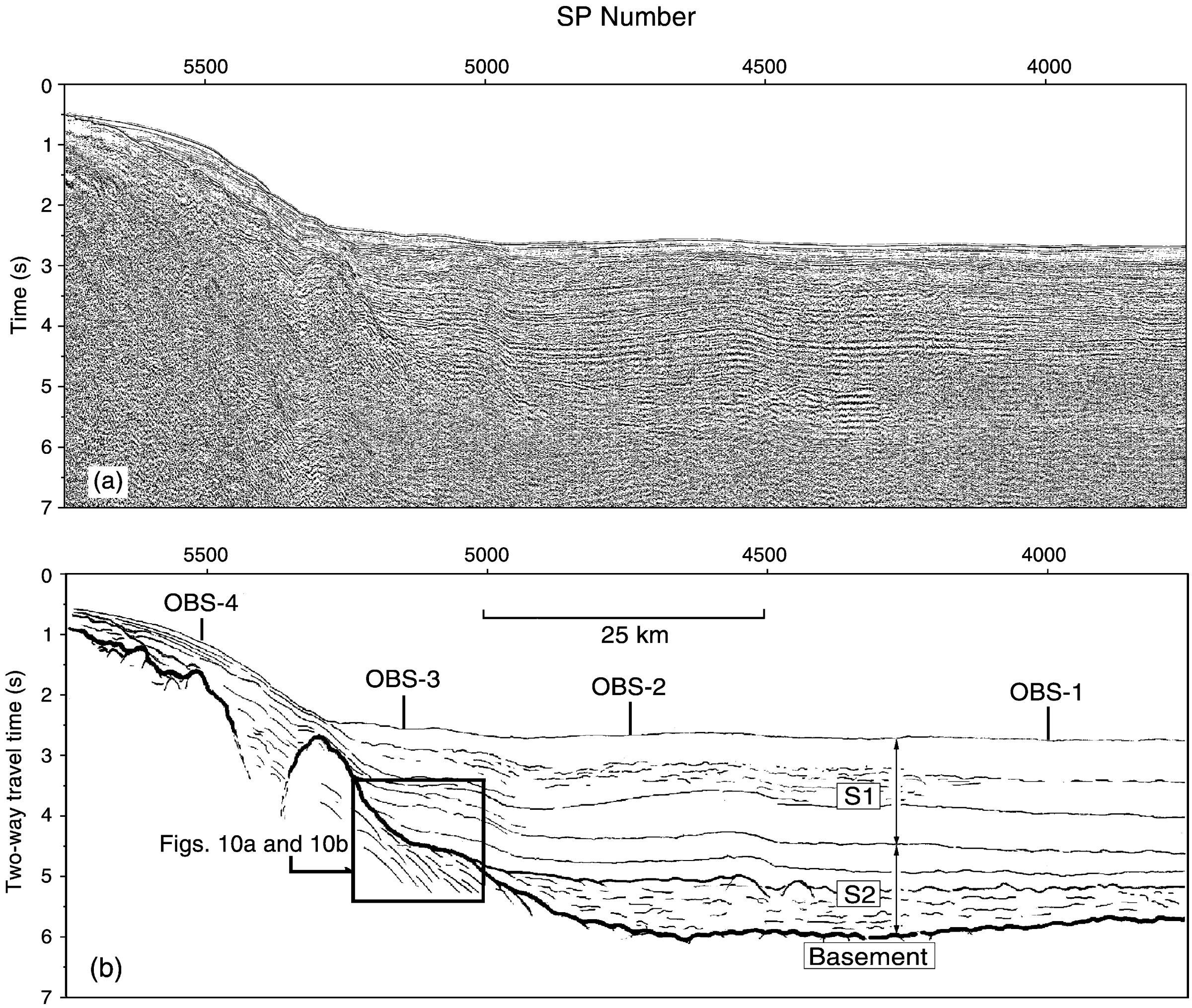


Fig. 3. (a) The MCS profile of KCP-98 with OBS positions and (b) its interpretive line drawings. Shot point (SP) numbers are shown on top of the profile.

2. Data and modeling procedure

MCS and OBS data were acquired along a straight line ("KCP-98"), about 130 km long, from the continental shelf to the center of the Ulleung Basin in 1997 and 1998, respectively (Fig. 2). The MCS data were collected using a 56-channel, 1400-m streamer with the group interval of 25 m that recorded shots from an 8-airgun, 690-in^3 source array. The shot spacing was 50 m, providing 14-fold coverage. Standard data processing of the MCS data included velocity analysis, stack, and 45° finite difference migration. As a special processing scheme to enhance reflection signals from acoustic basement, we applied the $\tau-g$ transform technique with hyperbolic velocity filtering ($\tau-g$ HVF) (Jou et al., 1996).

The DSS experiment employing OBSs was a collaborative effort of the Korea Ocean Research and Development Institute (KORDI), the Pacific Oceanological Institute of Russia (POI), and Chiba University in Japan. Five OBSs were deployed at a spacing of 20–40 km. The line was shot by two 20-l air guns at 90 s repetition rate, giving a shot spacing of about 170 m. The OBS data recorded at a rate of 100 samples per second were bandpass filtered for the frequencies from 6 to 14 Hz. In general, data recorded on OBSs show seismic arrivals that are adequate for crustal modeling. However, seismic arrivals from the deeper part of crust are not readily distinguishable from ambient noise on the record section of OBS-5 located in the continental shelf, which we postulate is due to the rapid thickening of crust under the continental rise. The other four

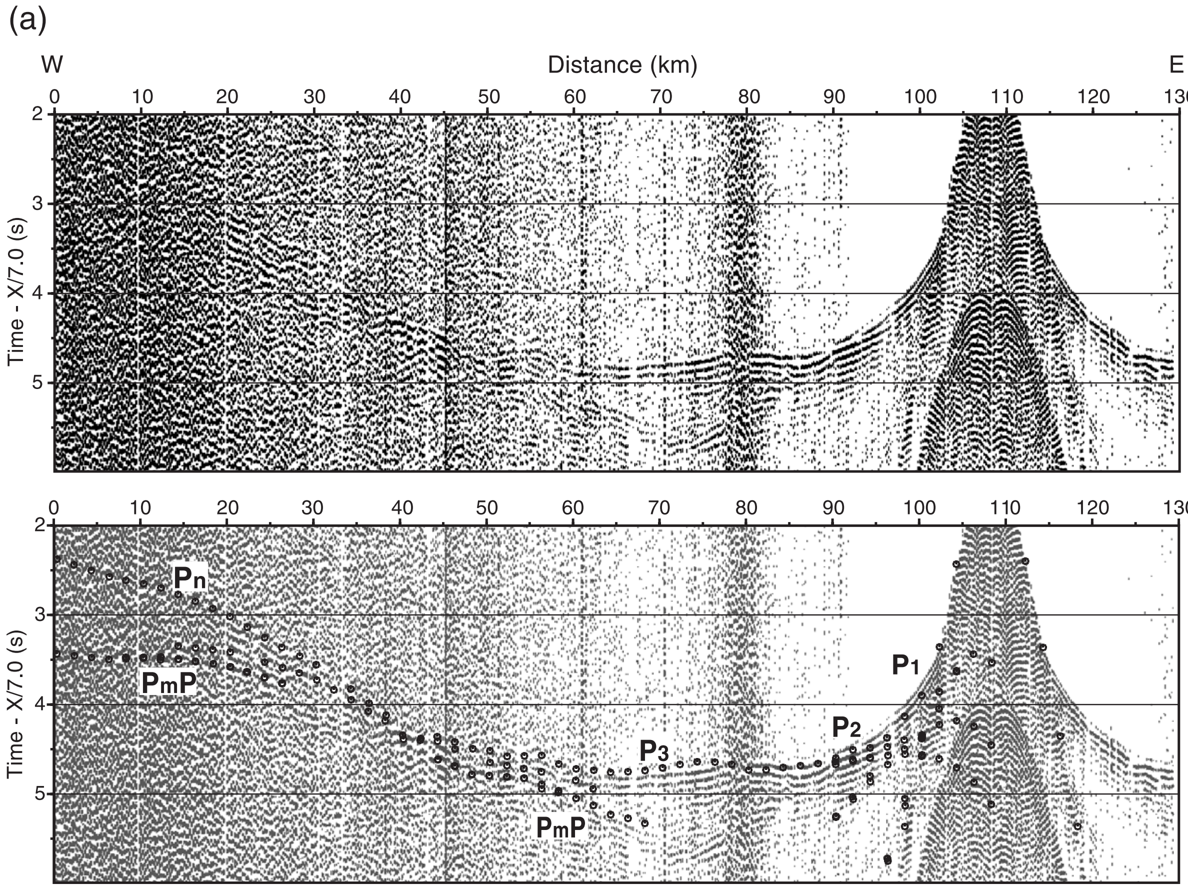
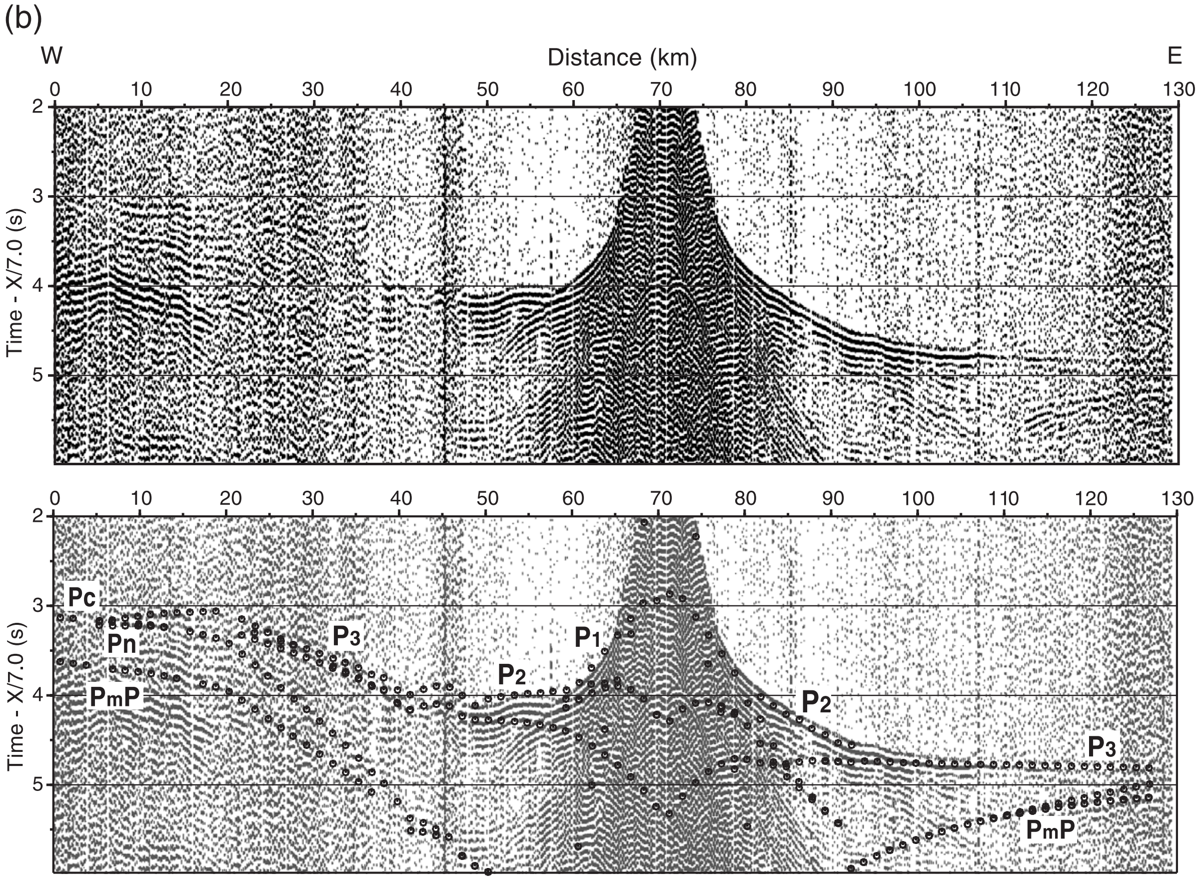


Fig. 4. (Upper) Record sections of (a) OBS-1, (b) OBS-2, (c) OBS-3, and (d) OBS-4b. (Lower) Travel time curves computed from the model in Fig. 6 are superposed on the record sections.



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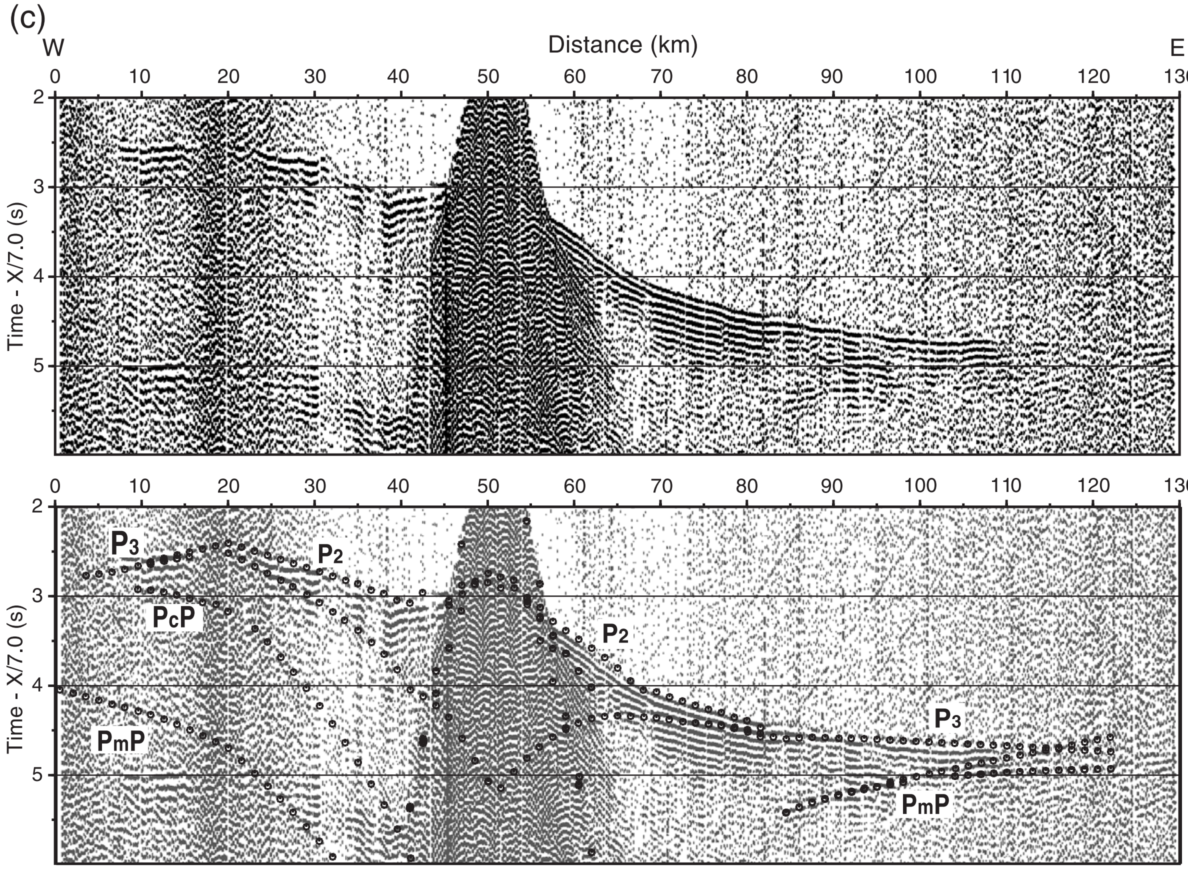
OBSs recorded refractions from the sediment cover and the entire crust; especially, wide-angle Moho reflections recorded on them gave good control on Moho structure across the line.

The OBS data were initially interpreted by tomography that computes a two-dimensional crustal model (Zelt and Barton, 1998). The travel times observed on OBS record sections are highly dependent on sedimentary structure above acoustic basement that corresponds to the top of crust. Continental margins usually exhibit thick accumulation of sediments with strong lateral changes in structure. We constrained sedimentary structure and geometry of acoustic basement using MCS data for complete interpretation of OBS data. The crustal model from tomography was refined into layered structure by forward modeling of travel times by ray tracing (Cervený et al., 1977). We processed part of OBS data using analytic minimum information deconvolution (AMID) (Kim and Marillier, 1996) to resolve seismic arrival phases by compressing phase-shifted waveforms.

3. Modeling results

Fig. 3 shows the MCS profile and its interpretive line drawings that provided control on sedimentary structure and basement geometry. Fig. 4 shows the record sections of OBS-1 to OBS-4. The starting model for tomography and the resultant model are shown in Fig. 5. The starting model is 130 km wide and 25 km deep, consisting of the grid with horizontal and vertical spacings of 1 km. In the starting model, the crust is represented by the isovelocity contours from 4.5 to 7.5



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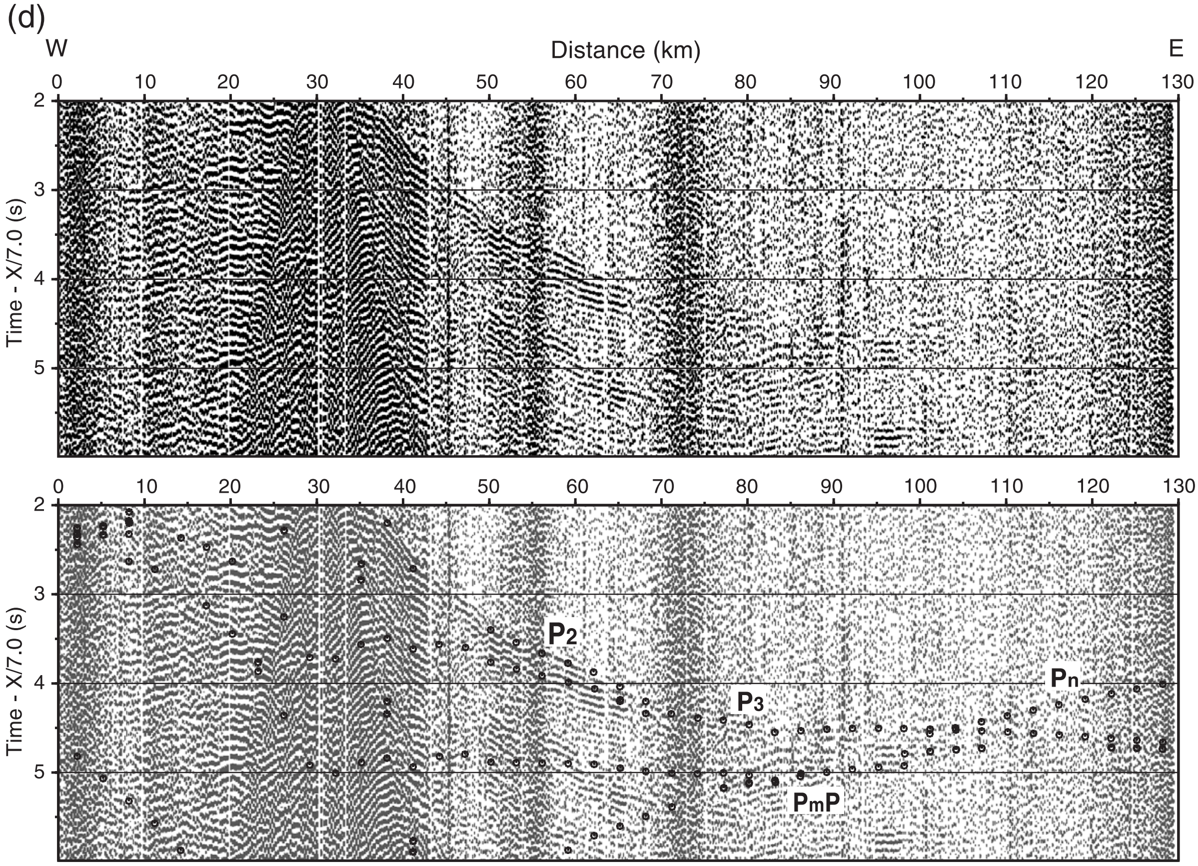
km/s that are uniformly spaced on the vertical direction, estimating the thickness to decrease monotonously to about 10 km seawards. The initial root-mean-square (RMS) travel time misfit is 280 ms. The resultant model after 10 iterations provides a RMS misfit of 44 ms. In this result, we discarded the cells whose velocity was not updated by rays. Because of the smoothing nature of tomography, the layer boundaries including the Moho are not easily determined. However, the result seems to show the transition of structure from rifted continental crust to oceanic crust on the continental margin. Strikingly, the 7 km/s contour comes up to about 10 km depth and goes down to 20 km depth, indicating the presence of a high-velocity ($\geq$ 7 km/s) crustal unit beneath the continental slope. This result was constrained into the final layered crustal model (Fig. 6) using iterative ray tracing modeling until a satisfactory match between calculated and observed travel times for individual arrival phases was found.

The layered structure of oceanic crust underlying the center of the Ulleung Basin (i.e., the eastern end of the model in Fig. 6) is well imaged by the data of OBS-1 (Fig. 4a) located farthest from the margin and its reversed profile in the 80–130-km range of the OBS-2 section (Fig. 4b). P1, P2, P3, PmP, and Pn are P-wave refractions from sediments, upper and lower crust, reflections from the Moho, and refractions from the mantle. The sediment cover observed on the MCS profile can be divided into two main sequences, S1 and S2 whose velocities range from 1.5 to 2.8 and 3.0 to 4.5 km/s, respectively (Figs. 3 and 6). The P1 velocity averaging to 4 km/s, therefore, is representative of the lower sedimentary layer S2. According to earlier works based on DSS and MCS data, S1 is equated



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with unconsolidated sediments, whereas S2 is interpreted as volcanics intercalated with sediments (Kim et al., 1998). Underlying the sediments, the model shows a two-layered crust (labeled II and III). The uppermost part of oceanic layer 2 is known to have a drastic increase in velocity to over 5 km/s once covered with a few hundred meters of sediments (Rohr, 1994). Sediment cover plays an important role in this process not only by directly decreasing the porosity but also by sealing the extrusive basalts and thus influencing convective hydrothermal circulation that triggers mineralization in the abundant porosity (Purdy, 1986). The velocities of 5.0–6.3 and 6.4–7.1 km/s of the upper (II) and lower (III) crustal layers, respectively, in the Ulleung Basin are thus typical of oceanic layers 2 and 3. The crustal thickness of 10 km on average is greater than normal by 2–3 km and Moho lies at 16–17 km depth. The crustal velocity structure in the central part of the Ulleung Basin is in good agreement with that computed by Kim et al. (1998).

From the continental shelf to the slope, the main part of crust is made up of three layers: mid-crustal layers II and III, and lower crust IV above the mantle (Fig. 6). Layer III here has significantly lower velocities at its base than its oceanic counterpart representing oceanic layer 3. The lower crustal lens (“IV”) above the Moho is characterized by unusually high velocities up to 7.4 km/s, with maximum thickness reaching more than 10 km. As this high-velocity lower crust (“IV”) pinches out between 40 and 60 km, the Moho shallows rapidly. Arrivals denoted by PcP on the OBS-3 record section (Fig. 4c) are interpreted as reflections from the top of layer IV, providing important constraints on crustal structure. Because refrac-

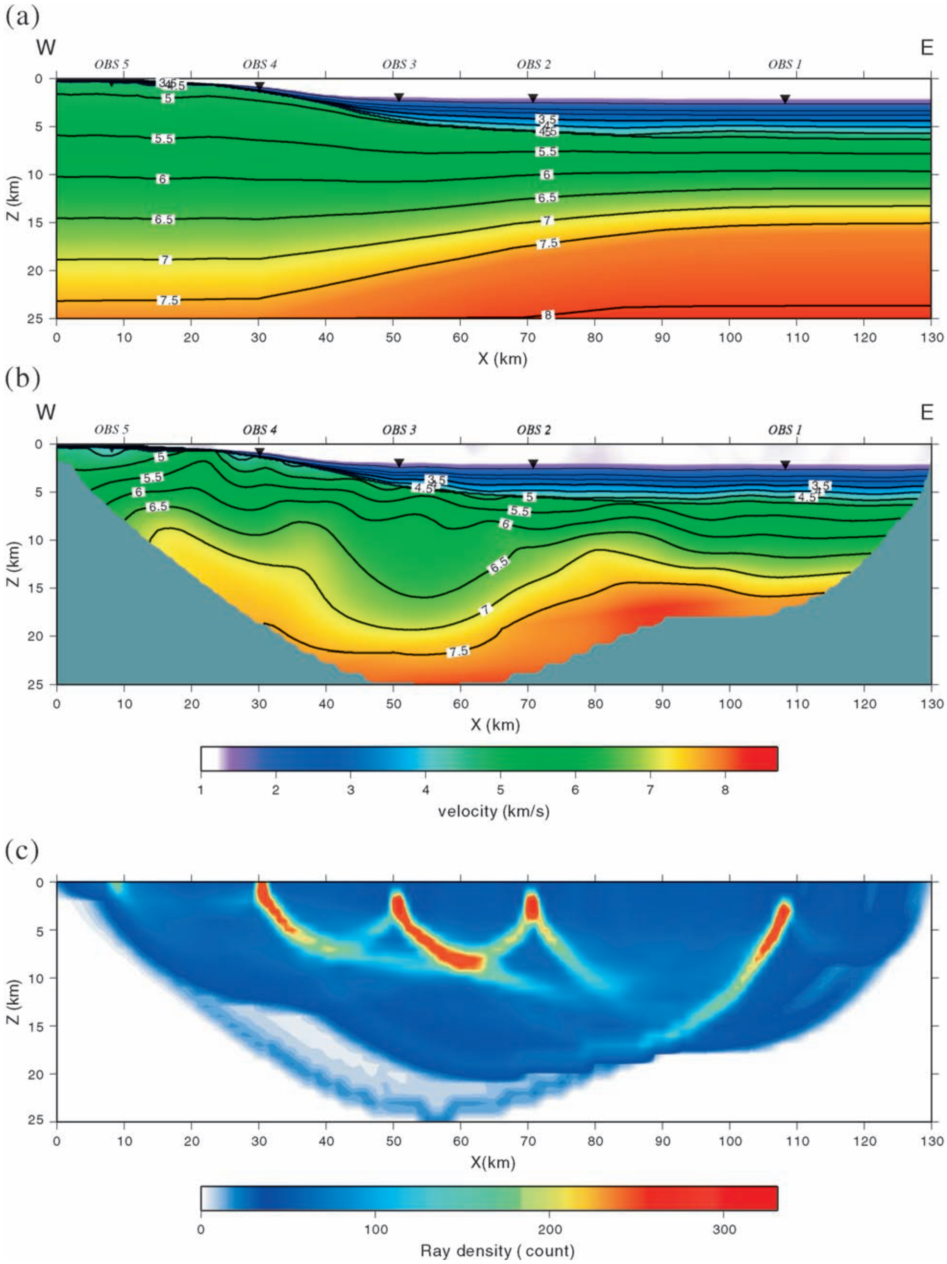


Fig. 5. (a) Starting crustal model for tomography. (b) Resultant crustal model after 10 iterations. (c) Ray coverage.

tions and supercritical reflections are phase-shifted, seismic traces of the OBS section no longer consist of the scaled replicas of the same wavelet when more than one of those arrivals are present. These arrival phases in many cases, recorded in a short time interval, are difficult to resolve. The resolution of seismic data could be enhanced by deconvolution that compresses the source waveform. However, any attempt to deconvolve OBS data generally fails unless the difficulty induced by the phase-shift is overcome. We used

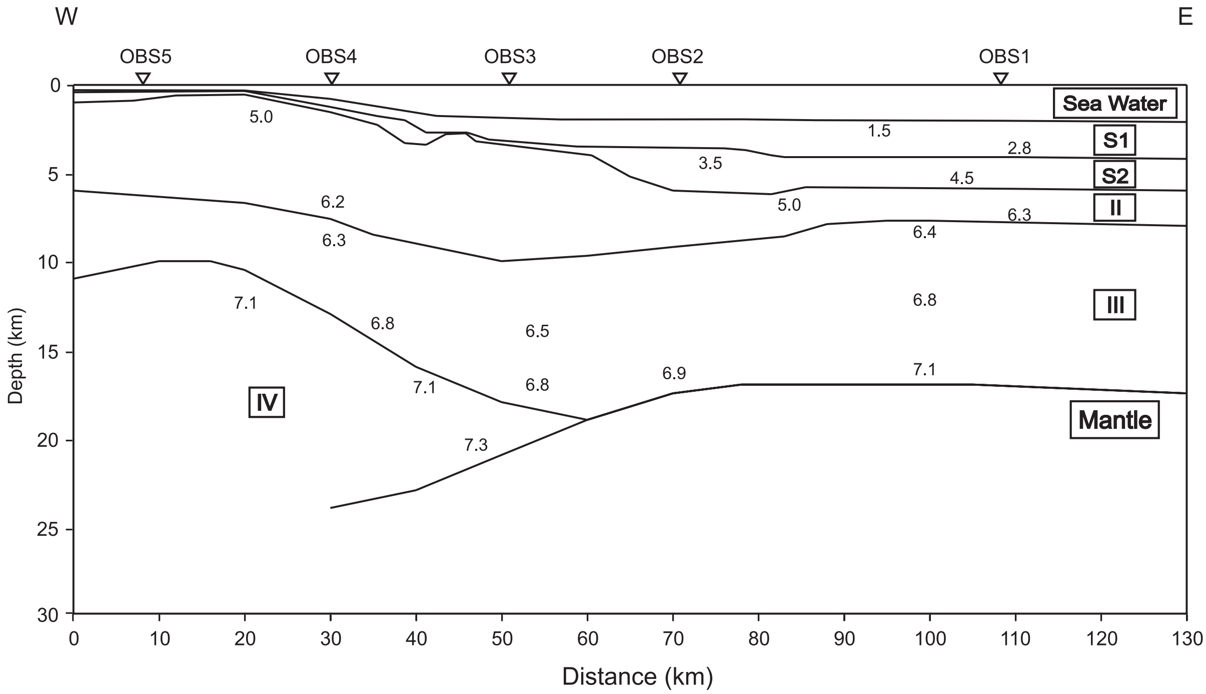


Fig. 6. Final crustal velocity model along line KCP-98 from which travel times were computed. Numbers are seismic P-wave velocities (km/s).

AMID (Kim and Marillier, 1996) that can deal with phase-shifted wavelets. Fig. 7a is part of the OBS-3 section data where calculated travel time curves indicate both P3 and PcP to be recorded. Fig. 7b shows the result of AMID. In this example, we plotted the real part of analytically deconvolved (i.e., complex-numbered) traces instead of their envelope equivalent to the modulus. Although the degree of the internal consistency of arrival phases is not much high due to a slight scatter, this result shows significant improvement of resolution as well as suppression of noise and enables us to discriminate PcP. Reflections designated as P_2P are from the boundary between layer II and layer III.

Fig. 8a shows a ray diagram for the OBS-1 record section (Fig. 4a) and the corresponding synthetic section. A comparison between them manifests first arrivals at the 0–30-km range as Pn that propagated through layer IV. The computed travel times and ray diagram for the OBS-2 record section indicate that various phases such as P3, Pc (refractions from layer IV), Pn, PcP, and PmP are recorded in the 0–40-km range (Figs. 4b and 8). In particular, Pn and PmP in this range pass through layer IV. Although all of the phases are not well discriminated, the synthetic section (Fig. 8b) seems comparable to the record section (Fig. 4b).

4. Discussion

4.1. Origin of high-velocity lower crust

A conspicuous feature of the rifted Korean margin, as shown in Fig. 6, is a HVLC body (“IV”). We could consider three models to account for its presence as Reid (1994) suggested. First, we may envision serpentinized mantle peridotite, which forms between rifted continental crust and normal oceanic crust (Whitmarsh et al., 1993). At non-volcanic margins, a crustal magma supply is not yet established immediately after rifting. This leads to the generation of a very thin and fractured mafic crust, which is insufficient to seal off hydrothermal circulation to mantle, causing extensive serpentinization; as spreading continues, the magma supply increases, resulting in a thicker mafic crust; once this crust reaches a critical thickness of around 3

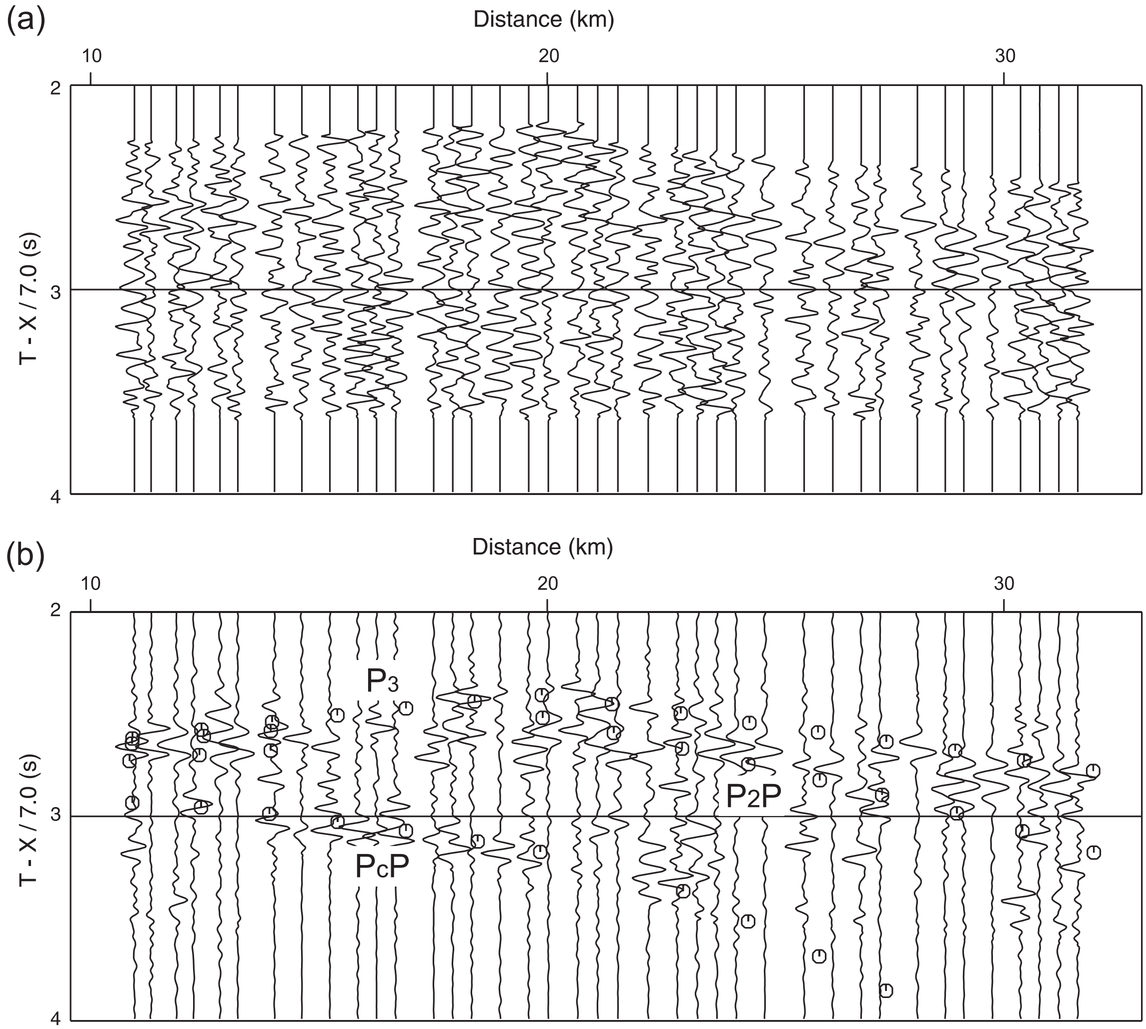


Fig. 7. Part of the OBS-3 record section in the 10–32-km range (a) before and (b) after AMID. Every other trace was plotted. Note significant improvement of resolution as well as noise suppression.

km, the mantle is largely sealed off and the degree of alteration is diminished (Reid, 1994). This model explains why serpentinized mantle mostly occurs on non-volcanic margins and under thinner than normal oceanic crust next to rifted continental crust. In addition, the P-wave velocity within the serpentinized mantle appears to increase with depth to near-mantle velocity possibly due to the gradual decrease of serpentinization with depth (Reid, 1994). The above features are not compatible with the crustal model of the Korean margin; above all, on the Korean margin the HVLC body lies under rifted continental crust; oceanic crust next to it is thicker than normal (Fig. 6). In addition, it is unreasonable in one way or another to think of the Korean margin as “non-volcanic” because rifting and subsequent opening of the Ulleung Basin is characterized by vigorous volcanism (Yoon and Chough, 1995). We thus rule out this possibility.

As the second explanation, it may be an older property of crust underlying the SE Korean Peninsula that preceded the rifting such as those common beneath platforms and shields (Christensen and Mooney, 1995). However, a lower crustal body with such high velocities is absent in the adjoining lower continental crust of the SE Korean Peninsula; the continental crust above the Moho here is 30 km thick and consists of two distinctive layers with representative velocities of 6 and 6.6 km/s, which are interpreted to be granitic and basaltic material, respectively (Kim and Jeong, 1985). Most of the Japanese Islands were part of the Sino-Korean continental massif before the opening of the East Sea. The SW Japan Arc, in particular, was attached to the SE Korean Peninsula prior to the opening. Indeed, the crustal structure of the SW Japan Arc (Hashizume and Matsui, 1979) is in exact accordance with that of the SE Korean Peninsula and consequently defies the existence of the high-velocity lower crust.

Finally, layer IV may represent magmatic underplating emplaced in association with rifting. Magmatic underplating underlying continental rift zones is known to occur at volcanic margins when asthenospheric potential temperatures are higher than normal during rifting (Kelemen and Holbrook, 1995). Layer IV, however, has slightly lower velocities in the uppermost part than underplated material reported

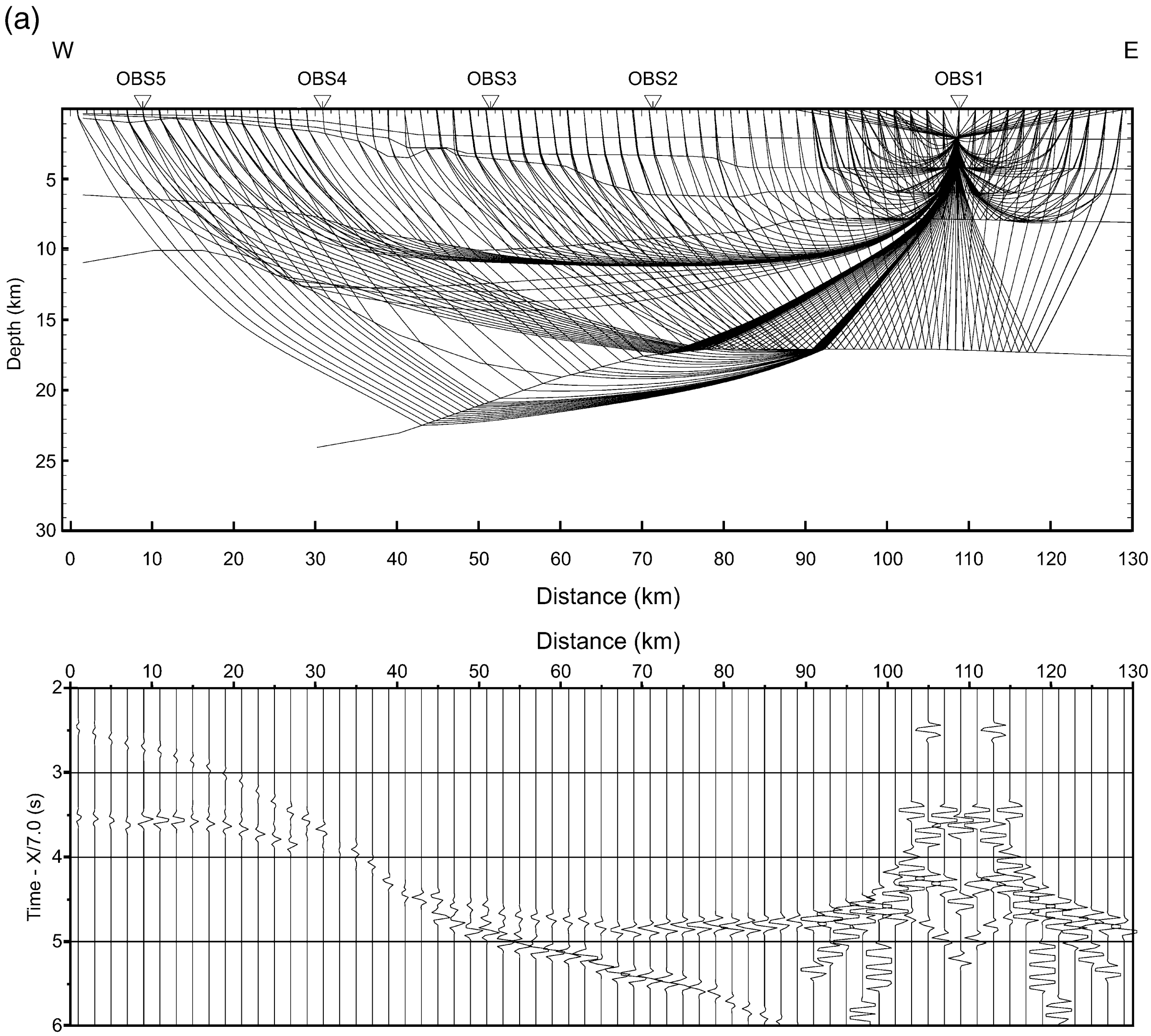
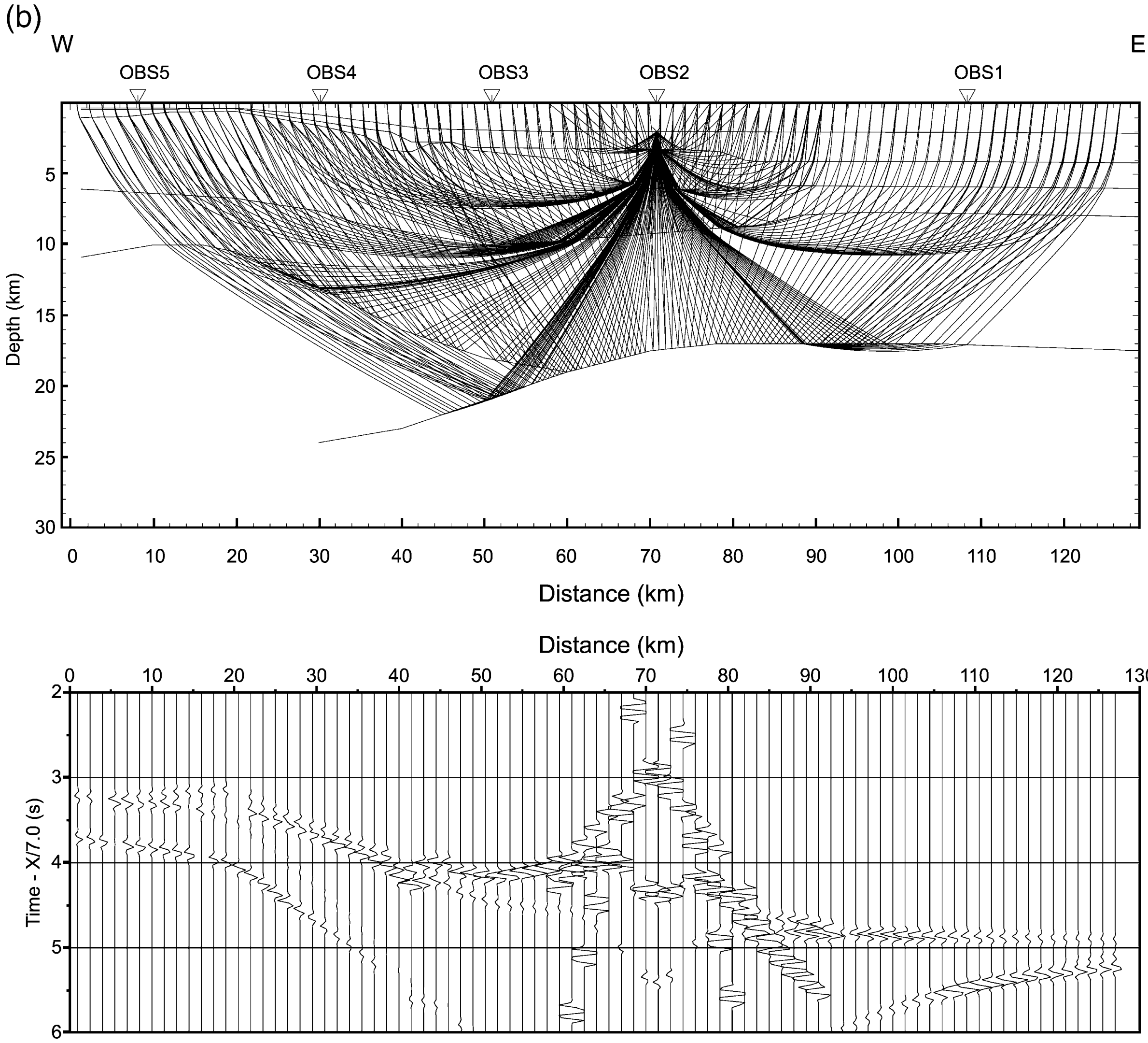


Fig. 8. Ray diagrams (upper) and synthetic sections (lower) for (a) OBS-1 and (b) OBS-2 record sections.



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worldwide (Eldholm and Grue, 1994). Magmatic underplating would be an appropriate explanation because it is consistent with the suggestion that the thicker than normal oceanic crust of the Ulleung Basin immediately next to the margin was created above the thermally anomalous mantle (Kim et al., 1998). The analysis of the fundamental mode surface wave traversing great circle paths across the Eurasian continent supports this suggestion by showing that the East Sea is the region of extreme low velocities (Curtis et al., 1998).

East Asia is one of the largest and least known areas of long-lived intraplate igneous activity. The basaltic volcanism in East Asia is little different in terms of chemical composition and eruption morphology from intraplate volcanism in other parts of the world that has been ascribed to plumes. Consequently, plume models have long been considered as a cause of large-scale rifting events in eastern China and the East Sea (Liu, 1987; Windley and Allen, 1993). However, the relatively low volumes of volcanism, lack of discernible age progressions, and lack of a deep-rooted low-velocity anomaly in seismic tomographic images (Anderson et al., 1992) are not in support of plume models. As an alternative, Smith (1998) invoked the model of thermally anomalous mantle cells induced by topographic variations at the mantle-asthenosphere boundary. Based on detailed geochemical analysis of Cenozoic basalts, Barry and Kent (1998) made a similar suggestion that a large compositional and thermal anomaly (potential temperature >1400 °C) has existed in the shallow mantle beneath East Asia since at least 30 Ma. Thus, the mantle structure of the Korean margin should be examined to infer its thermal affection on continental rifting.

We performed global travel time tomography to compute the mantle velocity structure from east China to SW Japan. The model of Bijwaard et al. (1998) was used that constitutes a considerable improvement over previous models by resolving the upper mantle structure on a scale as small as 0.6°. Shown in Fig. 9 is the tomographic cross-section beneath an extension of line KCP-98 on either sides to NE China and SW Japan. It is clear that the subducted slab of the Pacific Plate flattens in the transition zone and reaches far beyond the Korean Peninsula into east China. Most prominently, the Korean Peninsula and the East Sea are underlain by the low-velocity mantle. Another cross-section from NE China to SW Japan in Fig. 9 also exhibits the similar feature. Whether the low-velocity mantle resulted from the large thermal anomaly in East Asia or from the interactions with the subducting slab is beyond the scope of this work. Whatever the reason, the tomographic observation appears to confirm the primary association between rifting at the Korean margin and high mantle potential temperature. Therefore, we regard it appropriate to interpret the HVLC body ("IV") as magmatic underplating. Moreover, if the thermal anomaly in the upper mantle lasts for a short period of time, the adjacent ocean basin crust will have normal thickness (Kelemen and Holbrook, 1995). The thicker than normal oceanic crust in the Ulleung Basin suggests that the hot upper mantle under the Korean margin persisted for quite long after rifting. This suggestion is consistent with vigorous volcanism that continued until recently in the Ulleung Basin and on the Korean margin (Lee et al., 1999). It is intriguing that the Korean margin is not the only continental margin in East Asia where rifting was accompanied by voluminous volcanism to create a HVLC body. Kido et al. (2001) very recently identified high-velocity underplated material on the South China Sea margin emplaced possibly during the rifting to spreading stage.

Volcanic rifted margins such as the Vøring and Hatton Bank margins are characterized not only by magmatic underplating, but also by extrusive basaltic volcanism. MCS profiles demonstrate that the latter forms seaward dipping reflectors (SDRs) just below the top of basement (White and McKenzie, 1989). Because SDRs represent the continuous accretion of igneous material with intercalated sediments in an extrusion environment, their locations correlate with a strong positive magnetic anomaly (Keen and Potter, 1995). Likewise, a high-amplitude (>300 nT) magnetic anomaly lies along the edge of the eastern Korean margin (Fig. 2); across this magnetic anomaly well-developed SDRs have been recognized on the MCS profile obtained about 60 km south of line KCP-98 (Kim et al., 1998). However, the MCS profile of line KCP-98 after standard processing (Fig. 10a) does not clearly show SDRs, despite the fact that it crosses the same magnetic anomaly, too. We ascribe the inability to image SDRs to the small air gun source (690 in^3) that did not generate seismic pulses strong enough to penetrate into the igneous acoustic basement covered with thick (ca. 2 s in two-way travel time) sediments. In order to enhance reflection signals, we processed the MCS data using $\tau - g$ HVF (Jou et al., 1996), which performs hyperbolic slant stack and velocity filtering along the entire reflection trajectories in the shot gather domain. The result of this data processing apparently yields a better image of basement by revealing sub-basement reflections as well as reducing diffractions (Fig. 10b). Although not so prominent as those observed on other volcanic rifted margins (e.g., Mutter et al., 1988), these reflections demonstrate the arcuate and off-lapping sequences that are quite different from diffractions but similar to SDRs.

4.2. Continent–ocean boundary across the margin

The upper crust on the inner margin ("II and III" in Fig. 6) is interpreted as a thinned remnant of rifted continental crust heavily intruded by igneous rocks. The very irregular top of the shallow basement in the upper slope landward of OBS-4 is suggestive of extrusive volcanic origin (Fig. 3). According to Yoon

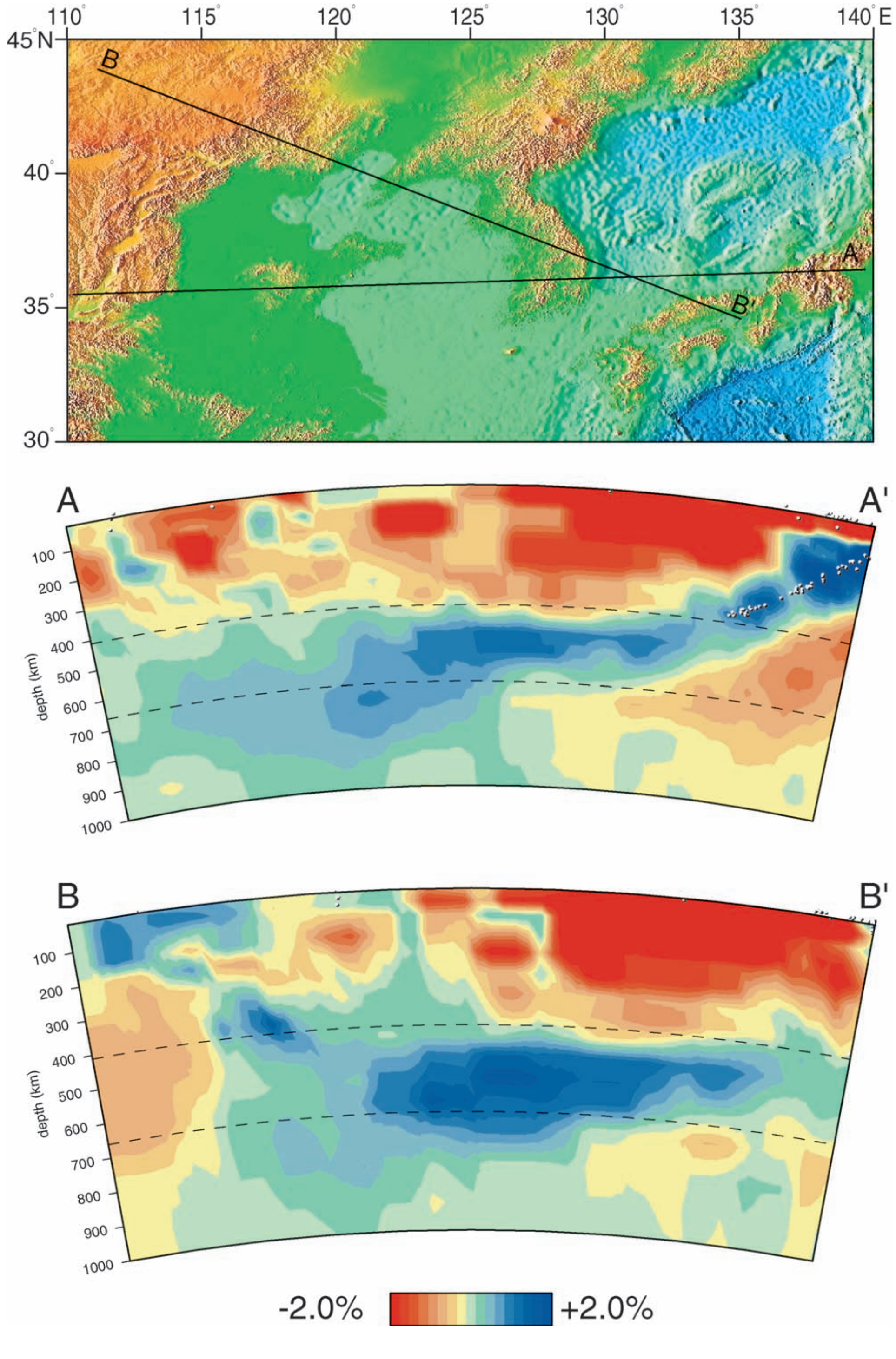

Fig. 9. Tomographic cross sections AA′ and BB′ from east China to southwestern Japan. AA′ is the extension of line KCP-98. Velocity anomalies are displayed in percentages (± 2%) with respect to the average P-wave velocity with depth.

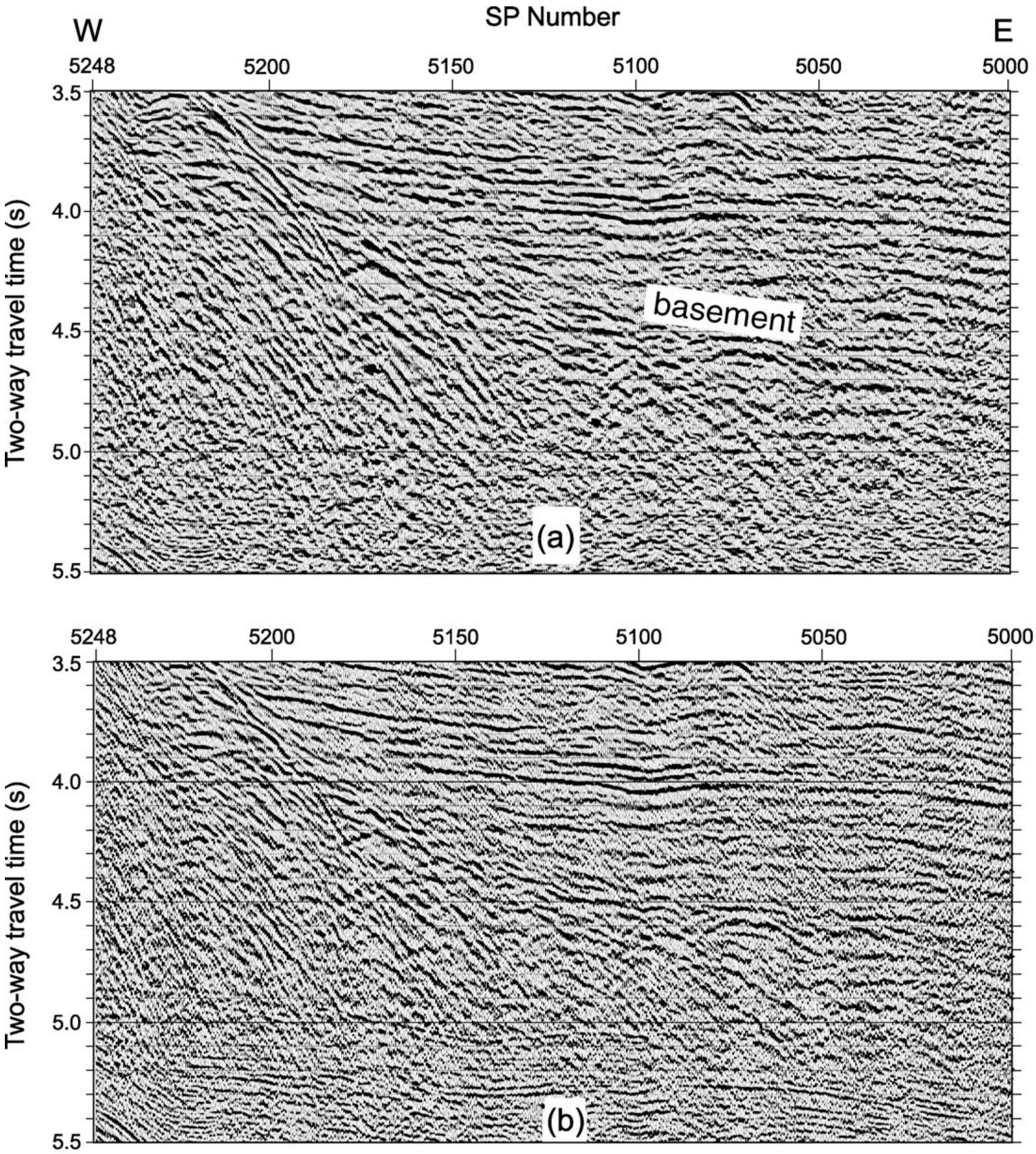

Fig. 10. Part of the MCS profile in Fig. 3 (a) before and (b) after tau-g HVF.

and Chough (1995), the basement in the continental shelf and upper slope at the inner margin of the SE Korean Peninsula is composed of extrusive volcanic rocks, which are assumed to be the extension of the NE–SW trending volcanic belt exposed on the adjacent SE Korean Peninsula. The K–Ar age of this volcanic belt ranging from Late Oligocene to Early Miocene times (Yoon and Chough, 1995) implies that it is tied closely to the continental rifting at the Korean margin. Skogseid and Eldholm (1987) placed the COB beneath SDRs on volcanic margins underlain by magmatic underplating. The MCS profile KCP-98 shows an extruded volcanic edifice forming on the acoustic basement on the slope flank under shot point 5300 (Fig. 3) that is approximately 2 s high in two-way travel time. This extruded volcanic body is interpreted to create scattering observable in the 40–50 km in OBS record sections (Fig. 4a and b). The spatial correlation of this volcanic structure with the strong magnetic anomaly suggests that the anomaly was created by a massive volcanic event anticipated in the initial stage of seafloor spreading, probably commencing during the latest stage of rifting. Further seaward, the acoustic basement is composed of a layered igneous sequence that appears to form SDRs. The HVLC body is shallowest under the rifted continental crust and deepens under the slope (Fig. 6), which seems to indicate its emplacement in association with continental rifting and subsequent seafloor spreading. In summary, there was considerable igneous activity on the Korean margin during the initial stage of seafloor spreading, including the emplacement of underplated igneous rock in the lower crust and the extrusive volcanism to form acoustic basement. The slope base is assumed to mark the geologic boundary between rifted continental crust and oceanic crust.

5. Conclusions

The analysis of MCS and OBS data provide constraints on the crustal structure of the continent–ocean transition zone at the Korean margin and of the adjacent Ulleung Basin in the East Sea. The crustal velocity model shows that the continental margin exhibits a significant seaward decrease in crustal thickness from 25 to 10 km over a distance of less than 50 km. The continental shelf and slope area is underlain by a high-velocity (up to 7.4 km/s) lower crustal body maximally 15 km thick. This body is interpreted to be magmatic underplating accreted onto the margin during continental breakup in Late Oligocene to Early Miocene times. The MCS data show a sequence of weak SDRs on the acoustic basement of the slope base. The boundary between rifted continental crust and oceanic crust appears to be located beneath the slope base that documents a massive volcanic eruption associated with the onset of seafloor spreading. These features suggest that the Korean margin was rifted above the anomalously hot asthenospheric mantle. Our interpretation is consistent with the positive relation between mantle temperature and thickness of oceanic crust because the thicker than normal crust in the Ulleung Basin formed in a region of hotter than normal mantle temperature. Global tomography provides confirmative evidence by defining the anomalously hot upper mantle beneath the Korean margin. Although there is no direct explanation for the cause of this thermal anomaly, the details of crustal structure imply that continental rifting and subsequent seafloor spreading at the Korean margin took place in a manner similar to that occurring at volcanic rifted margins.

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