Receive Function Imaging of the Amphibious NE Japan Subduction Zone—Effects of Low-Velocity Sediment Layer

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Abstract This study presents reflectivity images of the northeast (NE) Japan subduction zone continuous across the ocean and land. As nearly half of its forearc region is under the ocean, data from ocean bottom seismometers (OBSs) must be utilized to fully image the region by passive seismic analysis. The use of OBS data has been a challenge due to inherent characters of the ocean bottom observations: high noise level and effects of seafloor sediment. Now, decent imaging is possible in NE Japan overcoming the high level noise due to the accumulated data set of the OBSs. The low-velocity of seafloor sediment significantly delays and amplifies S waves passing through them, and thus complicates teleseismic waveforms. We identify and correct these effects to produce coherent receiver function images throughout the amphibious subduction zone. Our images provide a potential for discussing new structural features and will help better understanding of the dynamics of the NE Japan subduction zone.

Plain Language Summary In northeast Japan, the Pacific plate is subducting beneath the Japanese arc, and delineating how the actual subduction is taking place at depths has been the target of many seismological studies. This study presents our effort of continuous imaging of subsurface interfaces across the ocean and land employing an amphibious data set. On the land side, there are dense seismic networks that have been used to reveal the seismic interfaces using converted phases of distant earthquakes. On the ocean side, the accumulation of data from temporary ocean bottom seismometers in the last decade and the recently installed ocean bottom cable network has made it possible to use a similar approach as on the land. However, the low-velocity sediment beneath the seafloor causes systematic slower arrivals and larger amplitudes of the seismic phases of interest that result in highly disturbed images if we analyze them in the same way as the land. Here, we identify and correct the effects of the seafloor sediment to analyze the seismic interfaces across the ocean and land. As a result, we succeed in imaging the interfaces of the subducting oceanic crust throughout the region, as well as previously unidentified features under the ocean that may deserve future investigation.

1. Introduction

The northeast (NE) Japan subduction zone is one of the best seismologically equipped and studied subduction zones of the world, and many findings of the slab subduction related processes have been reported (e.g., Hasegawa et al., 1978, 1991; Kawakatsu & Watada, 2007; Kita et al., 2006; Tamura et al., 2001). The occurrence of the 2011 Tohoku earthquake has further accelerated the pace of research (e.g., Kanamori & Yomogida, 2011), and many seismic observations have been conducted in the past 10 years in the offshore area where the main rupture took place (e.g., Kodaia et al., 2017; Shinohara et al., 2013).

One of the key issues of the subduction process, in terms of both seismogenesis and geodynamics, is how water is transported into the arc system, and seismology offers the essential information for it through the structural and/or earthquake activity analyses. The general understanding is that sea water is stored in the oceanic crust and the shallow mantle as high-pressure pore-fluids (e.g., Audet et al., 2009; Kodaia et al., 2004; Peacock et al., 2011) and/or hydrated minerals before subduction in association with the plate bending around the outer-rise (e.g., Fujie et al., 2016; Ranero et al., 2003); the stored water is then released into the arc system respectively via change of plate boundary sealing (e.g., Audet et al., 2009;
Bostock, 2013) and/or dehydration conditioned by pressure and temperature at various depths during subduction (e.g., Hacker et al., 2003; Iwamori, 1998) that may be observed seismologically via structural imaging (e.g., Kawakatsu & Watada, 2007; Tsuji et al., 2008) or seismicity studies (e.g., Kita et al., 2006; Yamasaki & Seno, 2003). The seismic velocity of hydrated minerals becomes low compared to anhydrous counterparts, and hence detecting seismic low-velocity zones as indicators of water is important. As deeper parts of the NE Japan have been discussed through many land-based studies, mapping low velocities at shallower depths of NE Japan beneath the ocean is required for the full comprehension of the water transport in subduction. Although this part of the structural analysis is commonly conducted using active source techniques, here we attempt to employ teleseismic imaging technique, the receiver function (RF) method, that allows us to make continuous images from ocean to land, shallow to deep, via a single method.

Due to the amphibious character of the NE Japan subduction zone, we need the ocean bottom seismometer (OBS) data to image the whole region. Previously when OBS data were not available, passive seismic researches were spatially limited to land. Since the occurrence of the Tohoku earthquake, there have been extensive array deployments of OBSs in the offshore regions for aftershock (e.g., Shinohara et al., 2013; Yamada et al., 2011) and imaging studies (e.g., Yamamoto et al., 2011). In addition, since 2016, a novel ocean bottom cable network S-net, which includes 150 stations, has been deployed along the Japan trench (National Research Institute for Earth Science and Disaster Resilience, 2019a). This real-time telemetered network has greatly increased the size of the under ocean seismic data set, and the application of a passive imaging method to the noisy oceanic data has become tractable.

We apply the RF imaging technique to the amphibious data set of OBSs and land seismometers. The RF method is a widely used tool to map seismic discontinuities (i.e., reflectivity) such as interfaces of the hydrated oceanic crust (e.g., Bostock et al., 2002). Recently, the RF method is applied to amphibious datasets in SW and central Japan (Akuhara & Mochizuki, 2015; Ito et al., 2019) and the western part of the US (Audet & Schaeffer, 2018; Janiszewski & Abers, 2015; Reeves et al., 2015). In NE Japan, however, RF imagings have been done using only land station data (Kawakatsu & Watada, 2007; Tonegawa et al., 2005). Although active source studies at the offshore region of the NE Japan have reported the existence of a low-velocity layer at the top of the subducting slab that is the hydrated oceanic crust (Mochizuki et al., 2005; Takahashi et al., 2004), imaging the whole region continuously using a single technique should advance our understanding of the water transportation therein.

The presence of the low-velocity seafloor sediment, however, is known to be a huge obstacle for useful RFs of OBS data (Ball et al., 2014; Hannemann et al., 2017; Kawakatsu & Abe, 2016). The time delay of the phases caused by the sediment on the seafloor has been recognized in multiple studies (e.g., Agius et al., 2018; Doran & Laske, 2019) and, in some studies, is used to constrain the sediment structure (e.g., Doran & Laske, 2019; Tonegawa et al., 2019). Also, an attempt to remove the sediment S reverberations assuming a 1D structure under an array has been recently made (Zhang & Olugboji, 2021).

In the NE Japan subduction zone, the presence of multi-layered, low-velocity, and irregular-thickness seafloor sediment is reported using active sources (Miura et al., 2003; Takahashi et al., 2004) and more recently distributed acoustic sensing (Spica et al., 2020). The sedimentary units are identified as Pliocene-Pleistocene and Miocene sediments in this region (Kodaira et al., 2017) that have high Vp/Vs. The average Vp/Vs = 4.4 is estimated in the accretionary wedge by Nakamura et al. (2014), and it can be much higher at the topmost of the unconsolidated sediment (Hamilton, 1979). It is, therefore, essential to account for the severe effect of the sediment for our purpose of continuous imaging from land to ocean.

In this paper, we identify significant effects of the low-velocity seafloor sediment, and introduce corrections to those effects to obtain meaningful 2D RF images utilizing the amphibious array data. The attempt to make a continuous image using amphibious data set has made it possible to resolve the difficulty of dealing with the low-velocity sediment of the oceanic environment in the RF analysis.

2. Data and Methods

2.1. Amphibious Data Set in NE Japan

We include as many seismic stations as available for the land and the ocean to image the region (Figure 1). The land part of the array includes permanent networks of NIED (National Research Institute for Earth...
2.2. Receiver Function Analysis for Amphibious Data Set

We calculate RFs in the R-T-Z coordinate using the adhoc Wiener-filter deconvolution method (Aude, 2010) for the land data and the extended time multitaper method (Park & Levin, 2000; Shibutani et al., 2008) for the ocean data. The former takes advantage of high computation speed to handle ~17-year-long land data, and the latter does so in handling OBS records due to the spectral smoothing effect. A typical OBS record includes the water column reverberation that causes spectral holes leading to unstable frequency domain deconvolution (Akuhara & Mochizuki, 2015). Before the frequency domain deconvolution, records are high-pass filtered at a cut-off frequency of 0.05 Hz to suppress a long period trend in the ocean data (e.g., those due to infragravity waves in the ocean). We apply a low-pass Gaussian filter ($e^{-a^2 / 4 \omega^2}$) with the width factor (a) of 1.5 (corresponding cutoff frequency is ~0.4 Hz; e.g., Langston, 1979) to make final RFs for further imaging. We employ some criteria to filter out unreliable RFs. For the land data, we discard RFs with the absolute maximum value larger than 3 or the S/N ratio smaller than 1.1. For the ocean data, we first select records with a high S/N ratio in the vertical component (>1.5), and after obtaining RFs, we discard those with the maximum absolute value larger than 1. Here, the S/N ratio is the root mean square ratio of the signal to the pre-signal part with 100 s time windows.

The RFs are then migrated into space and stacked for common conversion points (CCPs; Dueker & Sheehan, 1997) if they lay within 2 km by 2 km grid and 50 km distance from a given profile. We assume flat layers and a Cartesian coordinate system during migration and grid stacking, which narrows and deepens the image compared to the spherical Earth case. We do not correct the dip as Kawakatsu and Watada (2007), and hence the subducting slab will be placed with a gentler slope toward the land side than the reality. As a tomography model (Matsubara et al., 2019) shows ~10% 3D seismic heterogeneity in both P and S wave velocities, we utilize the local 1D structure of the model beneath each station to incorporate velocity heterogeneities during migration (Akuhara & Mochizuki, 2015). To finalize the imaging, we apply corrections to the ocean side images that will be detailed in the next section.
3. Analysis of the Influence by the Seafloor Sediment

The slow and high-Vp/Vs seafloor sediment delays and amplifies S phases passing through the sediment. Figure 2 highlights these effects by showing synthetic elastic responses of a plane P wave incidence in the teleseismic situation for single-layer and double-layer sediment under a 4000-m-thick water layer and over a crustal half-space. Low-velocities make propagating rays near vertical in the sediment layer, and hence waveforms are dominated by P waves and S waves in vertical (Z) and radial (R) components, respectively. Because rays are near-vertical in the sediment, characters of sediment phases do not depend much on assumed slowness (i.e., distance). For the single-layer sediment case (Figure 2a), a first-arriving S wave in the radial-component, which is the P-to-S conversion at the sediment-crust interface, is delayed considerably with a significant amplitude (due to the large velocity contrast) that is followed by sediment reverberations. In the double-layer case (Figure 2b), where a thin extremely slow S-wave velocity layer (representing unconsolidated sediment) is added to the simple sediment-crust structure, the radial waveform becomes much more complicated: the amplitude of the first significant peak is much larger and its timing is further delayed, and the reverberation introduces many more phases. The sediment (and water) causes numerous reverberation phases that may overlap with deeper discontinuity signals, and thus the understanding of these effects becomes essential in the RF analysis of OBS data. It should be noted that the delay time of the initial S wave in the radial component is shared by all the later arriving S waves including possible P-to-S conversions at deeper discontinuities, and that we need to correct this time delay for the proper RF imaging that will be detailed below (Section 3.1).

Figure 3a shows typical RFs of land (TYSF) and OBS (C3) stations. While the land RF shows significant initial P phase followed by smaller phases that may originate from deeper structures, the oceanic RF is quite different. Understanding this difference, especially the origin of later large phases, is essential for the RF imaging of an amphibious data set. As will be discussed below, the presence of low-velocity sediment layers, especially the high-Vp/Vs unconsolidated sediment, makes the RF analysis in the oceanic environment challenging (e.g., Ball et al., 2014; Kawakatsu & Abe, 2016). In order to make continuous RF images from ocean to land, we need to introduce the following considerations and corrections to accommodate the effects of the sediment.

3.1. Time Delay of Scattered S Waves

The seafloor sediment is significant in time delay due to its extremely low S wave velocity unless it is incorporated in the velocity model used for migration. In the absence of such velocity models, the effect of the time delay in RF imaging should be corrected separately based on observations. The time delay here is the arrival time difference between the direct P phase and the P-to-S phase converted at the bottom of the sediment layer (we refer to this as PS-P time), and may go up to a few seconds depending on the sediment velocity and thickness (Figure 3b). As this time delay is also present in all following P-to-S converted phases scattered at deeper discontinuities, if not accounted properly, it will shift images to deeper depths. A time delay of one-second in a RF is equivalent to nearly a 10-kilometer depth change in migration, and thus a few seconds of time delay might deepen images a few tens of kilometers that may severely affect the interpretation.

We measure the time delay of each station by stacking teleseismic radial waveforms (Kumar et al., 2010). Due to its low-velocity character, rays in the sediment layer turn nearly vertical at the base of the sediment. Hence, the P-S phase is dominant in the radial component whereas the direct P phase and any P multiple...
are dominant in the vertical component (Figure 2). The P-S phase from the base of the sediment is the first significant peak in the radial. The time delay can be estimated from the time difference between the first significant peaks in the vertical and the radial components (Figure 3c). First, we filter the waveforms in a slightly higher frequency range (0.1–1.0 Hz) than that employed in our RF analysis (0.05–0.4 Hz). This higher frequency range allows us to identify clear onsets on vertical components. Second, we manually pick
3.2. Amplification of S Phases

The previous researches in the study region indicate that the sediment is divided into multiple sub-layers (e.g., Spica et al., 2020; Takahashi et al., 2004). The presence of slow sediment sub-layers at the top may amplify the teleseismic waves enormously (Figure 2). The amplification that we can expect with two-layer or three-layer sediment is about two times or even higher (Figure 3d) through the ray parameter range of a teleseismic P waves (0.04–0.08 s/km; Figure S3). When a S wave travels through a low-velocity and high-Vp/Vs sediment, the amplification occurs due to the transmission coefficients of the S wave that is larger than unity, while the S-to-P conversion is almost negligible. As a number of the sub-layers in the sediment increases, the amplitude of the S phase increases to dominate the waveform. Figure 3d shows such examples of S-wave amplification in different sediment models. NE Japan is known to have an average Vp/Vs of ~4 and Vp = 2.0 km/s in the sediment (Nakamura et al., 2014), and Vp/Vs increases to the shallow depths for seafloors in general (Hamilton, 1979). To see the amplification factor variation due to different velocities, we varied shear velocities in the sediment while keeping the Vp constant. In the calculation, the 2-layer case assumes Vs = 500 m/s (Vp/Vs = 4) in the lower layer and varies the Vs in the upper layer from 100 m/s to 500 m/s (Vp/Vs = 20–4; see Table S2). The 3-layer case introduces an additional thin low-Vs top sediment layer of Vs = 100 m/s (Vp/Vs = 20). Note that the amplification becomes about three times when the top layer has Vs = 100 m/s in the example.

Due to the amplification effect, images created without the adjustment of OBS data will have much larger amplitudes beneath the ocean than the land. To correct the effect, it is necessary to know the exact amplification factor. However, the exact amplification is predictable only when we know the exact structure of the seafloor sediment that is not available. As different sediment models can produce the same delay time, the delay time information alone is not sufficient for the purpose.

To deal with the situation, we chose to empirically estimate the correction factor focusing on the primary P-S phase of the subducting oceanic Moho to measure the amplitude ratio between the land and the ocean images. In order to fully appreciate how the amplification works, however, we need to understand the interference effect of the sediment reverberations.

3.3. Interference of Various Sediment Reverberations

Another influence from the sediment on the RF amplitude is through the interference of deep P-S phases with the sediment reverberation phases. The water and sediment layers produce many higher-order ray
combinations of P and S waves that are significant in amplitude within the main time window of interest and overlap with the primarily P-S phases from deep discontinuities. If the sediment is multi-layered, there will be numerous higher-order reverberations (Figure 2). Let us consider that the target phase is positive (e.g., subducting oceanic Moho). If such a phase overlaps with a positive reverberation phase, its amplitude will be larger. If it overlaps with a negative reverberation phase, its amplitude will be smaller or the sign will change; that is, an illusion of disappearance of the originally positive phase in the image occurs. Figure 4 exemplifies how this type of interference occurs in the RF imaging at subduction zones as explained below.

Let us consider a water-sediment-crust-mantle layer structure where the thickness of the crust changes through horizontal location (Figure 4a). We calculate synthetic teleseismic radial-component waveforms assuming a 1D flat layered structure locally at a distance x. In Figures 4d–4f, which show for the upper-right area of Figure 4a, the positive phase inclined toward left is the Moho phase. In the absence of sediment, the Moho signal dominates in radial-component waveforms and a simple image can be obtained (Figure 4d). If there is either 2-layer or 3-layer sediment (Figures 4e and 4f), there are horizontal patterns which are due to the reverberations in the sediment layer; overall amplitudes are larger than in Figure 4d, and the Moho phase overlaps with the higher order reverberations which is positive or negative depending on the timing. The relative amplitude of the Moho phase increases or decreases depending on the location (Figure 4c). Due to the interference, the Moho may disappear (Figure 4b, x = 340 km) and in some places, the apparent peak location deviates from the timing of the Moho (Figure 4b, x = 260 km). In some places, the synthetic calculations do not show the Moho in the image (Figures 4e and 4f), although the Moho is actually present in the model; that is, even if discontinuous Moho images are obtained by RFs, it does not necessarily indicate that the actual Moho is discontinuous. The generally larger amplitudes (both positive and negative) in the image are owing to the large amplitude of the sediment reverberations and amplification.

Figure 4. The effect of interference of the sediment reverberations on receiver function images. (a) The schematic of the entire modeling region with a dipping Moho interface which is used for Figures 4 and 5. The sky-blue region represents the ocean underlain by a low-velocity sediment layer. Note that the rest of figures are for the oceanic part of the model (x > 240 km). The region that corresponds to panels (d–f) is enclosed within the white dashed rectangle. (b) Example radial waveforms at three representative distances for the 3-layer sediment structure for the oceanic region (Table 1). Red crosses are the timing of the Moho phase. (c) The amplification of the Moho phase due to the presence of the sediment layer. The green, red, and blue lines are for the no-sediment case as in (d), the 2-layer sediment in (e), and the 3-layer sediment in (f), respectively. (d–f) Amplitude of radial-component waveforms at the seafloor (d) without sediment, (e) with a 2-layer sediment, and (f) with a 3-layer sediment (Table 1). The right y-axis is given in time and the left y-axis in corresponding migrated depth for the primary P-S conversion. Note that the time is corrected in (e and f) using the theoretically estimated PS-P time.
Correcting the Effects of Sediment

In order to get a coherent image across the shoreline, we have to reduce artifacts caused by the seafloor sediment. If we assume an amphibious structure (Figure 4a), the synthetic radial component waveforms (i.e., pseudo RFs) become very different from those calculated for a land only structure (Figures 5a and 5b). While the land side (< 240 km) of the two figures are identical, they are significantly different on the ocean side (> 240 km): with the presence of the water and sediment layers on the top, amplitudes are much stronger, and the dipping phases are placed at deeper depths (i.e., larger time delays) on the ocean side, and the dipping Moho images are not continuous from at $x = 240$ km. These characteristics appear in real data that need to be corrected to make a continuous image from land to ocean using the amphibious data set, and we employ the following two-step procedure, which is schematically shown in Figures 5b–5d.

First, we correct the effect of the time delay for the oceanic stations. We start migration from the time of the sediment PS-P time and the depth of the corresponding OBS at the seafloor. This migration approach starting from the seafloor assumes that the sediment is negligibly thin compared to the target depths. The sediment thicknesses have been reported to be $\sim$2 km in the study region (e.g., Spica et al., 2020), supporting this assumption. We do not use any PS-P time and sediment thickness relation since we have no exact estimation of $P$-wave and $S$-wave velocities of the sediment. Correcting the effect of the time delay greatly improves the coherency and continuity of the dipping phase in the image (Figure 5c). If not corrected, the Moho phases will lie incoherently at depths $\sim$30 km deeper beneath the ocean because oceanic stations have PS-P times of $\sim$3 s in the model (Figure 5b).

Second, we adjust the amplitude of the oceanside to reduce the overall amplification effects of the oceanic RFs. After the time correction, we have a coherent geometry of the dipping Moho (Figure 5c) that is selected as a target to estimate an amplitude ratio (i.e., an amplification factor) between land and ocean as detailed in the next paragraph. Then, we adjust the amplitude of the oceanic images by dividing them with the determined amplification factor to equalize them with the land ones (Figure 5d). The use of a single ratio is equivalent to assuming that the amplification due to sediment is uniform throughout the region due to similar layered velocities (although the thickness may vary; Figure 3d) and imposes a certain limitation to the interpretation of the images.
Figure 6 shows the detailed procedure of how we determine the amplification factor with the actual data. In the synthetics shown in Figure 5, we know the amplification from the model, but here we determine the ratio using the image; after the delay time correction, we measure the maximum amplitude of the image at each horizontal location around the expected location of Moho (Figures 6a and 6c), and take the median of amplitudes on the land side and the ocean side, respectively (Figures 6b and 6d). Then, we obtain the ratio of the median amplitudes between ocean and land. In the two profiles, the amplification factors are 4.04 (profile N) and 3.39 (profile S), which are comparable to (though slightly larger than) the values shown in Figure 3d. Without the adjustment of the amplitude, the velocity contrast at discontinuities might be systematically overestimated beneath the ocean. The equalization of the amplitude also allows easier tracking of the other structural phases (Figures S4c and S4h).

4. Amphibious Receiver Function Images of NE Japan

Figure 7 presents images of two profiles N and S (Figure 1). The boundary between ocean and land regions is located at $x = 250$ km in both profiles. The profile N has a good ray-path coverage that allows continuous imaging across the coastline (Figure S4b), but the number of ray-paths beneath the ocean is not as large as that of the profile S (Figure S4g); the continuity is possible partly because of the coastline geometry. The profile S has a spatial gap between the land part and the ocean part, but it is in the middle of the densest OBS distribution. Two profiles share about half of the stations to image above a depth of 100 km (Figures S4a and S4f). The time correction significantly improves the continuity of the resolved structure. For example, laterally continuous strong positive features exist in depths of 20 km or deeper (Figures 7c and 7f, at a distance range of 300–400 km): they are due to the misplaced P-to-S converted phases at the sediment bottom. After the correction, more coherent features can be traced from land to ocean (Figures 7a and 7d).

The images of both profiles include the features interpreted in Kawakatsu and Watada (2007) (Figures 7b and 7e). There are a positive feature (red solid line) that is dipping westward (i.e., subducting direction) and a negative one (blue solid line) that lies parallel above. Both features exist across the ocean and the land. The existing spatial gap (Figure 7d) obscures continuous delineation of the negative phase. Within the ocean part, both profiles coherently show shallow positive features at depths of 10–20 km (green line). Lastly, in the land part at depths of 20–40 km, there exist coherent features (pink line) in the west of the volcanic-front.

The coherent features listed are the robust parts of the images (Figure 8). We estimate the standard error of the CCP-stacked RF (image) in each cell. If the absolute amplitude of a stacked RF is smaller than the error, we can consider that the cell has an insignificant signal. Those coherent features remain in the images even after removing cells of amplitude smaller than twice the standard error, indicating that they are statistically significant (Figures S4d and S4i). Also, they are seen in images created with higher frequency RFs (Figure S5). The PS-P times measured with OBS data are neither uniform nor explained by a single trend (Figure 3e) and the water depth decreases westward. Hence, the higher-order multiples from the sediment and water layer are unlikely to disguise a coherent westward dipping structure we see in Figures 7a and 7d.
5. Discussion

5.1. Continuous Mapping of NE Japan Arc

We use the continuity of the ocean side from the land to interpret the main features in the image. We interpret the dipping positive feature as the Moho of the subducting oceanic crust (hereafter OM), and the upper dipping negative one as the top of the subducting oceanic crust (TOC). The coherent image around a depth of 30 km on land is the arc Moho (AM). From the continuity, we infer that the oceanic crust exists as a low-velocity zone under the ocean. Based on the active source study, Mochizuki et al. (2005) reported that the subducting oceanic crust is hydrated beneath the ocean. The shallow positive feature (green line in Figures 7b and 7e) above the crust (TOC) indicates the presence of a positive velocity discontinuity with-
in the arc crust, because we do not expect an arc Moho in this portion (Takahashi et al., 2004). Considering that the sediment on top is laterally variable along the profile (Figure 3e and Kodaira et al., 2017), it is unlikely that scattered phases within the sediment layer (i.e., PpPs) results in the coherent dipping feature. This forearc crustal discontinuity (FCD) might correspond to the bottom of the low-Vp region reported by Liu and Zhao (2018).

Synthetic tests show that the interference of sediment reverberations sometimes weakens or deletes the positive amplitude of the OM phase (Figures 4e and 4f). The absence of the dipping OM signature, seen in the ocean side of the image at $x = 300–320$ km for profile N and $x = 260–280$ and $330–350$ km for profile S (Figure 7), is likely due to this effect. Our synthetic test shows a similar gap width for the OM signature ($x = 330–350$ km, Figure 4e), supporting our interpretation. Not only weakening but also some misplacement or dip-modification may also be happening (e.g., $x = 280–300$ km at a depth of 40 km in Figures 7a and S6a).

The presence of water dehydrated from the oceanic crust (e.g., Kawakatsu & Watada, 2007; Tsuji et al., 2008) may also be blurring the overriding arc Moho and the discontinuities above that are detected with the active source studies ($x = 270–400$ km; e.g., Takahashi et al., 2004). Especially in the offshore forearc region, at the left side termination of forearc crustal positive phase (green line), there appears no arc Moho. The positive-negative-positive features, which respectively result from the forearc crustal, slab-top, and subducting oceanic Moho interfaces, are clear only before the TOC reaches ~25 km depth where some numerical studies predict pressure-dependent dehydration reaction releasing fluid upwards (Iwamori, 1998, 2007). If this fluid hydrates the arc crust and/or the mantle wedge, the velocity gradient above the slab decreases, which might make the shallowest positive phase and/or arc Moho signature disappear (e.g., Bostock, 1999; Bostock et al., 2002).

The gap of the station coverage at the vicinity of the land-ocean boundary still appears to hamper truly continuous RF imaging of the whole amphibious NE Japan. Nevertheless, signatures of the subducted hydrated oceanic crust reported previously beneath land can be now continuously traced seaward by few tens of kilometers (up to $x = 280$ km in profile N and $x = 260$ km in profile S) where signatures disappear abruptly, possibly due to the reverberation interference effect discussed above. It is interesting to note that, in profile S, there appears conspicuous nearly vertical positive signature in a depth range of 40–70 km above the level of the imaging error (Figure S4). We see similar features in RFs of multiple stations, implying that it is not a reflection of noisy RFs of a single station. While acknowledging that it is very difficult that the RFs image such a vertical structure, we also note that it coincides with the location of a slow P wave velocity anomaly reported in tomography (Figure S4; Matsubara et al., 2019) that extends N-S direction and may deserve further investigation. The widened spatial coverage of the image achieved by using the amphibious array may give a possibility of mapping a structure that is not reported previously.

### 5.2. Comparison With the Active Source Profiling

The arc Moho detected only in the western side of the land is consistent with the active source result where the clear seismic refraction signals throughout the western side and less clear reflection signal (PmP) on the eastern side are observed (Iwasaki et al., 2001). On the other hand, the depth of the detected arc Moho in our images is 30–40 km, which is ~5–10 km deeper than the reported depth from the active source profiling (Iwasaki et al., 2001).

The time delay caused by the near-surface sedimentary unit may partly explain this apparently deeper Moho (e.g., Yeck et al., 2013). The delay of the first positive peak timing of stacked RFs is approximately 0.5 s for stations of the western side located at $x < 180$ km, while no delay is observed for stations at $x = 180–220$ km. This spatial pattern correlates well with surface geology (Geological Survey of Japan, 1992). Additionally,
the time delay of ~0.5 s roughly corresponds to a thickness of ~1 km for a low-velocity (Vp = 2 km/s, Vp/Vs = 2) surface layer, which agrees with the sedimentary unit previously reported (Iwasaki et al., 2001). Since the velocity model used in migration does not include such a thin low-velocity structure (Matsubara et al., 2019), the time delay caused by the land sediment can misplace the arc Moho about 4–5 km deeper in the image. How this might affect the actual images should be discussed in the future analysis with a careful examination of land RFs.

To further discuss the full along-arc structure in the NE Japan subduction zone, such artifacts from land sedimentary units (e.g., Kanto basin) should be corrected in future studies. Our study implies that it is important to consider the sediment effect not only for the offshore region but also for the inland region.

In the offshore region (x = 270–400 km), the location of the profile in Takahashi et al. (2004) is almost the same as our profile S. The active source survey detects the arc Moho clearly whereas our image does not, and the FCD terminates at the initiation of the mantle wedge. This may imply that the offshore mantle wedge is resolvable only with high frequencies, and/or the Vs contrast at the Moho is weaker than the Vp contrast because of the high-Vp/Vs feature of a serpentinized mantle (Bostock et al., 2002).

5.3. Significance of Sediment Correction for OBS Studies

This study shows the necessity of correcting the first-order time and amplitude effects to use OBS data in the RF analysis. Correction of the time delay prevents misinterpretation of the structures and is the key to make a coherent image throughout the amphibious subduction zone (e.g., Akuhara & Mochizuki, 2015). The time uncorrected images (Figures 7c and 7f) do not show coherence in terms of phases. Amplitude uncorrected images (Figures S4c and S4h) are not coherent in terms of amplitudes. The measured delay times (Figure 3e) and the amplitude difference (Figures 6b and 6d) are consistent with what we can expect from 2- or 3-layered sediment which is reported in the active source studies. Our attempt to image the NE Japan arc using the amphibious array has clearly demonstrated the significance of the sediment correction, as well as how to make it.

The first-order corrections introduced in this study should be applied for future OBS RF imaging studies. The significant effects of the seafloor sediment and the water layer have been known to hamper the proper interpretation of the RFs (Audet, 2016; Ball et al., 2014; Kawakatsu & Abe, 2016). Instead of the proposed first-order corrections, one may wish to use lower frequency filtering to neglect sediment effects, but such low-pass filtering would not work as intended due to dominant reverberation phases (Text S1, Figure S7). Similarly in a study on a region with thin sediment (~300–400 m), Hannemann et al. (2017) showed that RFs in the higher frequency are easier to identify deep discontinuity phases than in the lower frequency. Because the seafloor sediment is a ubiquitous feature for all offshore regions, our first-order correction method will offer benefits to studies of other regions. For example, the RFs from the Cascadia subduction zones show the presence of nonzero delay times for the offshore stations (e.g., Audet & Schaeffer, 2018; Janiszewski & Abers, 2015), which may indicate the seafloor sediment influence on the data. Our study also implies that, to use multiple phases stacking with the OBS data (e.g., Audet & Schaeffer, 2018), the time correction, amplitude adjustment and phase-weighting should be taken in detail because the number of S-legs passing the sediment differs among the phases.

Although our first-order correction is successful in obtaining coherent and continuous images from ocean to land using the amphibious array data set, there are certain limitations and some rooms for improvements. As we do not intend to remove the sediment reverberations, the observability of deeper structures is highly limited. If sediment reverberations are too severe and obscure a detectable coherent structure across the whole array, the empirical estimation of amplitude amplification would be difficult. The use of a single amplification factor between land and ocean imposes limitations to the interpretation of the images, as the sediment structure likely varies laterally; for example, the lateral variability in the amplitudes of the imaged oceanic Moho might be due to that of the sediment, instead of OM itself. Developing a method that can better model and/or remove water/sediment-reverberation effects will increase the detectability of deeper structures, as well as their lateral variability of the signal amplitude.
6. Summary and Conclusion

We have constructed continuous seismic reflectivity images of the NE Japan subduction zone from ocean to land employing a single approach applied for an amphibious data set. Based on theoretical calculations and the RF analysis, we have identified the severe effects of low-velocity and high-Vp/Vs oceanic sediment on RFs, and introduced how to correct them to make meaningful images that should be used in the future RF studies using ocean bottom seismic data. The final images delineate the subducting oceanic Moho and the top of the oceanic crust continuous further to the ocean side than previously known. Our results have the widest spatial coverage of the RF images in the NE Japan. Our results show that the corrections of the sediment effects significantly improve the images to reveal coherent structures across an amphibious region. We see the low velocity oceanic crust throughout the amphibious region. While the images capture some along-subduction variability, it may be an artifact due to the reverberation interference effect identified in this study, or a real structural feature that is expected from previous numerical studies (Iwamori, 1998, 2007) and tomography observation (Matsubara et al., 2019).

Data Availability Statement

The land network stations and S-net data are available upon registration on http://www.hinet.bosai.go.jp. The R-T-Z component telesismic waveforms of OBS campaign networks used in the study are available from zenodo (https://doi.org/10.5281/zenodo.4500650).

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