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Mantle transition zone beneath a normal seafloor in the northwestern Pacific: Electrical conductivity, seismic thickness, and water content

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ABSTRACT

We conducted a joint electromagnetic (EM) and seismic experiment to reveal the mantle structure beneath a normal seafloor at 130–145 Ma in the northwestern Pacific, where the seafloor is relatively flat and the underlying mantle is expected to be normal (free from tectonic perturbations). In the experiment, we deployed state-of-the-art instruments in two arrays from 2010–2015. Here, we report the result of analyses of the EM and seismic data for investigating the mantle transition zone (MTZ) structure. The EM data analysis revealed that an electrical conductivity structure below both arrays was approximated by an average 1-D model of the north Pacific, and showed a possible downward increase in conductivity at the top of the MTZ. From the P-wave receiver function analysis, perturbations in the MTZ thickness from a global average were estimated to be +20 km and +2 km below the northern and southern arrays, respectively, from which temperature profiles in the MTZ below these two arrays were then estimated. We jointly interpreted the profiles of electrical conductivity and thus estimated temperature, with reference to the experimental values of the effects of water on the electrical conductivities of MTZ minerals (wadsleyite and ringwoodite) from mineral physics. The upper bound of the water content below the northern array was determined to be 0.4 wt.% or 0.04 wt.%, depending on different results of mineral physics, and that below the southern array was determined to be slightly smaller. The lower bound of the water content was not constrained by our data. Our results indicate that the MTZ beneath the normal seafloor in the northwestern Pacific is drier than subduction zones, and may be a water-poor region in a plum-pudding mantle model.

1. Introduction

Water or hydrogen in the Earth's interior plays important roles in plate tectonics, mantle dynamics, and evolutionary processes of the Earth through viscosity and rheology control, solidus condition, chemical partitioning, etc. (e.g., Karato, 1986; Bercovici and Karato, 2003). A number of studies on mineral physics have revealed that a huge amount of water can be stored in the mantle transition zone (MTZ) by the most abundant MTZ minerals, wadsleyite and ringwoodite. The maximum water content stored in the MTZ is ∼1.5 wt.% by wadsleyite and ∼0.8 wt.% by ringwoodite at the MTZ pressure and temperature conditions, which are averages of the laboratory measurements conducted so far (Thio et al., 2016), and could be up to ∼3 wt.% for both minerals (e.g., Smyth, 1987; Kohlstedt et al., 1996). Because of MTZ's potential as a water reservoir, the amount and distribution of water in the MTZ has a significant impact not only on the dynamics and evolution of the Earth, but also on the budget of the Earth's water cycle (e.g., Bercovici and Karato, 2003; Hirschmann, 2006).

A major volume of the MTZ below the ocean underlies the "normal" seafloor. Here "normal" means the seafloor whose age/depth dependence can basically be explained by a plate-cooling or a half-space cooling model (Korenaga and Korenaga, 2008). In other words, it means the seafloor is sufficiently far from areas of anomalously high residual topography or the thick crust that is usually found at oceanic plateaus and subduction zones (Korenaga and Korenaga, 2008). The MTZ below the normal seafloor, namely

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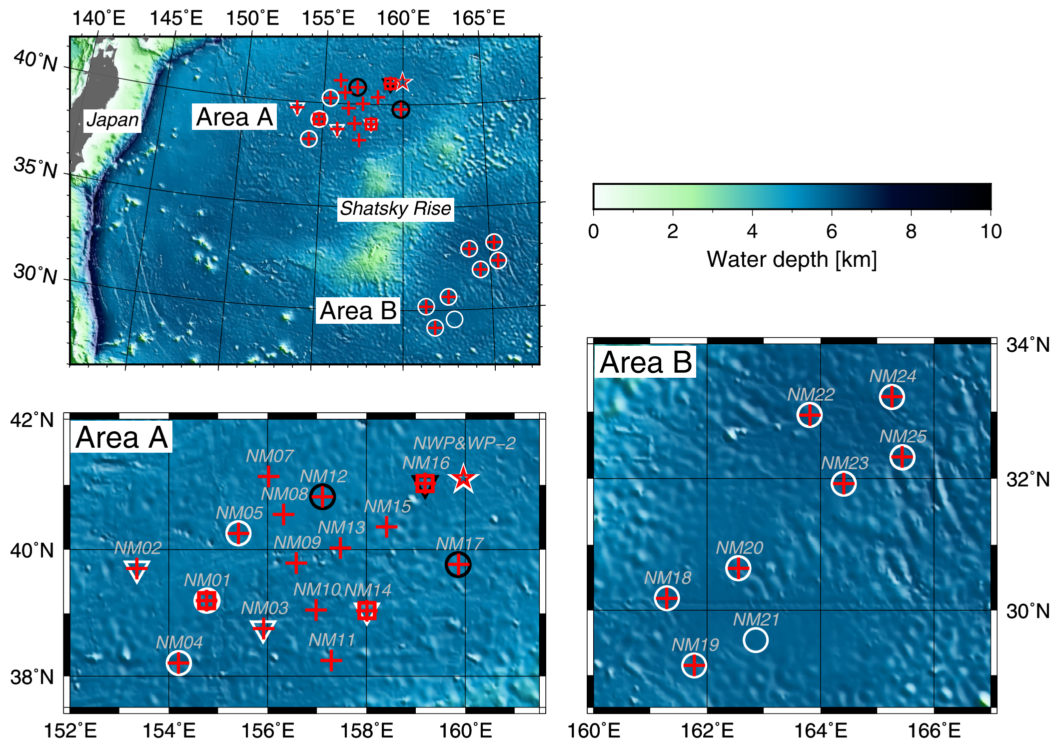

Fig. 1. Bathymetric map with stations where data were available for this study. Symbols denote the following ocean bottom instruments: red squares, EFOS; red crosses, OBEM; white and black inverted triangles, BBOBS-NX; white and black circles, BBOBS; red stars, seafloor magnetic observatory, NWP (Toh et al., 2006); and white stars, seafloor borehole broadband seismometer, WP-2 (Shinohara et al., 2008). White symbols of BBOBS-NX and BBOBS represent stations at which data were used for estimating MTZ thickness perturbations, whereas black symbols for these instruments represent stations at which data were analyzed but not used for estimating MTZ thickness perturbation due to substantial noise. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

the normal oceanic MTZ, should be able to reserve a large amount of water across the entire Earth as suggested by mineral physics; however, the actual amount held remains to be investigated by geophysical observations.

Global EM induction studies using magnetic observatories or satellite data have recently provided global views of electrical conductivity of the MTZ (e.g., Kelbert et al., 2009; Sun et al., 2015), but the lateral resolution of these images is too low over the oceans. Existing global models exhibit significant differences that may be at least partly ascribed to the low resolution. Semi-global induction studies using magnetic observatory and submarine cable network data in the limited regions where such datasets are available greatly improve the lateral resolution (Shimizu et al., 2010b). Furthermore, use of the electric field data obtained by submarine cables improves the model sensitivity immediately below, compared to those using the magnetic responses only, which are also affected by lateral heterogeneity with respect to the station location (Shimizu et al., 2009). However, as mentioned, such datasets are only available in limited areas of the ocean, because of the high cost of installation and maintenance of such systems.

Global seismic studies have provided images of seismic discontinuities, P- and S-waves, and seismic wave attenuation in the MTZ. The lateral resolution of such seismic images (e.g., Ritsema et al., 2011; Flanagan and Shearer, 1998; Gu et al., 1998) is much higher than that of global EM induction images, but is still low for investigating the shorter wavelength anomalies (<1000 km) that are related to the normal oceanic MTZ structure, because of sparse data coverage in the oceanic region.

We carried out a scientific project to study a normal part of the oceanic mantle, called the Normal Oceanic Mantle (NOMan) project, from 2010 to 2015 (http://www.eri.u-tokyo.ac.jp/yesman/). One of the aims of this project was to investigate water content in the normal oceanic MTZ below the northwestern Pacific from ocean bottom geophysical (EM and seismic) data, and the present paper reports the first results of this investigation. Results for the other aim of this project – to reveal the physical properties of the lithosphere–asthenosphere structure below the normal seafloor – were partly published by Baba et al. (2013), and will be reported elsewhere.

The sensitivity of electrical and seismic parameters to the physical properties of the MTZ are different; electrical conductivity is more sensitive to water content than to temperature, major element chemistry, and oxygen fugacity, while seismic parameters are more sensitive to temperature and major element chemistry than to water content (Karato, 2011). To provide a strong constraint on water content in the normal oceanic MTZ through utilizing these different sensitivities of electrical and seismic parameters, we conducted a joint EM and seismic experiment by deploying two seafloor arrays, consisting of our state-of-the-art ocean bottom instruments, in the northwestern Pacific at 130–145 Ma seafloor age (Fig. 1).

2. Field experiment and data

The target region of our study consisted of two areas; an array of ocean bottom EM and seismic observations was deployed in each. One area was to the northwest of the Shatsky Rise (hereafter, Area A) and the other lay to the southeast of the Shatsky Rise (hereafter, Area B). The main experiment was conducted in Areas A and B from November 2011 to September 2014, following a pilot observation at five stations in the western part of Area A from June 2010 to August 2012 (Baba et al., 2013). Subsequently, an EM observation was conducted at the NM03 station until September 2015. The ocean bottom instruments used for the EM study were the Earth's electric field observation system (EFOS) and the ocean bottom electro-magnetometer (OBEM) (Utada, 2015). Those used for the seismic study were the broadband ocean bottom seismograph (BBOBS) and its next generation model (BBOBS-NX)