Water Content in the Mantle Transition Zone Beneath the North Pacific Derived from the Electrical Conductivity Anomaly

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Fukao et al. (2004) inverted semi-global electromagnetic network data for three-dimensional electrical conductivity structure in the mantle transition zone beneath the north Pacific. In this paper we interpret the electrical conductivity structure in terms of the water distribution in the mantle transition zone, using partial derivatives determined by laboratory experiments on mantle materials. Fukao et al. (2004) explained both electrical conductivity and seismic P-wave velocity anomalies with thermal anomalies because of the overall coincidence of high electrical conductivity with low seismic velocity. However, a significant discrepancy is found beneath the Mariana islands where the seismic tomography would indicate little temperature anomaly, while electromagnetic tomography implies high temperatures. Despite limitations and differences in spatial resolution, this result indicates that this particular feature may not be explained by only a thermal effect. Taking into consideration that this region is well populated by subducted slabs, we further assume that this discrepancy is caused by water dehydrated from those slabs. Under this assumption, by combining the Nernst-Einstein relationship (e.g. Karato, 1990) and the recent result of laboratory measurements of hydrogen diffusivity in wadsleyite (Hae et al., 2006), the water content anomaly was estimated from the electrical conductivity anomalies. We find that the mantle transition zone beneath Mariana islands could contain about 0.3 weight % water.

1. INTRODUCTION

Electrical conductivity is an important physical parameter that elucidates the Earth's deep interior because it varies by orders of magnitude with environment, and can therefore detect some anomalies in physicochemical state of the Earth. Electromagnetic (EM) induction methods can do as well as seismological methods at estimating Earth's mantle structure from the surface to about 1000 km deep in the mid-mantle (e.g. Yukutake, 1965; Banks, 1969) by using the response of the EM field variation induced in the Earth by fields of external origin.

To estimate the deep and large-scale structure such as the mid-mantle, however, it is necessary to measure the EM fields for long periods, say, 100 days to several years at observatories covering a wide area. Conventional studies used geomagnetic variation data from permanent observatories around the world to estimate the electrical conductivity structure by separating the potential of geomagnetic field

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variation into external and internal parts. It is easily shown that the ratio of external and internal parts is a function of the electrical conductivity in the Earth (Schuster, 1889; Lahiri and Price, 1939; Rikitake, 1950; Banks, 1969; Olsen, 1999). The EM method that uses only the geomagnetic field is called the geomagnetic depth sounding (GDS) method, in which a ratio of vertical and horizontal component in the frequency domain is used as the so-called induction response functions.

$$Hz(f) = T(f)\ Hh(f), \tag{1}$$

where $Hz(f)$ and $Hh(f)$ are vertical and horizontal components of geomagnetic field in a frequency f, respectively. $T(f)$ is a GDS response, which includes information on the electrical conductivity structure in the Earth.

This GDS method, however, is useful only in the period range of several days and longer, because the vertical geomagnetic variations due to source field morphology are very small at shorter periods. This means that shallow mantle structure, above the mid-mantle, cannot be estimated only by measurement of the geomagnetic field. Because the electrical field variations do not vanish at shorter periods it is essential to use an EM induction method based on electric field data, such as the MT method (Cagniard, 1953) .

$$Eh(f) = Z(f)\ Hh(f), \tag{2}$$

where $Eh(f)$ and $Hh(f)$ are horizontal components of geoelectric and geomagnetic field in a frequency f, respectively. $Z(f)$ is a MT response or a MT impedance.

To elucidate the Earth's interior, the electrical conductivity structures estimated by EM induction methods are compared with laboratory measurements of the electrical conductivity of mantle materials (Akimoto and Fujisawa, 1965; Omura, 1991; Shankland et al., 1993; Xu et al., 1998). EM induction methods are very sensitive to highly conductive media such as hot regions and fluids, and can thus detect some anomalies in mantle temperature and composition (Tarits et al. 2004, Ichiki et al. 2006). Regional EM studies can detect anisotropic structure (Lizarralde et al, 1995; Evans et al. 2005; Baba et al. 2006), using theoretical and experimental results of mineral physics (Karato, 1990; Mackwell and Kohlstedt, 1990; Constable et al., 1992; Simpson and Tommasi, 2005).

Utada et al. (2003) applied both the GDS and MT methods to geomagnetic field data from observatories and voltage data from submarine cables, and estimated a one dimensional reference model for the electrical conductivity structure of the mid-mantle beneath the Pacific region. The mid-mantle model of Utada et al. (2003) has two jumps at 400 and 650 km depth and is very similar to the model derived from laboratory measurement of the electrical conductivity of the mantle materials at high pressure and high temperature (Xu et al., 1998, 2000). The χ^2 misfit, however, is greater than one even for the one dimensional reference model, which implies significant lateral heterogeneity in the mid-mantle.

In this paper, heterogeneous structures derived from both the electrical conductivity and a seismic velocity model are compared. We then elucidate the origins of these anomalies. Finally we use the electrical conductivity structure to estimate anomalies in water content in the mid-mantle beneath the north Pacific.

2. THREE-DIMENSIONAL EM TOMOGRAPHY

Koyama (2001) used the same geomagnetic field data from sixteen observatories/stations, voltage data from eight submarine cables in the Pacific region (Fig. 1), and calculated MT and GDS response data as used in Utada et al. (2003) and Fukao et al. (2004). In these studies, the GDS response (eq. 1) is defined as the ratio of the vertical and northward components of the geomagnetic field in the frequency domain, and the MT response (eq. 2) is defined as the ratio of voltage $V(f)$, that is, integrated value of the horizontal geoelectric field along the submarine cable, and the northward component of the geomagnetic field $Hx(f)$ in the frequency domain f.

$$Z(f) = V(f)/Hx(f) = \left(\int -Eh(f)dl\right)/Hx(f) \tag{3}$$

To calculate the value of the voltage V in numerical modeling in practice, V is evaluated by summing discretized electrical field Eh in each line element of the cable dl, that is, $V(f)=-\Sigma Eh(f)dl$.

Utada et al. (2003)'s 1-D reference model for the electrical conductivity beneath the Pacific has a jump of about 1.5 orders of magnitude at 400 km and one of 0.5 orders of magnitude at 650 km. This 1-D model is remarkably similar to the conductivity profile deduced from laboratory measurement by Xu et al. (1998, 2000). On the other hand, this 1-D study suggested significant lateral heterogeneity beneath the Pacific from the joint D^+ analysis for all the data (Parker, 1980).

Koyama (2001) imaged the 3-D electrical conductivity anomalous structures relative to the 1-D reference model of Utada et al. (2003). Koyama (2001) estimated the 3-D heterogeneous conductivity structure of the north Pacific area: longitude 90 to 270 degrees east and latitude 0 to 90 degrees north. Vertically, the region extends from 350 to 850 km depth, because the skin depth at one day period is about 650 km and the electrical conductivity in the upper

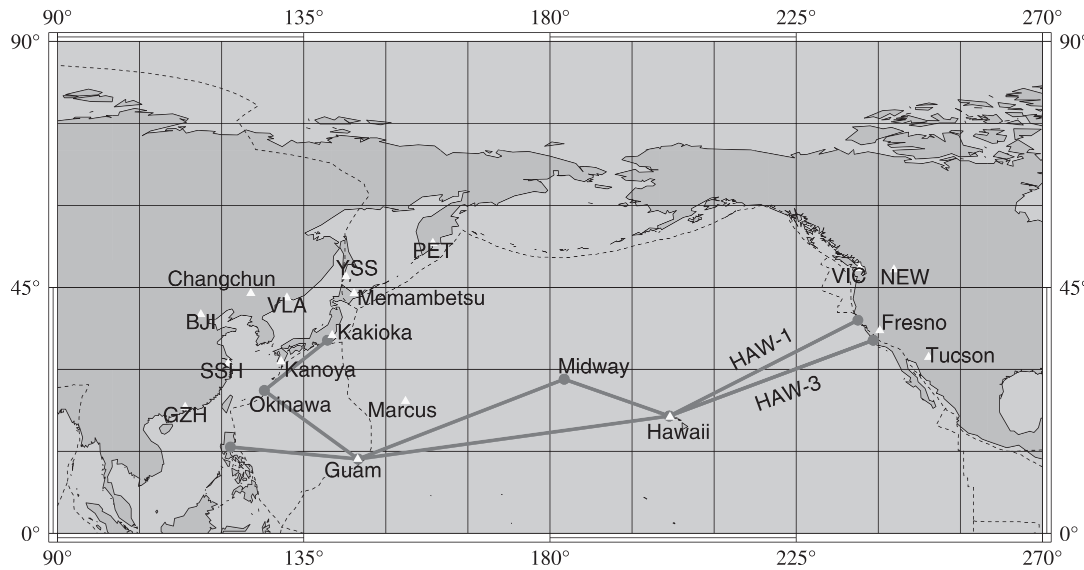

Fig.1. Observatory map: grey lines and white triangles indicate submarine cables and geomagnetic observatories, respectively. The voltages are measured between two ends of each cable. Dashed lines indicate plate boundaries.

mantle is much smaller than that in the transition zone (see Fukao et al., 2004). This 3-D model provides the logarithmic electrical conductivity $\log(\sigma_{3D}/\sigma_{1D})$ in each cell, where σ_{3D} is the estimated three-dimensional heterogeneous structure of the electrical conductivity and σ_{1D} is the electrical conductivity of the reference 1-D model of Utada et al. (2003). The grid size of each cell is 15 degrees horizontally and 100 km vertically. The total number of model parameters is 360 (= 6 by 12 by 5). The other regions of the Earth are fixed to the 1-D reference model of Utada et al. (2003) except for the surface layer including ocean-land contrasts of electrical conductivity.

At the surface, ocean-land contrasts are critical for EM induction problems, known as galvanic distortions (e.g. Jiracek, 1990; Utada and Munekane, 2000). The galvanic distortion is due to contamination by the charge accumulating at the surface topographic contrast and the associated contrast in the electrical conductivity must be taken into account. Therefore, a top layer with a homogeneous thickness of 3000 m was included with laterally heterogeneous conductance values corrected for topography. Topographic data is taken from ETOPO5 data. In inversion processing, the 3-D forward calculations were carried out with 3 degrees grids horizontally and 50 km grids vertically except the surface layer with 3000 m thickness by using a 3-D forward modeling code in the spherical Earth (Koyama et al., 2002). The data are both the real and imaginary parts of MT and GDS responses along with their estimated errors. The MT responses are estimated at eight periods for each of the eight submarine cables. The GDS responses are estimated at eight periods for each of the eight geomagnetic observatories, except at Marcus where GDS responses only at five periods are estimated. The so-called *C* responses are given at five periods for each of the eight geomagnetic observatories by Fujii and Schultz (2002) and are converted to the GDS responses. The total number of responses, which are complex numbers, is 165, and thus the total number of data is doubled, 330. Hereafter, the geomagnetic variation of the external origin is approximated by a dipole field due to a ring current in the magnetosphere (Banks, 1969).

3. THREE-DIMENSIONAL CONDUCTIVITY STRUCTURE BENEATH THE NORTH PACIFIC

Using the 1-D reference model as the initial model in this 3D inversion, Koyama (2001) inverted the data from submarine cables and geomagnetic observatories for 3-D anomalies of the electrical conductivity beneath the Pacific to minimize the objective function Φ.

$$\Phi = \sum_i \left(\frac{d_i - f_i(m)}{e_i} \right)^2 + \lambda (Lm)^2, \tag{4}$$

where the first and second terms of the right hand side indicate the total residuals of data parameters and the constraint on model parameters, respectively. d_i and $f_i(m)$ are the EM response data at i-th observatory and the corresponding synthetic response for the model parameter m, respectively. e_i is the data error of d_i. L is the constraint operator for the model parameter m. In this study, horizontal smoothness was adapted for L. λ is a hyper parameter, which determines the weight of the model constraints. In this study, λ is fixed to 5.

Thirty iterations of the quasi-Newton method were made. The data residuals were reduced by 20 %, relative to those for the initial model. A resultant ratio of the term of the model constraints to the objective function Φ in eq. (4) is about ten percent. Fig. 2 shows the resultant three-dimensional model of the electrical conductivity. The model provides logarithmic conductivity anomalies relative to the 1-D reference model, $\log_{10}(\sigma_{3D}/\sigma_{1D})$. Three notable large-scale features can be seen in this model. The electrical conductivity of the mantle transition zone beneath Hawaii is twice as conductive as the 1-D reference model. The transition zone beneath Mariana is thrice as conductive. On the other hand, the uppermost lower mantle beneath Philippine is half as conductive.

A checkerboard test was conducted as in seismic tomographic studies. The result of the test shows that the region beneath the submarine cables through Hawaii, Guam and Philippine has relatively good resolution (Fig.3). However, the electrical conductivity relates non-linearly to MT and GDS responses and, unlike linear seismic tomography, the checkerboard test may not be applied to EM induction problems. The intensity of the anomalies in our 3-D model (Fig.2) is almost as small as the anomaly intensity of the checkerboard test (Fig.3a), allowing us to regard the test's intensity resolution as applicable to the data. We conducted another resolution test by calculating the sensitivity of the electrical conductivity of each model cell on the data set, which is supposed to be the following,

$$S_j(m) = \sum_i \left| \frac{\partial f_i(m)}{e_i \partial m_j} \right|^2 , \qquad (5)$$

where $S_j(m)$ is the total deviation of set of data parameters divided by its error, by slightly changing each model parameter m_j,. that is $\log(\sigma_{3D}/\sigma_{1D})$ of the j-th cell, and then can represent the sensitivity of each model parameter on data set. $S_j(m)$ can express the effect only by each model cell unlike the previous checkerboard test which may have inductive interactions between the checkers, and thus this sensitivity test can be complementary to the checkerboard tests. Fig.4 shows $S_j(m)$ in logarithmic scale, and it turned out that there is high sensitivity at the region which can be also well-resolved in the checkerboard test, and then the result of both tests are

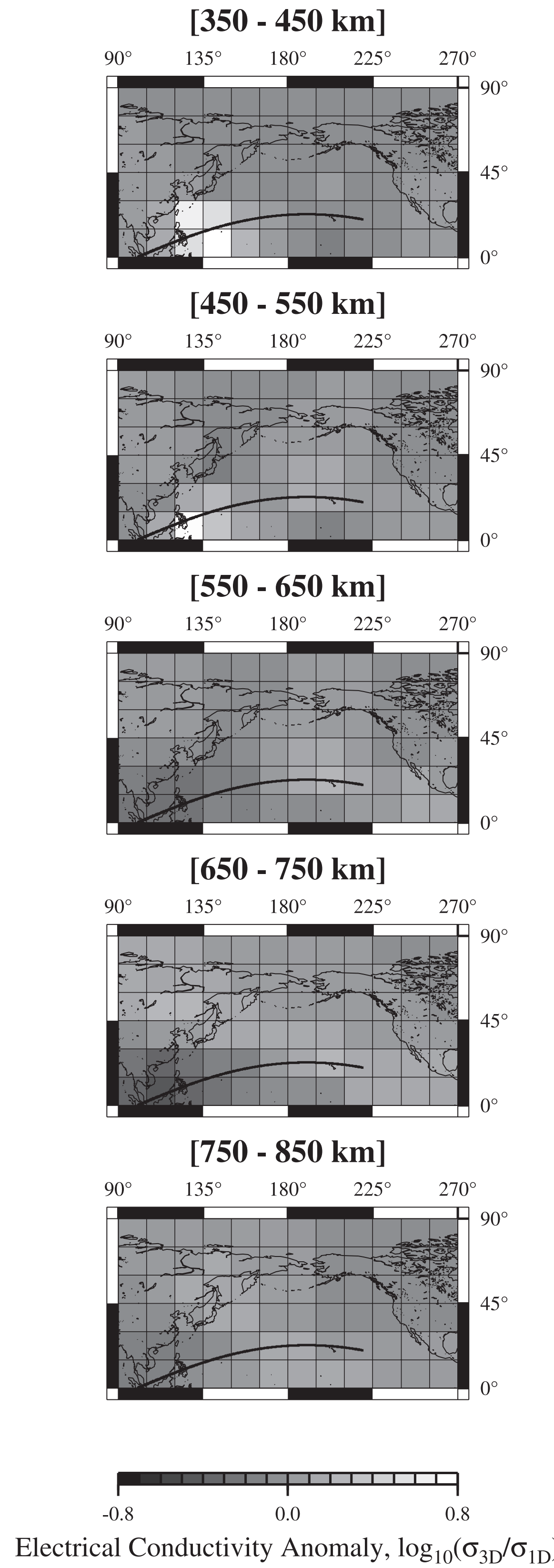

Fig.2. The contour map of three-dimensional model of the electrical conductivity inverted from the data of MT and GDS responses: Each model grid size is 15° x 15° (horizontal) x 100 km (vertical). A unit is anomalies from a 1-D reference model (σ_{1D}) by Utada et al. (2003) in logarithmic scale, $\log_{10}(\sigma_{3D}/\sigma_{1D})$.

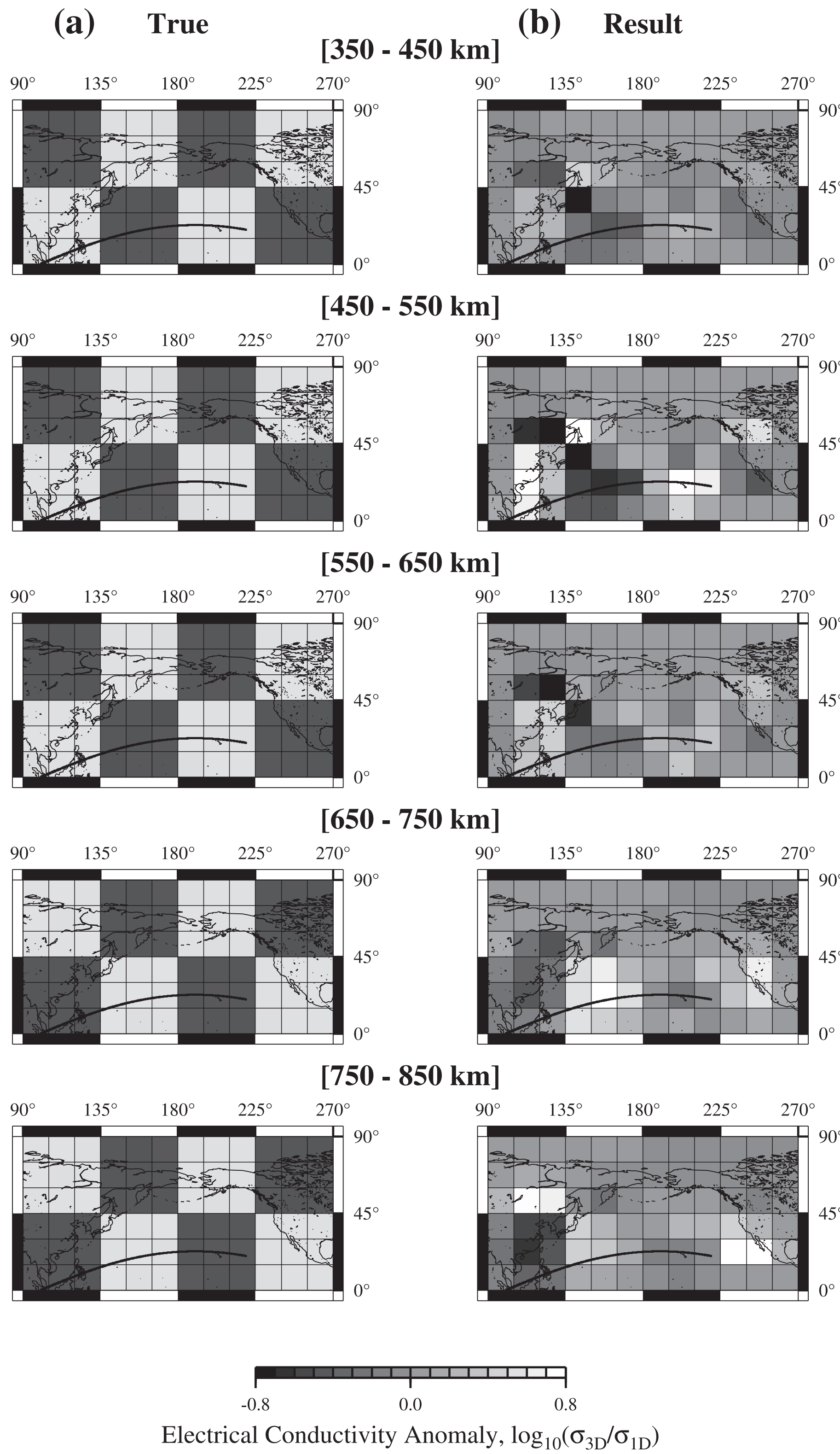

Fig.3. Checkerboard test: (a) checkerboard model given a priori which are ±0.5 unit. (b) result of checkerboard test inverted from synthetic MT and GDS data responses for a checkerboard model (a).

almost consistent. Hereafter, we focus on the presumably high-resolved region. Details on resolution of both seismic and electrical structure are shown and discussed in Fukao et al. (2004).

4. ESTIMATING WATER DISTRIBUTION IN THE MANTLE TRANSITION ZONE

As in Fukao et al. (2004), we compare the electrical conductivity structure with seismic P-wave velocity structure (Fukao et al., 2003). Fig. 5 shows both models. On large scales, both models seem similar, for example, the mid-mantle beneath Hawaii has high conductivity and low velocity, and the uppermost lower mantle beneath Philippine has low conductivity and high velocity. Fukao et al. (2004) assumed both conductivity and P-wave velocity anomalies were simply due to thermal perturbation in the mantle and converted them to thermal anomalies, by using the experimental relationship derived from laboratory measurements (Karato, 1993; Xu et al., 2000). They concluded that these features thermal in origin because the temperatures derived from electrical conductivity and from seismic velocity are similar. A very high conductive region in the mid-mantle beneath Mariana, however, cannot be explained with a thermal origin, because the seismic velocity is not very anomalous. This anomaly may thus be explained by compositional differences. The existence of small ions is effective at enhancing electrical conductivity because the diffusion of small ions is very fast. On the other hand, *P* wave velocity does not change as much due to existence of small ions, such as H^+ from water (Yusa and Inoue, 1997). Therefore we find hydrogen from water the most preferable explanation for the discrepancies in thermal model derived from seismic and electrical structures. This region is well populated by subducted slabs, and it might have a lot of water carried by and dehydrated from these slabs. The electrical conductivity σ (S/m) is related to concentration of hydrogen c (atom/m^3), that is, water content linearly by the Nernst-Einstein relationship (Karato, 1990)

$$\sigma = cDq^2/kT, \tag{6}$$

where D, q are diffusivity and electrical charge of hydrogen, respectively. q is equal to the elementary charge, 1.60×10^{-19}(C). k is the Boltzman's constant. T is a temperature, of which we used a reference model in Ito and Katsura

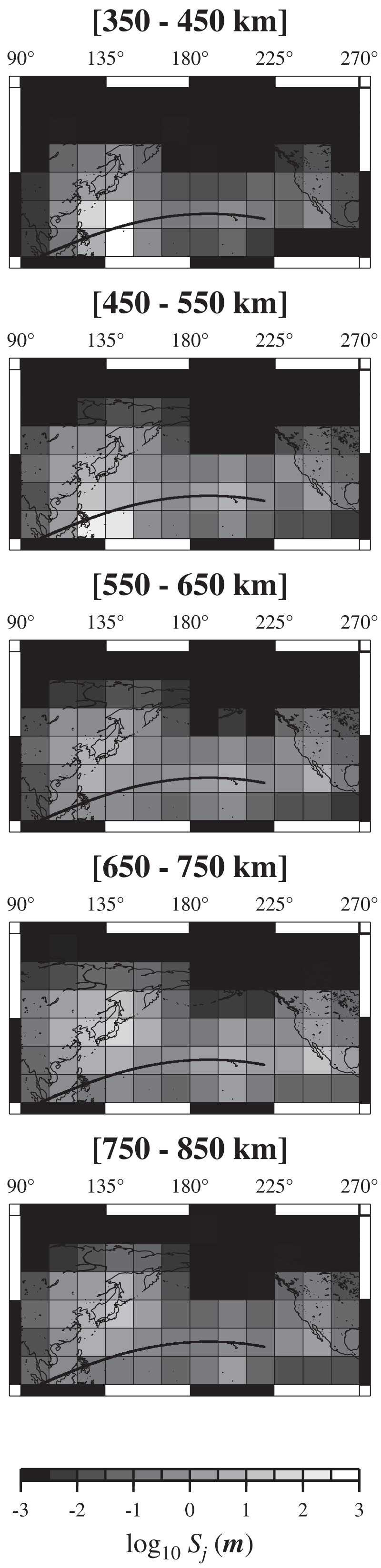

Fig. 4. The value of sensitivity $S_j(m)$ in logarithmic scale is contoured in each model cell, which is defined at eq. (5). It shows how sensitive to used data sets in this analysis each model parameter is.

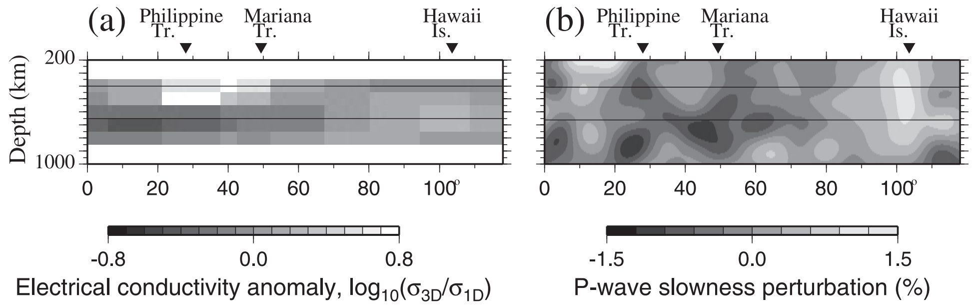

Fig. 5. Profile of anomalies beneath curve through Hawaii, Guam and Philippine shown in maps of Fig 2 as a black curve. (a) electrical conductivity (b) seismic velocity anomaly in Fukao et al. (2004). Two horizontal black lines in each map indicate the upper and lower boundaries of the mantle transition zone.

(1989), which was also used in Xu et al. (2000) for conversion of temperature to the depth profile, and in Fukao et al. for conversion of physical anomaly to temperature anomaly. Water content c_w (weight% H_2O) is estimated by using c (atom/m^3) as c_w / 100 = $(c/N_A/2) * M_{water} / d$, where N_A, M_{water} and d are the Avogadro's number 6.02x10^{23}(atom/mol), a molecular weight of H_2O 18(g/mol) and a density of wadsleyite 4x10^6(g/m^3), respectively. Although we cannot preclude that the Mariana anomaly may be partly affected by a temperature anomaly, we assume that the Mariana anomaly is caused only by hydrogen, for reasons of simplicity, limitations in resolving power, and differences in the resolution length scales between the seismic and conductivity data.

Very recently, Hae et al. (2006) measured the diffusivity of hydrogen in wadsleyite at high pressure (15–16 GPa) and temperature (900–1200 °C) with a Kawai-type multi anvil. The measured diffusivity D is $D = 9.6 \times 10^{-6}$ exp [-123 (kJ mol^{-1}) / RT]. With this value for D by following eq. (6), we estimate the water content in the upper transition zone beneath Mariana to be about 0.3 weight % H_2O (Fig. 6).

Recently, Huang et al. (2005) measured the electrical conductivity of hydrous wadsleyite and ringwoodite at pressure of 14–16 GPa and temperature of 500–1000 °C, and found the relationship between the electrical conductivity σ and water content c_w (weight% H_2O),

$$\sigma = A c_w^{\,r} \exp(-H^*/RT), \tag{7}$$

where H^*(kJ/mol) is activation enthalpy, and A(S/m) and r are experimental constants, 88(kJ/mol), 380(S/m) and 0.66 for wadsleyite, 104(kJ/mol), 4070(S/m) and 0.69 for ringwoodite, respectively. R is the gas constant. T is the temperature, just the same as one in eq. (6). In this paper, just the laboratory measurement was simply accounted and the oxygen coefficient correction was not adapted, although it is assumed by Huang et al. (2005). Unlike eq. (6), r is not unity, and then electrical conductivity is not linearly related to water content. Huang et al. suggested that it means that not all hydrogen atoms are free and a ratio of free hydrogen atoms decreases as the water content increases. If this relationship by Huang et al. (2005) is adapted to the electrical conductivity structure beneath the Pacific, the water content could be about 2.3 weight %.

5. DISCUSSION

We discuss the water content anomaly in the mid-mantle beneath the Marianas estimated in the previous section. The value of 0.3 weight % H_2O is well below the saturation limit of water in wadsleyite of about 3 weight % H_2O (Kohlstedt et al., 1996).

The water in wadsleyite decreases P wave velocity Vp. The dependency of the bulk modulus on water content in wadsleyite is found to be -2 to -4 (%)/(weight% H_2O) (Yusa and Inoue, 1997). For ringwoodite (Jacobsen et al., 2004), the dependency of Vp on H_2O is (-0.4 (km/s)/(weight % H_2O). Because the anelastic effect of water on Vp is unknown, only the anharmonic effect is included in the above evaluation (Karato, 1993, 2003). According to this water effect on Vp,

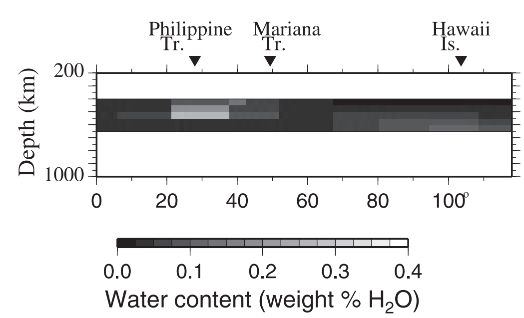

Fig. 6. Water content anomalies in the upper mantle transition zone derived from the electrical conductivity anomalies in Fig 5(a) by using the Nernst-Einsnstein relationship combining with the laboratory measurement of diffusivity of hydrogen in wadsleyite by Hae et al. (2006). A unit is weight % H_2O.

0.3 weight % H_2O decreasess Vp by 0.3–0.6 %, consistent with the small anomaly in the seismic velocity structure (Fig. 5). Thus 0.3 weight % H_2O is feasible to explain both electrical conductivity and seismic velocity anomalies in the mid-mantle beneath Mariana.

However, the 2.3 weight % H_2O estimated by using the Hunag et al (2005) relationships seem inconsistent with the result of seismic tomography. If this inconsistency is a consequence of having ignored temperature anomalies, the temperature should be about 300K lower than the reference model to explain the seismic structure in the presence of this amount of water (see Suetsugu et al., in this volume). It, however, should require much more water to explain the electrical conductivity with lower temperature and water content exceeds its limit solved in wadsleyite. Then thermal effect cannot explain the both anomalies of seismic and electrical structure including water according to the relationship of Huang et al. (2005).

Therefore if a relationship by Huang et al. (2005) is correct, other mechanisms than water and thermal effects must be considered to explain both seismic and electrical conductivity structures in the future work.

Fig.7 shows the temperature dependency of the electrical conductivity inferred from the laboratory measurement by both Hae et al. (2006) and Huang et al. (2005), that is, experimental relationship of eqs. (6) and (7) in which water content is supposed to 0.1 weight % H_2O. This figure indicates the both estimations of the electrical conductivity are not very different in the temperature range where the measurements were conducted in the laboratories. Therefore large discrepancy of estimation of water content may be caused by extrapolation of the temperature dependency. Therefore laboratory measurements of both hydrogen diffusivity and electrical conductivity at the condition of the mantle transition zone are aspired to estimate the water content more precisely. Non linear relationship between electrical conductivity and water content, that is, the fact that *r* in eq. (7) is not unity may be true, and this coefficient is also required to be measured in the mid-mantle condition.

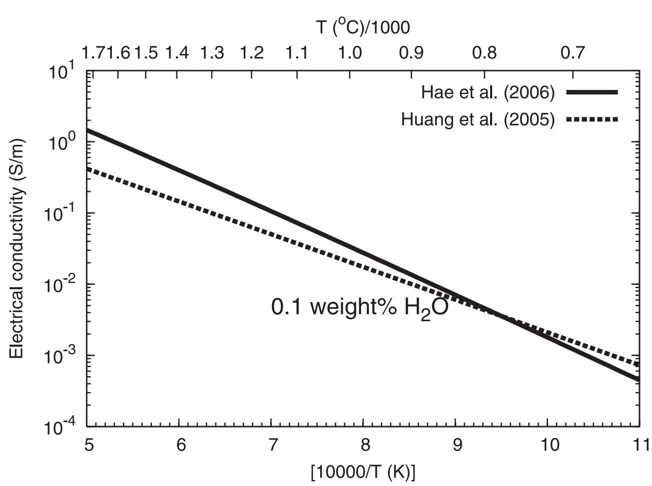

Fig. 7. Arrhenius's plots of electrical conductivity of hydrous wadsleyite inferred from laboratory measurement. Bold line shows temperature dependency of electrical conductivity derived from Hae et al. (2006), that is eq. (6). Dashed line shows one derived from Huang et al. (2005), that is eq. (7). Water content is supposed to 0.1 weight% H_2O.

Combined with other geophysical information such as seismic velocity structure and laboratory studies, electrical conductivity can provide important information on the deep Earth's interior, including the distribution of water. To elucidate further details on the electrical conductivity structure in the whole Earth's mantle, the efforts should be paid to install and maintain the long term measurement of geoelectrical and geomagnetic field on land and on the sea floor, including geomagnetic measurement by long life satellites.

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