Three-dimensional electrical conductivity structure beneath the Philippine Sea using three-dimensional marine MT inversion dealing with topographic effect

Noriko Tada[1, 2] , Kiyoshi Baba[2] and Hisashi Utada[2]
[1]Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
[2]Earthquake Research Institute, The University of Tokyo

SUMMARY

We performed three-dimensional (3-D) inversion analysis for a data set of seafloor electromagnetic (EM) survey in the Philippine Sea and in the western edge of the Pacific Ocean. The EM data were obtained using ocean bottom electromagnetometers (OBEMs) at 25 sites. The data obtained have been analyzed based on a magnetotelluric (MT) method. The seafloor bathymetry and land/ocean distribution are known to significantly affect the EM data observed by OBEMs because of high contrast in the conductivity between seawater and crustal rocks. Thus, we have developed new 3-D inversion scheme for marine MT data, which can treat both regional large-scale and local small-scale topography. The best electrical conductivity model shows four features. (1) The conductivity of the Philippine Sea mantle is higher than that of Pacific mantle shallower than 200 km depth, and become almost equal to that of Pacific mantle in deeper parts. (2) A conductive anomaly is located at around 125 km depth beneath the Sikoku and Parece-Vera Basins. (3) A resistive anomaly is located at around 40 km depth beneath the Daito and Oki Daito ridges. (4) A resistive anomaly is located at shallower than 240 km at the northern part of the Shikoku Basin.

Keywords: Marine magnetotellurics, 3-D inversion, Topographic effect, Upper mantle, Stagnant slab

INTRODUCTION

The Western Pacific area is a field of significant mantle downwelling. The old Pacific Plate (125~150 Ma) subducts at the Kurile-Japan, Izu-Bonin, and Mariana trenches. The Pacific slab penetrating into the mantle beneath the back-arc regions was imaged as high-velocity anomaly by seismic tomography, and the high-velocity anomaly tends to be distributed horizontally in the mantle transition zone, which is called stagnant slab (Fukao et al. 2001). The stagnation mechanism plays important role in mantle dynamics, but this mechanism is not fully understood so far.

A collaborative experiment of seafloor electromagnetic (EM) observations and seismic observations was conducted in the Philippine Sea and on the western edge of the Pacific as a part of the Stagnant Slab Project (Shiobara et al. 2009). The EM observations aim to image electrical features of the stagnant slab and the surrounding mantle in three-dimensions (3-D). Resultant electrical conductivity structure will be compared with other physical properties (e.g., seismic velocity, experimental study of mantle mineral rocks under high pressures) in order to reveal the stagnation mechanism. Baba et al. (2010) analyzed the obtained EM data, based on magnetotelluric (MT) method. They also obtained representative one-dimensional (1-D) conductivity models beneath the Philippine Sea Plate and beneath the Pacific Plate as the first step of the imaging of the mantle conductivity. As the next step, we inverted the data in 3-D to investigate the lateral heterogeneity in the mantle beneath the observation array.

However, several technological difficulties that hamper inversion of marine MT data must be overcome to obtain accurate 3-D electrical conductivity images at a regional mantle scale. Topographic effect is one of a crucial issue for a long time. The EM fields observed on the seafloor are generally distorted by rugged seafloor topography and land/ocean distribution because of large contrast in the conductivity between seawater and crustal rocks (Schwalenberg and Edwards 2004). For an accurate estimation of deep mantle conductivity distributions in 3-D, these topographic effects have to be properly and accurately taken into account in inversion analysis. In reality, topography variations occur over a wide range of horizontal scales from local (~100 m) to regional (~1000 km) with amplitudes of only a few kilometers. In this study, we will introduce a scheme of the 3-D marine MT inversion which can treat whole scale topographic variations, and show a 3-D electrical conductivity structure beneath the Philippine Sea plate and the western Pacific plate as a result of the inversion analysis.

DATA

Figure 1 shows the location of marine MT sites which we have used for inversion analysis. Ocean bottom electromagnetometers (OBEMs) were settled at 25 sites and observed three components of magnetic field and two-components of electric field (Baba et al. 2010; Baba et al. 2005; Seama et al. 2007; Utada et al. 2005). 21 sites of all sites were located on the Philippine Sea Plate, while 4 sites were on the Pacific Plate. MT impedance tensors for 24 sites were analyzed by Baba et al. (2010) and impedance tensor for the other one site (T08) was also calculated in the same way. In this study, we used full MT impedance tensors for 13 periods from 960 to 61,440 seconds except for xy- and yy-components longer than 10,000 seconds, because the MT responses of xy- and yy-components show discontinuous change around 10,000 seconds. This is probably due to the imperfect removal of Quasi-periodic solar daily variation (Sq) and its higher harmonics (Utada et al., 2008).

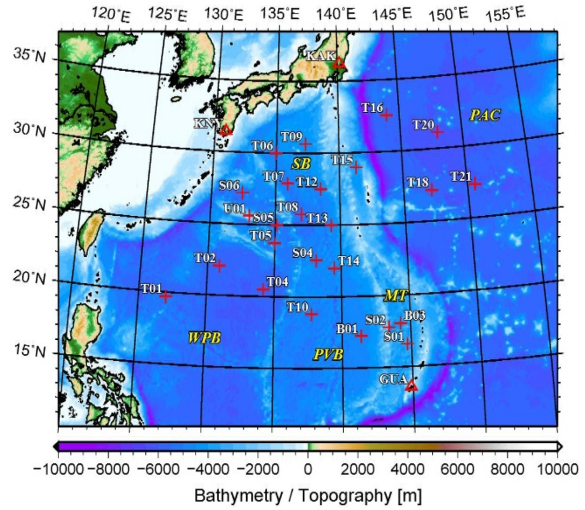

Figure 1. Location of the marine MT sites (red crosses) superimposed on a bathymetric map. Red triangles indicate the geomagnetic observations from which data were used as remote references for the response estimation. PAC, Pacific Plate; MT, Mariana Trough; SB, Shikoku Basin; PVB, Parece Vela Basin; WPB, West Philippine Basin.

The topographic change around the observation array, which is known information, was incorporated as conductivity structure into inversion analysis and was used for estimation of small-scale topographic effect. The topographic model was produced from 2-minute mesh ETOPO2 (NOAA) and finer 250 m mesh data near the observation stations based on multi-narrow beam soundings which were collected by research cruises of Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

INVERSION ANALYSIS

Three-dimensional inversion is carried out using the algorithm of Baba et al. (Submitted) which modified the algorithm of Tada et al. (2012), hereafter referred to as WSINV3DMT with Approximate Treatment of Topography (ATT), in order to treat local and smaller-scale topographic effects. The WSINV3DMT with ATT is based on the inversion developed by Siripunvaraporn et al. (2005) with expansions to incorporate the topography in the model and to calculate the MT response on the seafloor. To keep computational cost moderately, the WSINV3DMT with ATT treats topography with a length scale larger than the horizontal mesh used for inversion calculation. However, small-scale surface heterogeneities such as the semi-linear abyssal hills and valleys, which have length scales smaller than the horizontal mesh, also influence impedance tensors. Thus we use the inversion scheme proposed by Baba et al. (Submitted) which considers the effects of both regional large-scale and local small-scale topography on deep ocean MT data.

Initial and prior models for inversion analysis are a 3-D model that the representative 1-D conductivity models of Philippine Sea mantle and Pacific mantle obtained by Baba et al. (2010) are combined along the Japan, Izu-Bonin, and Mariana Trenches. Because these two models are significantly different each other in terms of the thickness of the upper resistive layer though to be lithosphere. We assumed mean conductivity for seawater of 3.2 Sm^{-1}. We calculated electrical conductivity in each numerical block including the seafloor or land surface so as to conserve the horizontal conductance in order to incorporated large-scale topography into the initial and prior models (Tada et al., 2012).

The entire dimension of the computational region of inversion analysis was the horizontal area of 5500 × 5500 km^2 and basal depth of 1026 km below the sea surface. The central 2525 × 2525 km^2 area was discretized every 50 km and the outer area was discretized more coarsely as getting away from the center in the horizontal directions. The vertical meshes were discretized every 1 km near seafloor and became wider as getting deeper.

We applied initial error floors of 25.0 % and 2.5 % for the diagonal and off-diagonal elements of the MT impedance, respectively. Once the inversion had converged on the almost constant root mean square misfit (RMS) of the data, the values of error floors for the off-diagonal elements were reduced to 5.0 %. We set the maximum number of iteration for each inversion step was 10.

The effect of local small-scale topography is evaluated by the local topographic distortion term $\mathbf{D}^{\mathrm{lt}}(\mathbf{r},T)$ in the inversion scheme proposed by Baba et al. (Submitted). They assumed that the MT response $\mathbf{Z}(\mathbf{r},T)$ is approximately equal to the MT response to the total structure $\mathbf{Z}^{\mathrm{ts}}(\mathbf{r},T)$, expressed by multiplication of $\mathbf{D}^{\mathrm{lt}}(\mathbf{r},T)$ by the response to the regional structure $\mathbf{Z}^{\mathrm{rs}}(\mathbf{r},T)$ that consists of regional topography over the mantle electrical conductivity structure,

$$\mathbf{Z}(\mathbf{r},T) \approx \mathbf{Z}^{\mathrm{ts}}(\mathbf{r},T) = \mathbf{D}^{\mathrm{lt}}(\mathbf{r},T)\mathbf{Z}^{\mathrm{rs}}(\mathbf{r},T), \qquad (1)$$

where $\mathbf{r}$ is position and T is period. $\mathbf{Z}$, $\mathbf{Z}^{ts}$, $\mathbf{D}^{lt}$, and $\mathbf{Z}^{rs}$ are all 2×2 complex tensors and hereafter their dependence on $\mathbf{r}$ and T will be implicit.

To estimate distortion matrix, $\mathbf{D}^{lt}$, we separately obtained $\mathbf{Z}^{ts}$ by using a 3-D forward program, FS3D (Baba and Seama, 2002). The background electrical conductivity structure of the forward modeling was the same as the initial model for the inversion analysis, and the computational area of the forward program was also same as that of the inversion analysis. To describe topographic variation near MT site accurately, the central 7×7 km^2 area was discretized every 1 km.

RESULTS AND DISCUSSION

We obtained the best model with the minimum RMS data misfit, 3.84, at the second iteration through the seventh inversion step (Figure 2). For the first three inversion steps, the error floors for off-diagonal elements of MT impedances were set to be 25%. After the inversion was converged in the third step, the values of error floors for off-diagonal elements were reduced to 5.0%. Again the inversion was converged in the seventh step, and the minimum RMS misfit was obtained at the second iteration in the step.

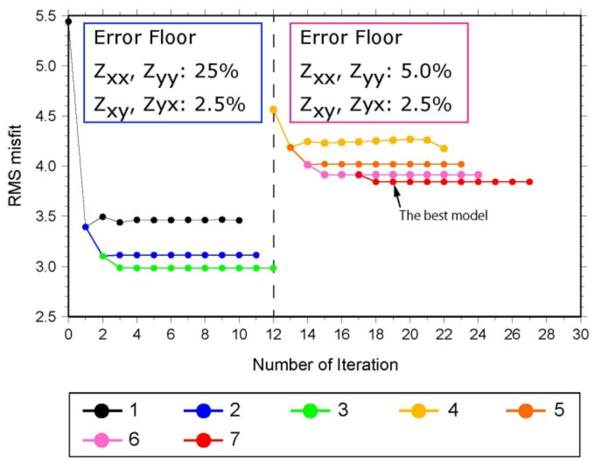

Figure 2. RMS misfit versus number of iteration for the inversion analysis. Color indicates an inversion step.

We recalculated distortion tensor for the best model, $\mathbf{D}^{lt\prime}$, in order to evaluate the effect of electrical conductivity structure beneath the seafloor on the distortion tensor.

We proceeded the inversion analysis using $\mathbf{D}^{lt\prime}$ and the best model as initial and prior models. The electrical conductivity model obtained using $\mathbf{D}^{lt\prime}$ is almost the same as the best model obtained using $\mathbf{D}^{lt}$. The differences of resistivity values between the two models are within 0.1 in most regions and at most 0.2 on a logarithmic scale of resistivity. Although at sites on rough topography, values of distortion matrix at periods shorter than 10,000 seconds have big differences between the two models, they make no difference to electrical conductivity structures. Then, we have concluded that the distortion matrix can ignore an effect of an electrical conductivity structure beneath the seafloor.

We examined resolution of the best model using checkerboard pattern models. We added perturbation of ±0.5 on a logarithmic scale of resistivity for the best model. Synthetic MT responses were calculated from the checkerboard pattern models, and were added 2.5% Gaussian noise. We inverted the synthetic MT responses as we inverted the observed MT responses. Initial and prior models for the checkerboard test were the same as the best model. In case the size of checkerboard pattern was 500 km × 500 km, the electrical conductivity model with the minimum RMS misfit recovered the true structure shallower than 250 km depth, especially around EM sits. But in case the size was 300 km × 300 km, the electrical conductivity model with minimum RMS misfit didn't recover the true structure. From these resolution tests, the best model has 500 km × 500 km resolution shallower than 250 km at least.

Figure 3 shows the best electrical conductivity model obtained from this study. There are four big features in the best model. (1) The conductivity of the Philippine Sea mantle is higher than that of Pacific mantle shallower than 200 km depth, and become almost equal to that of Pacific mantle in deeper parts. This feature is consistent with 1-D conductivity models by Baba et al. (2010). (2) A conductive anomaly is located at around 125 km depth beneath the Sikoku and Parece-Vera Basins. The center of this anomaly is positioned beneath T10 site on the Parece-Vera Basin. (3) A resistive anomaly is located at around 40 km depth beneath the Daito and Oki Daito ridges. (4) A resistive anomaly spread northeastward from T09 site might suggest the Pacific slab.

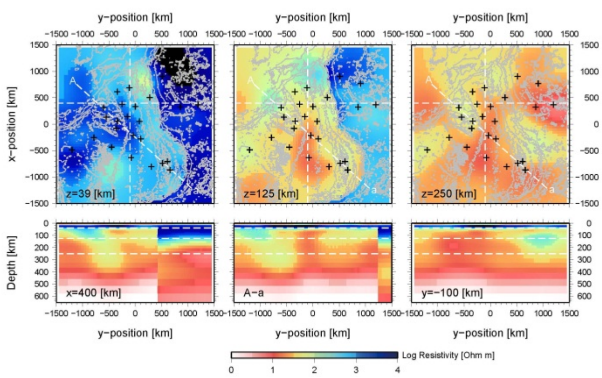

Figure 3. The best electrical conductivity model. The top panels show plane views at 39, 125 and 250 km depths, respectively. The bottom panels show cross-section views. Gray lines indicate bathymetric feature. Black crosses indicate MT sites. White dashed lines

indicate the position of plane views or cross-section views.

CONCLUSIONS

We have applied 3-D marine MT inversion which can treat both regional large-scale and local small-scale, topography to 25 data obtained on the Philippine Sea plate and the western edge of the Pacific plate to the inversion, and obtained 3-D electrical conductivity model. The distortion matrix which relate to small-scale topography can ignore an effect of an electrical conductivity structure beneath the seafloor. The best electrical conductivity model has 500 km × 500 km resolution shallower than 250 km at least according to the resolution tests. The best model shows four features. (1) The conductivity of the Philippine Sea mantle is higher than that of Pacific mantle shallower than 200 km depth, and become almost equal to that of Pacific mantle in deeper parts. (2) A conductive anomaly is located at around 125 km depth beneath the Sikoku and Parece-Vera Basins. (3) A resistive anomaly is located at around 40 km depth beneath the Daito and Oki Daito ridges. (4) A resistive anomaly is located at shallower than 240 km at the northern part of the Shikoku Basin.

ACKNOWLEDGMENTS

The bathymetry data based on multi-narrow beam sounding that we used in this study were provided by the JAMSTEC Data Site for Research Cruises. All figures were produced using GMT software (Wessel and Smith, 1998). This work was supported by grants 16075204 from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. This work was also supported by Grants-in-Aid for Scientific Research 220003 and 23740346, Japan Society for the Promotion of Science (JSPS). For this study, we used the computer systems of the Earthquake Research Institute, the University of Tokyo.

REFERENCES

Baba, K., Tada, N., Utada, H., and Siripunvaraporn, W., Practical incorporation of local and regional topography in three-dimensional inversion of deep ocean magnetotelluric data, *Geophys. J. Int.*, submitted.

Baba, K., Utada, H., Goto, T., Kasaya, T., Shimizu, H., and Tada, N., 2010, Electrical conductivity imaging of the Philippine Sea upper mantle using seafloor magnetotelluric data, *Physics of the Earth and Planetary Interiors*, **183**, 44-62.

Baba, K., Seama, N., Goto, T., Ichiki, M., Schwalenberg, K., Utada, H., and Suyehiro, K., 2005, Electrical structure of the upper mantle in the Mariana subduction system, *IFREE report 2003-2004. Frontier Research on Earth Evolution 2*.

Baba, K., and Seama, N., 2002, A new technique for the incorporation of seafloor topography in electromagnetic modelling, *Geophys. J. Int.*, **150**, 392-402.

Fukao, Y., Widiyantoro, S., and Obayashi, M., 2001, Stagnant slabs in the upper and lower mantle transition region, *Rev Geophys* **39**, 291-323

Schwalenberg, K., and Edwards, R. N., 2004, The effect of seafloor topography on magnetotelluric fields: an analytical formulation confirmed with numerical results, *Geophys. J. Int.*, **159**, 607-621.

Seama, N., Baba, K., Utada, H., Toh, H., Tada, N., Ichiki, M., and Matsuno, T., 2007, 1-D electrical conductivity structure beneath the Philippine Sea: results from an ocean bottom magnetotelluric survey, *Phys Earth Planet Int*, **162**, 2-12.

Shiobara, H., Baba, K., Utada, H., and Fukao, Y., 2009, Ocean bottom array probes stagnant slab beneath the Philippine Sea, *Eos Trans. AGU*, **90**, 70-71.

Tada, N., Baba, K., Siripunvaraporn, W., Uyeshima, M., and Utada, H., 2012, Approximate treatment of seafloor topographic effects in three-dimensional marine magnetotelluric inversion, *Earth, Planets and Space* **64**, 1005-1021.

Utada, H., Hibiya, N., Uyeshima, M., Shimizu, H., Mikada, H., Goto, T., and Kawaguchi, K., 2005, An experimental study of the Earth's electric field, *Report of grant-in-aid for scientific research*, No.14204041 (in Japanese).

Wessel, P., and Smith, W. H. F., 1998, New, improved version of the generic mapping tools released, *Eos Trans. AGU*, **79**, 579.