Electrical structure of the upper mantle in the Mariana subduction system

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1. Introduction

The Mariana region, the eastern most part of the Philippine sea plate, is a predestinated area for investigating the mantle dynamics of subduction – oceanic island arc – back arc systems. The Pacific plate is subducting beneath the Philippine sea plate in northwest direction with the relative rate of 35– 45 mm yr^{-1} at 19°N [*Kato et al.*, 2003]. The recent volcanic front is the Mariana Island chain. The fore arc region is characterized by island origin sediments and serpentinite mud volcanoes. The Mariana Trough is an active back arc basin since ~6 Ma [*Iwamoto et al.*, 2002]. The spreading rate of the central Mariana Trough is slow (< 25 mm yr^{-1} half spreading rate) and asymmetric with a faster spreading in westward direction. The west Mariana Ridge is thought to be a remnant volcanic arc separated from the Mariana island arc by the opening of the Mariana Trough.

For studies of mantle dynamics associated with subducting slabs, the temperature distribution is the primary information. In addition, there is a general agreement that water carried into the mantle by the subduction process plays a key role for volcanic activity, back arc spreading, and rheology of the wedge mantle. The properties of the mantle can be imaged using geophysical methods. Electromagnetic methods have become a standard tool and have been often applied as a complementary approach to seismic method.

The electrical conductivity is a parameter which can constrain the state of the mantle. The conductivity of mantle materials depends strongly on temperature, on composition (including the degree of mantle hydration) and on the melt fraction, provided that the melt forms in an interconnected network. The subsolidus conductivity of dry mantle rocks is a strong function of temperature, and has been accurately determined in the laboratory [e.g., *Constable et al.*, 1992; *Xu et al.*, 2000]. The conductivity of olivine is thought to be substantially enhanced by the presence of water in the form of dissolved hydrogen [*Karato*, 1990]. The intrinsic conductivity of basaltic melt is many orders of magnitude higher than that of the host mantle rock [*Roberts and Tyburczy*, 1999], but the manner in which partial melting impacts bulk conductivity depends on the geometry and interconnectedness of the melt pockets.

To image the conductivity structure of the upper mantle beneath the region, a marine magnetotelluric (MT) experiment was conducted in 2001–2002. The observation array is a line along the spreading direction (N75°E) of the Mariana trough at 18°N and covers the Pacific to the Parece-Vela basin through the Mariana Trough (Fig. 1). Ten ocean bottom electromagnetometers (OBEMs) were deployed during YK01-11 Yokosuka cruise, September 26th – October 15th, 2001 [*Goto et al.*, 2002]. Two OBEMs at sites 8 and 9 were recovered in April 2002, with R/V M. Ewing, and three OBEMs at sites 1, 3, and 11 were recovered during KR02-14 Kairei cruise, October 28th – November 12th, 2002 [*Seama et al.*, 2003]. The recovery of the remaining OBEMs was, unfortunately, not successful because of problems with the anchor release systems.

2. Data and data analysis

In this study, the data at five sites collected in the 2001–2002 experiment and data at three sites collected in previous experiments [*Filloux*, 1983; *Seama et al.*, 2004] have been jointly analyzed. Time-series of the electromagnetic field data from our experiment have been processed and the MT responses (transfer functions between electric and magnetic fields) with jackknife errors were obtained for each observation site using a robust estimation method [*Chave and Thomson*, 1989]. The responses at sites 9 and 11 have been estimated using magnetic field data at each site and the electric field data at site 3, because of the lack of the electric field data at sites 9 and 11. The additional three sites from *Filloux* [1983] and *Seama et al.* [2004] are located in the western edge of the Mariana Trough (Seama2), about 30 km west from the trough axis (Filloux1), and the forearc basin (Filloux2), respectively (Fig. 1). For Filloux1 and Filloux2, we reprocessed the time series data and estimated MT responses as described above. The MT response at Seama2 are provided by *Seama et al.* [2004].

The obtained MT responses are corrected for the topographic effect and inverted using the method of Baba and *Chave* [2005]. The topography in the area changes significantly through the Mariana Trench (~7000 m) and the active and remnant volcanic arcs (above sea level at some volcanoes). Moreover, in the Mariana Trough, small scale trough parallel lineations and inner corner highs along the ridge segment boundaries can be distinguished (Fig. 1). Both the large and small scale topographic changes are taken into account for the correction. The bathymetric data plotted in Figure 1 are re-discretized with a finer mesh resolution (1-1.5 km) around the observation sites. The area of 3950 × 4650 km centering on the survey area is incorporated into the model for the topographic effect simulation.

The corrected responses are plotted in Figure 2. The tensor decomposition analysis accounting for the electric and magnetic galvanic distortions [*Chave and Smith*, 1994] shows that the responses are predominantly two-dimensional (2D) with a modal regional strike along the direction of the trough axis (N15°W). Hence, *xy* and *yx* elements of the responses are regarded as TE (strike aligned electric field) and TM (strike aligned magnetic field) modes, respectively. In general, the apparent resistivities are higher at the short periods and decrease with increasing periods (Top panels in Fig. 2). This leads to the assumption that the mantle beneath the Pacific and the Philippine sea is conductive and overlain by a resistive lid. The TM mode apparent resistivities at site 8 (53 km east from the trough axis) are abnormally low compared to those at the other sites. This is probably due to the effect of near surface structural inhomogeneities embedded in the sediments which cause a static shift. The TM mode phases at site 9 (111 km east from the trough axis) vary significantly at shorter periods which is unlikely for a 2D structure (Right bottom panel in Fig. 2). Local 3D structures associated with the adjacent Mariana islands are a plausible explanation. Consequently, the TM mode apparent resistivity at site 8 and all the components for the period shorter than 10,000 seconds at site 9 have been excluded from the following 2D inversion analysis.

The off-diagonal terms of the corrected MT response (TE and TM modes) are inverted jointly to a model with a 4 km thick water layer and a flattened seafloor. The 2D inversion program by *Uchida* [1993] has been applied to the data. In this program, Akaike's Basian Information Criterion (ABIC) is used to find an optimal minimum structure model. A 3% error floor was applied to both the apparent resistivities and phases in the inversion. The resistivity of a few model blocks, where hypocenters have been localized, were fixed to 1000 Ωm during the inversion. This assumption is reasonable because the subducting Pacific plate is very old (~150 Ma) so that it is thought to be cold and resistive. Further, fixing the resistivity leads the inversion models to be more realistic because it is essentially difficult to resolve resistive and vertically long bodies from MT data alone. The consideration of the a *priori* information provides a better convergence in the inversion with smaller ABIC and RMS misfits than without the information.

3. Results and discussions

The resultant 2D model is shown in Figure 3. The resistivity model fits the data moderately with a RMS misfit of 3.36. The seismic P-wave tomography model from *Obayashi and Fukao* [2001] is also shown in Figure 3. We compared the P-wave and resistivity models below 200 km, since the P-wave structure is poorly resolved above 200 km. The main features of the resistivity models are: 1) a conductive mantle is overlaid by a resistive lid. 2) Below ~70 km, the mantle in the back arc is about 3 times more conductive than the Pacific mantle. 3) At the depths between 150 and 350 km, the mantle in vicinity of the slab (~-250 to ~-50 km and ~200 to ~350 km from the trough axis) is relatively more conductive than away from the slab (< ~250 and > ~350 km from the trough axis). The second and third features are also seen in the P-wave structure: The Philippine sea mantle is slower than the Pacific mantle and the area immediately east and west of the slab is relatively slower than the area away from the slab.

The first feature can be the result of the water redistribution due to the partial melting process beneath the Mariana Trough axis. The calculated resistivities of about 100 Ωm are comparable to the resistivity of dry mantle peridotite [*Xu et al.*, 2000]. The thickness of such resistive layer is about 70 km and the basal depth agrees approximately with the depth of the dry solidus of mantle peridotite [e.g., *Hirth and Kohlstedt*, 1996]. Moreover, it is too deep to be interpreted as a thermal boundary inferred from plate cooling models for such a young seafloor. The obtained resistivity model can be explained by the following scenario: Water that is dissolved in mantle peridotite is extracted into melt due to the partial melting processes. Then, the mantle is dried out and spreads in westward direction of the trough axis. *Baba et al.* [2004] and *Evans et al.* [2005] discussed a similar scenario studying the super fast spreading southern East Pacific Rise. The results suggest that the mantle conductivity is mainly controlled by the composition rather than the temperature in the seafloor spreading regimes.

The second feature may be the key to understand mantle dynamics associated with the plate subduction, because it may be related to the different properties of the back arc mantle compared to a normal mantle. This was carefully tested by forward modeling. In two subsequent tests, the resistivities of the Philippine sea mantle and the Pacific mantle were changed in order that they both have the same level. First, the resistivity of the Philippine sea mantle (the area surrounded by a blue line in Fig. 3) was multiplied by 3. Second, the resistivity of the Pacific mantle (the area surrounded by a red line) was divided by 3. Figure 4 shows the respective responses for sites 3 (50 km west from the trough axis) and Filloux2 (206 km east from the axis). In either case, the modified model responses do not fit the data as compared with the "best" model response. The changes in the mantle resistivity significantly affect the responses of the sites over the modified areas. Consequently, the differences in the resistivity between the Philippine sea mantle and the Pacific mantle are required by the data.

The mantle temperature and its water content cannot be estimated independently from the resistivity structure alone, but may be estimated by comparing the resistivity structure and the seismic P-wave structure. *Ichiki et al.* [2004] developed a method to separate water content and temperature using the electrical conductivity structure and seismic P-wave velocity structure. In this study, we apply *Ichiki et al.* [2004]'s method assuming a pyrolitic mantle composition. The temperature is estimated from the P-wave structure because P-waves are dominantly dependent on the temperature but poorly on small amounts of water [*Karato*, 1993]. The water content is estimated from the electrical conductivity structure using thus obtained temperature structure. The obtained estimates of the temperature and lower bounds of the water content are shown in the Figure 5. The results show that the Philippine sea mantle is about 100°C hotter than the Pacific mantle. To explain the resistivity model, water at least ~100 ppm H/Si is required for both the Philippine sea and the Pacific mantles. The difference in the water contents between the two mantles is unresolved because the range of estimated water content is very wide (~100–~2000 ppm H/Si), although the lower bounds are slightly higher for the Philippine sea mantle. The relatively high conductive regions immediately east and west of the slab can be interpreted as the high temperature anomaly. The temperature is about 50 °C higher compared to the regions away from the slab. The lower bounds of water content are almost the same between the regions east and west of the slab and it is lower (higher) than that in the region far west (east) from the slab (Fig. 5). The excess water is not required to explain the enhanced conductivity near the slab.

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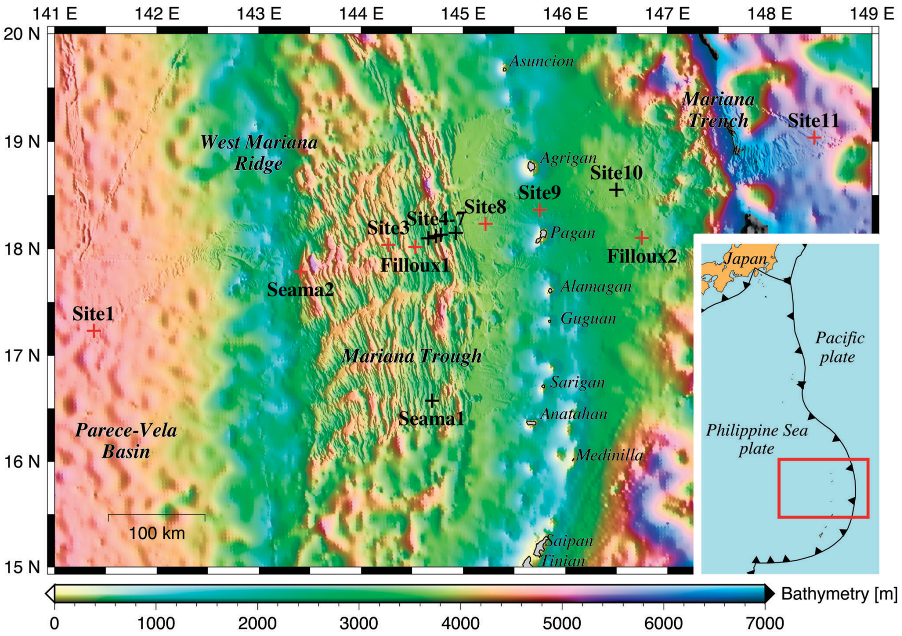

Figure 1. Bathymetry map of the Mariana region. The map was created by combining multi-beam data with the predicted bathymetry from *Smith and Sandwell* [1994]. Crosses are the site locations. Redden crosses indicate that these data are utilized for the analysis in this study. The sites labeled Seama1, Seama2, Filloux1, and Filloux2 are collected by *Seama et al.* [2004] and *Filloux* [1983]. The inset shows the location of the experiment area (red box) and plate boundaries (black lines with triangles).

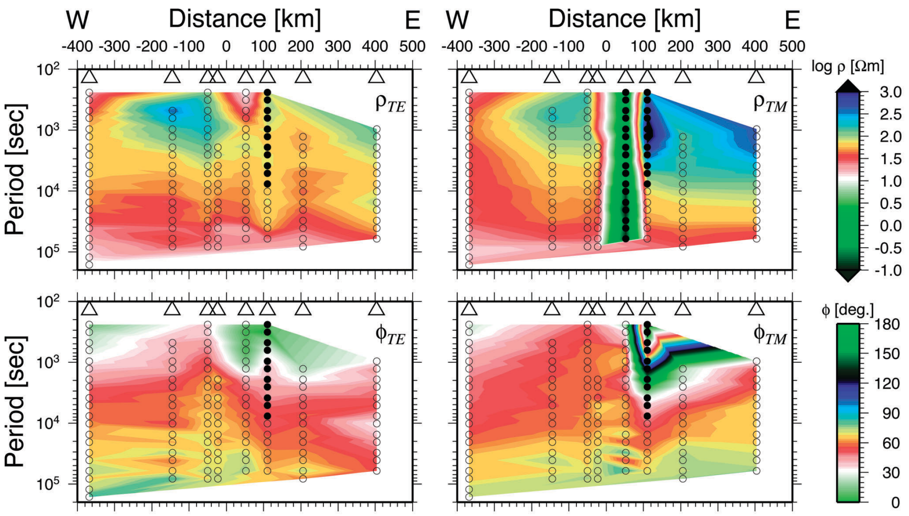

Figure 2. Pseudo-sections of the MT responses which are corrected for the topographic effect. The horizontal axis is the distance from the Mariana Trough axis (the right is the east). Triangles indicate the site locations. Circles are the data points. Solid circles are the points not applied to the inversion.

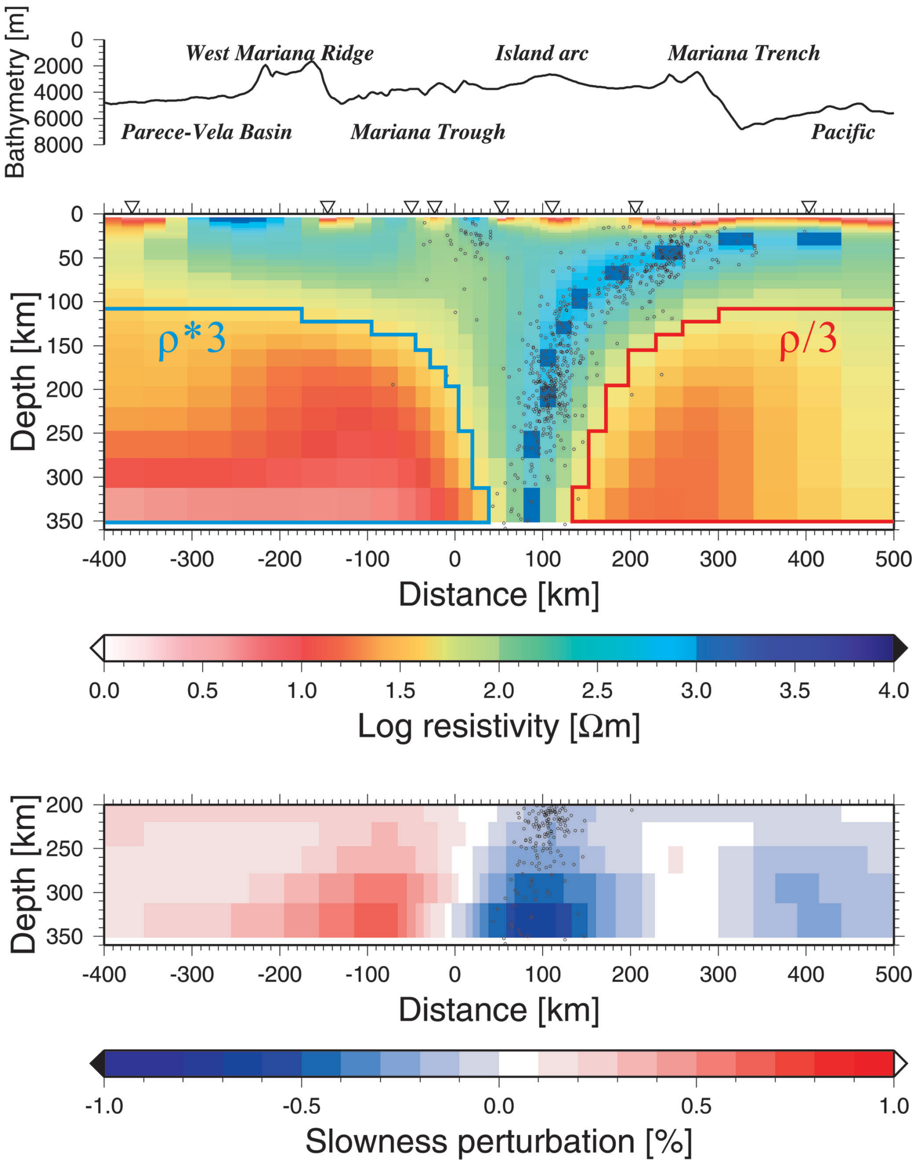

Figure 3. 2D resistivity model obtained by inversion. The horizontal axis is the distance from the Mariana Trough axis. Triangles indicate the site locations. Dots are hypocenters. For the sensitivity tests, the resistivity in the area surrounded by blue or red lines have been multiplied or divided by 3, respectively (See text for detail). The bathymetry along the profile is shown at the top. Seismic P-wave tomography model from *Obayashi and Fukao* [2001] is shown at the bottom.

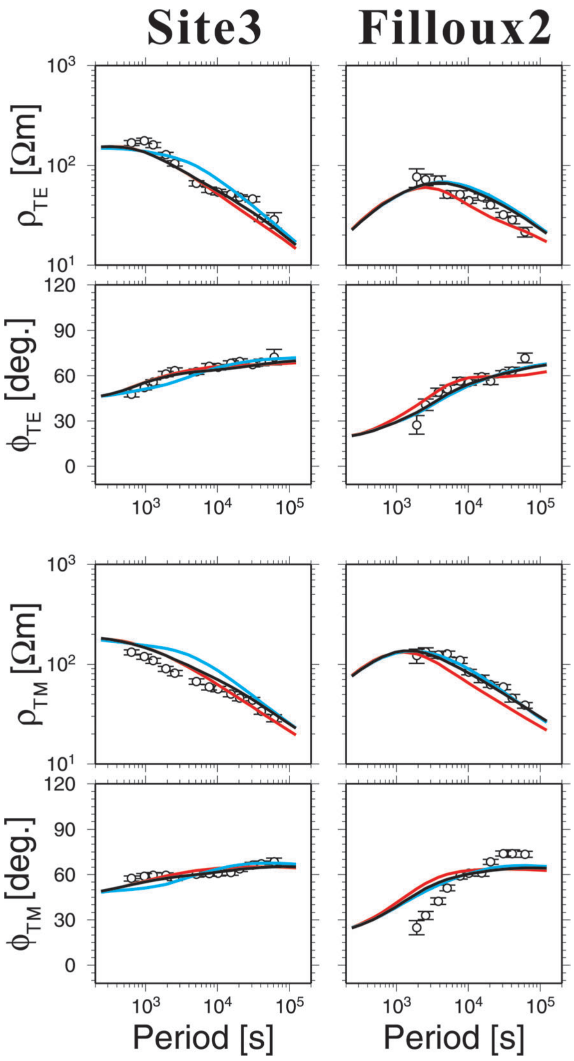

Figure 4. The MT responses at sites 3 and Filloux2. Circles with error bars are the observed responses after the topographic effect correction. Black, blue, and red lines are the model responses for the "best" inversion model, for the model when the Philippine sea mantle is 3 times more resistive, and for the model when the Pacific mantle is 3 times more conductive.

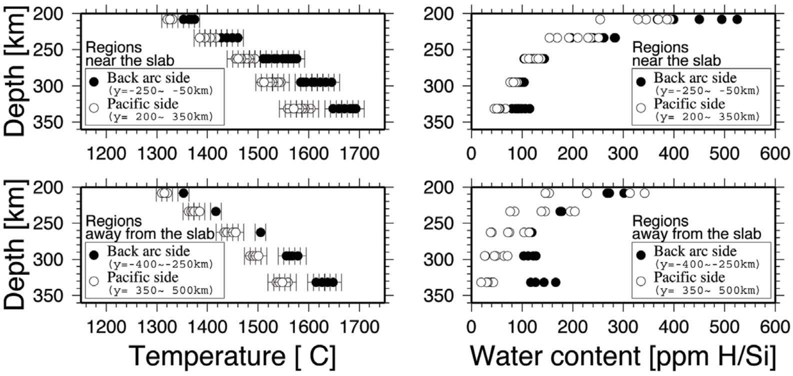

Figure 5. Temperature distributions estimated from the P-wave structure (left) and water contents from the temperature and electrical conductivity structure (right). Top panels are the values in the relatively high conductivity and low velocity regions (between -250 and -50km and between 200 and 350km from the trough axis). Bottom panels are the values between -400 and -250km and between 350 and 500km. The error bars of the temperature indicate the possible range based on Hashin-Shtrikman bounds of the P-wave velocity. Only lower bounds are plotted for the water content for simplicity because the bounds of the conductivity are very wide.