Three-dimensional inversion analysis of seafloor magnetotelluirc data collected in the northwestern Pacific and implications for the source of petit-spot volcanoes

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SUMMARY

Petit-spot is young volcanic activity on very old (about 130 Ma) oceanic plate characterized as a clump of small Knolls which erupted strong to moderate alkaline basalt. This volcanic field is associated with neither any plate boundaries nor hot spots. To elucidate the magma generation process of this new-type volcanic activity, marine magnetotelluric (MT) surveys were carried out using ocean bottom electromagnetometers (OBEMs) in May - August, 2005 and in May, 2007 - August, 2008. Total nine OBEMs were deployed and seven of those were successfully recovered with good quality data. We compiled data at two other sites collected in July, 2003 - November, 2004 and analyzed the nine sites data in total in this study. We first estimated a one-dimensional (1-D) electrical conductivity structure model which explains the data of all sites averagely correcting topographic effect on the observed MT responses. Then, we carried out 3-D inversion analysis using the 1-D model as the initial and prior model. The 3-D inversion program that we used is WSINV3DMT (Siripunvaraporn et al., 2005) but modified for seafloor MT data by Tada et al. (2012). The obtained 3-D model shows two distinct features. 1) The lithospheric mantle beneath the petit-spot field at 37.5ºN, 149.8ºE (Yukawa Knolls) is relatively more conductive than surrounding area. The conductivity is about 0.003 S/m at about 70 km depth. This feature is depicted as thinned resistive layer in the vertical section. 2) High conductivity (~0.1 S m^{-1}) layer at around 200 km depth is not isolated beneath the petit-spot field but rather distribute widely beneath the survey area except for the area to the northwesten area of the Yukawa Knolls. Checker board inversion and forward modeling tests support that these features are reasonably resolved by the data. The above features make us to speculate that the asthenospheric mantle is partially molten and the melt is extracted to the lithosphere (and partly to the seafloor) by the petit-spot activity. The electrical conductivity at 200 km depth can be explained by small fraction of hydrous and carbonated melt on temperature above the solidus of peridotite including H_2O and CO_2.

Keywords: marine magnetotellurics, lithosphere, asthenosphere, petit-spot

INTRODUCTION

A petit-spot is a newly recognized type of volcanic activity that is characterized by a cluster of young small Knolls not associated with mid-ocean ridges, island arc volcanism, or hot spots (e.g., Hirano et al. 2006). The first example of a petit-spot, named the Kaiko Knolls, was discovered on the oceanward slope of the Japan Trench at 39.4ºN, 144.3ºW. The plate motion was traced using ages estimated from basaltic rock samples (~6 Ma), leading to the discovery a second petit-spot, named the Yukawa Knolls, in the northwestern Pacific Ocean at 37.5ºN, 149.8º, ~600 km offshore from the Japan Trench (Fig. 1). The second petit-spot field is believed to be currently active based on the very young age of the basaltic rock samples (<1 Ma) (Hirano et al., 2006) and the detection of seismic activity in the region over the past 20 years by the Japan Meteorological Agency. A third example, the Choco-chip Knolls, was recently identified on the outer rise at 38.0ºN, 145.0ºW, a site that deviates from the line of plate motion tracking the Kaiko and Yukawa Knolls (Fig. 1) (Abe et al., 2007).

The origin of young volcanisms on old, cold, and thick oceanic plates is enigmatic, and should be elucidated. Through analyses of the distribution of the petit-spot fields and geochemical signatures of rock samples, Hirano et al. (2006) proposed a hypothesis that the asthenosphere is partially molten layer and the melt leaks through fractures due to plate bending before subduction. This hypothesis implies that, unlike other major types of volcanism on Earth, the melt generation and magma extrusion processes may be considered separately for the formation of petit-spots. Knowledge of both processes in the northwestern Pacific is limited because the basin was previously recognized as a non-

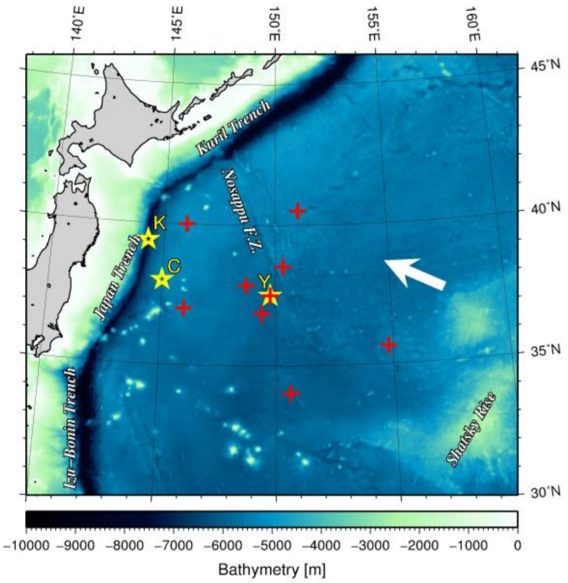

Figure 1. Location of the seafloor MT sites (red crosses) superimposed on a bathymetric map. Yellow stars indicate locations of petit-spot fields (K, Kaiko; Y, Yukawa, C, Choco-chip). White arrow indicates direction of Pacific Plate motion.

tectonic region and thus has not been explored sufficiently.

Seafloor magnetotelluric (MT) surveys are suitable for investigating melt generation fields involving petit-spot activity. The electrical conductivity of the mantle minerals depends strongly on the temperature, composition (including the degree of mantle hydration), and the fraction and connectivity of melt. Thus, the electrical conductivity model obtained from the seafloor MT data can constrain the values of one or more of these parameters when employed in conjunction with independent observations.

Investigation of the process of petit-spot volcanism in the northwestern Pacific has involved a collaborative study by various geophysical and geochemical approaches. The MT surveys conducted as a part of this study are intended to constrain the physical state of the lithosphere and asthenosphere. Two surveys were conducted in May – August, 2005 and in May, 2007 – August, 2008. Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Earthquake Research Institute (ERI), University of Tokyo supplied the surveys ocean bottom electromagnetometers (OBEMs), which were made by Tierra Technica Ltd. Total nine OBEMs were deployed and seven of those were successfully recovered with good quality data using R/Vs Yokosuka and Kairei of JAMSTEC.

DATA ANALYSIS

The raw time series obtained by the OBEMs were edited to eliminate spikes and jumps, and corrected for instrumental clock shift and tilt. The cleaned data were further processed by the bounded influence robust remote reference method (Chave and Thomson, 2004) to yield the MT impedance tensor at each site. The MT responses were estimated accurately in the period from 240 to 64,400 s.

We first estimated one-dimensional (1-D) conductivity structure model which explains the data of all sites averagely correcting topographic effect on the observed MT responses. We calculated square root of the determinant of the MT impedance tensor for each site and averaged the determinant responses among the sites. The averaged response was inverted using Occam's inversion (Constable et al., 1987) to obtain 1-D model. Then, three-dimensional (3-D) forward modeling using FS3D (Baba and Seama, 2002) was carried out for a model that consists of surface 3-D heterogeneity due to topography/bathymetry and the 1-D structure beneath the seafloor, in order to simulate the topographic effect on MT response at each site. The topographic effect was then removed from the observed MT responses and the 1-D model is estimated again using the corrected responses. This iterative procedure is based on Baba and Chave (2005).

We then conducted 3-D inversion analysis. The 3-D inversion program that we used is WSINV3DMT (Siripunvaraporn et al., 2005) but modified for seafloor MT data by Tada et al. (2012), thus the inversion can incorporate topographic/bathymetric change in conductivity structure model.

The data inverted is full elements of the observed MT responses in 11 periods (240~7,680 s) at nine sites, so that total number of data parameter is 792. We avoided using the responses for the periods longer than 10,000 s because they are likely to be affected by non-plain wave sources, such like solar daily variation (Sq) and its harmonics. We set error floors of 2.5% for off-diagonal elements of the MT impedance tensor and 5.0% for diagonal elements, respectively.

The model space consists of 41×41×57 rectangular blocks. The electrical conductivities of the blocks for sea water and land crust were fixed to 3.2 S m^{-1} and 0.1 S m^{-1}, respectively, so that total number of free model parameters is 882,268. For initial and prior models, we used the 1-D model obtained by the analysis mentioned above.

The inversion was run several times updating the initial and prior models. The model that the root mean square (RMS) misfit was the smallest in 10 iterations was

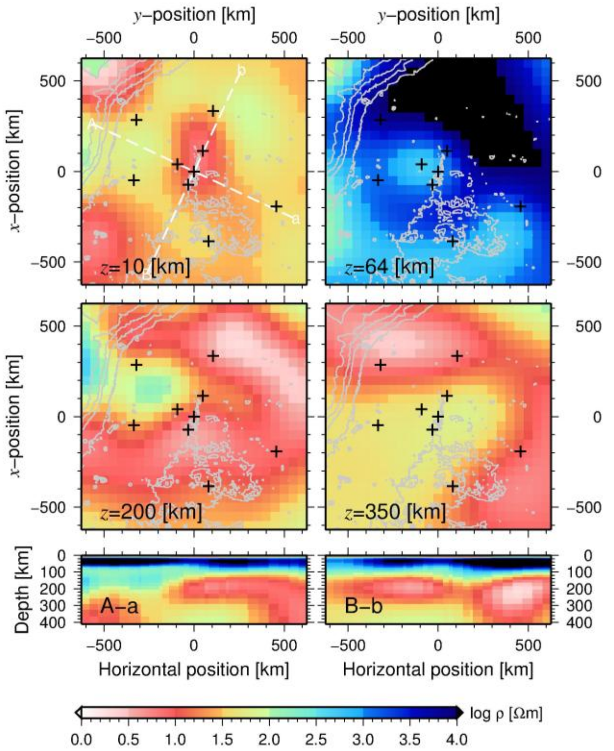

Figure 2. Optimal electrical conductivity structure model obtained by the 3-D inversion analysis. Top and middle four panels show the horizontal slices at different depths. *x*, *y*, and z are the geographical north, east, and vertical downward, respectively. Crosses indicate the site locations. Yukawa knolls locates at the center of the area. Bottom two panels show the vertical sections along the dashed lines, A-a and B-b, in the top left panel, which are parallel and perpendicular to the direction of the Pacific Plate motion, respectively.

selected as new initial and prior models. We selected the model at the first iteration of the fourth inversion as the optimal model because the RMS misfit no longer decreased. The RMS misfit improved from 6.218 (for the initial model) to 2.448 (for the optimal model).

RESULTS

The optimal model is shown in Fig. 2. There are two distinct features. 1) The central area down to ~100 km depth is much more conductive than the surrounding area. This feature can be seen in the vertical section as the resistive layer of this area is thinner than that of the surrounding area. 2) High conductivity (~0.1 S m^{-1}) layer at around 200 km depth distribute widely beneath the survey area except for the northwestern area of the Yukawa Knolls. The normalized residual plotted in Fig. 3 indicates that the model explains the data evenly.

We carried out checker board tests to examine if the main features are reasonably resolved by the data. We superimposed a checker board pattern on the optimal model. The horizontal dimension of the checker is 350 km × 350 km. The disturbance in the conductivity is 0.5 log unit. Synthetic MT responses were produced by forward modeling of the checker board model and then by adding Gaussian noises to the forward responses. Then, the synthetic MT responses were inverted starting from the optimal model. The inversion was carried out several times updating the initial and prior models as for the inversion of the real data, until the RMS misfit decreases to unity. The checker board pattern in the central area was recovered very well down to ~300 km depth. For the northwestern area at ~200 km depth, it is also recovered in some level but is not as good as for the central area.

We further test the second feature by forward modeling. We replaced the conductivity value of the blocks in the relatively resistive anomaly in the northwestern area to 0.1 S m^{-1} and calculated the MT responses. Then, the RMS misfit increased to 2.585. The difference of the RMS misfit with that of the optimal model (2.448) is significant with the significance level of 10%, according to *F*-test.

The results obtained by the checker board and forward modeling tests suggest that the two major features were reasonably constrained by the observed data.

DISCUSSION

The electrical conductivity can be converted into temperature under some assumptions, using results of conductivity measurement of minerals in laboratories. Here, we assume that the conductivity of mantle is represented by the conductivity of olivine which is the most abundant mineral.

We converted the conductivity value to temperature for possible water content in olivine (0, 50, 20, and 1000 ppm), referring experimental results by Yoshino et al. (2009). For the mantle beneath Yukawa Knolls, the resultant temperature is about 1200 ºC and 1700 ºC at ~65 and ~200 km depths, respectively, if the mantle is dry, which is much higher than the temperature predicted by plate cooling model for 135 Ma mantle.

The temperature at ~65 km depth is however much lower than dry solidus. This situation does not change if we assume hydrous mantle. The high conductivity anomaly at around this depth beneath the Yukawa Knolls may suggest high temperature anomaly because of petit-spot activity.

For the depth of ~200 km, estimated temperature is close to or higher than the corresponding solidus, suggesting partial melt. If we assume 200 ppm H_2O in the mantle at ~200 km depth, corresponding solidus temperature is

~1720 ºC. And if temperature of the mantle is equal to the solidus temperature and use the experimental result by Ni et al. (2011), the 0.004% hydrous basaltic melt is required to explain the conductivity. If we assume 1000 ppm H_2O in the mantle, the solidus temperature is ~1600 ºC and 0.033% hydrous basaltic melt is required. In any cases, such temperatures are unrealistically high.

Carbonated melt may explain the conductivity with realistic temperature and melt fraction. Solidus of carbonated peridotite is lower than the temperature predicted from the plate cooling model (Dasgupta & Hischmann , 2010). If we assume 1400 ºC for the mantle temperature at ~200 km depth and adopt the experimental result by Yoshino et al. (2012), 0.25% of carbonated melt (CO_2 content in melt is 50%) is required to explain the conductivity.

The relatively low conductivity anomaly at ~200 km depth in the northwestern area of the Yukawa Knolls requires less amount of melt. We speculate that the melt in this area may be extracted by the petit-spot activities.

CONCLUSIONS

We estimated 3-D electrical conductivity structure of the upper mantle beneath the northwestern Pacific where petit-spot volcanoes distributes from seafloor MT data. 3-D inversion results show two distinct features. 1) The lithospheric mantle beneath the Yukawa Knolls is more conductive than the surrounding area. At ~65 km depth, the temperature explaining the electrical conductivity (~1200 ºC) is much higher than that predicted from plate cooling model (~800 ºC). 2) High conductivity zone distribute at ~200 km depth, except for the northwestern area of the Yukawa Knolls. It is unrealistic to explain the high conductivity by silicate melt because extremely high temperature is necessary to produce melt but is possible to explain by small amount (< 1%) of carbonated melt. Relatively low conductivity anomaly in the northwestern area of the Yukawa Knolls may suggest the extraction of melt due to the petit-spot activities.

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