1-D electrical conductivity structure beneath the Philippine Sea: Results from an ocean bottom magnetotelluric survey

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Abstract

Eight-months of observation using Ocean Bottom Electro-Magnetometers (OBEMs) have allowed us to estimate the regional electrical conductivity structure beneath the Philippine Sea. Six OBEMs were deployed along a line crossing the Philippine Sea from NW to SE and five of them recorded useful data. The raw time series data were cleaned up before we estimated the magnetotelluric (MT) impedance tensor. Conductivity structure at five sites is estimated using 1-D Occam’s inversion to fit the determinant average of each MT impedance tensor after a correction for the effect of topography. We examined effect from two dimensionalties on the 1-D conductivity structure and the robustness of solutions. The results of the 1-D conductivity structural model are strongly related to tectonic setting and the crustal age beneath each site. The structure beneath the spreading axis of the Mariana Trough shows a distinct low conductivity structure at depths of 50–150 km and it probably reflects the upwelling dynamics operating beneath the spreading axis. These low values are comparable with that of olivine with low hydrogen content, implying that (1) the melting process extracts water from minerals such as olivine, and (2) the melt beginning depth in the Mariana Trough is deeper than that of the typical MORB source region. The off-axis conductivity profiles infer the existence of a high conductivity peak or a conductivity gradient change at mid-depth. The depth level of the peak increases with crustal age, suggesting that the conductivity structure is related to a geothermal structure and that these conductivity profiles are explained by the temperature gradient change, possibly combined with the presence of partial melt. Our results suggest that further ocean bottom EM study has high potential to investigate the temperature gradient change and amount of hydrogen (water) and melt in the upper mantle.

Keywords: Philippine Sea; Upper mantle conductivity structure; Crustal age; Water; Mantle temperature; Marine magnetotelluric

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1. Introduction

The Philippine Sea is one of the major marginal seas in the western Pacific and consists of three major basins: the West Philippine Basin, the Shikoku-Parece Vela Basin, and the Mariana Trough. Previous studies indicate that these basins have been formed by successive episodic opening from west to east (e.g., Karig, 1971; Hall et al., 1995), although a more complicated history of the West Philippine Basin was proposed by Okino et al. (1999), using detailed geophysical mapping. The crustal age of the variety of its crustal ages. The Philippine Sea varies from the present at active back-arc spreading axis in the Mariana Trough to around 60 Ma (e.g., the DSDP site 445 in the West Philippine Basin shows the basement age of 59.0 ± 3 Ma, according to Ozima et al. (1980)). This variety of crustal ages allows us to examine the upper mantle structure beneath the ocean floor related to its crustal age.

The active back-arc spreading axis in the Mariana Trough is one of the plausible targets to reveal the role of water in the melting process through the upwelling dynamics, because H$_2$O-enriched basalts exist in the Mariana Trough (Stolper and Newman, 1994). The water content affects the depth at which partial melting initiates, and the initial depth in the typical MORB source region is estimated as ∼115 km using petrological constraints (Hirth and Kohlstedt, 1996), while the depth in the source region of back-arc type MORB (higher water content) is estimated as ∼250 km (Karato and Jung, 1998). The extraction of water from minerals such as olivine through the melting process reduces the viscosity of olivine, strongly influencing the mantle dynamics beneath the spreading axis (Karato, 1986; Hirth and Kohlstedt, 1996). Thus, water is believed to play a key role in the melting process. In other words, geophysical constraints in higher water content regions are considered to be crucial in understanding the melting process beneath the spreading axis related to water content.

The Philippine Sea is a suitable target to study seafloor age dependence of various depth parameters that characterizes the dynamics of the back-arc spreading, because of the variety of its crustal ages. The Philippine Sea shows a linear relationship between the seafloor depth and the square root of age (Park et al., 1990), which has been found for other major oceanic floors (Davis and Lister, 1974; Parsons and Sclater, 1977). The basement depth of the Philippine Sea is, however, about 800 m deeper than that of the other major ocean floors of the same age (Park et al., 1990). The reason for this distinct deeper depth is still one of the major scientific questions. Moreover, the depth of the low velocity zone beneath the Pacific oceanic floor, which was obtained by surface wave techniques, shows a linear relationship against the square root of age (Forsyth, 1977), and that of the high electrical conductive zone also shows a similar relationship (Oldenburg, 1981; Oldenburg et al., 1984). On the other hand, the depth of the Gutenberg discontinuity, where there is a sharp decrease in seismic wave (particularly shear wave) velocities, does not change with age, but its depth in back-arc regions is somewhat deeper than those in the typical oceanic upper mantle (Karato and Jung, 1998). Thus, the comparison of the relationship between these depth parameter and age from the Philippine Sea back-arc region with that from major oceanic basins will be useful to understand the dynamic process of back-arc spreading.

The ocean bottom electromagnetic (EM) data using the magnetotelluric (MT) method allows us to estimate the electrical conductivity structure beneath the ocean floor. The outcome of this method is dependent on temperature, the presence of melt, the influence of hydrogen such as water, and the direction of preferred orientation in the case of crystal anisotropy. The relationship between temperature and electrical conductivity of dry olivine is well documented by Standard Olivine 2 (the S02 model; Constable et al., 1992), which has been determined by various laboratory conductivity measurements. The presence of a melt fraction in a subsolidus matrix strongly affects the electrical conductivity values (Shankland and Waff, 1977; Sato et al., 1989). Furthermore, hydrogen content in olivine also increases the electrical conductivity, which is estimated from its solubility and diffusivity through experimental data by using the Nernst–Einstein relation (Karato, 1990; Lizarralde et al., 1995). Moreover, the a-axis of olivine in an anisotropic fabric possibly causes an additional enhancement in the conductivity (Lizarralde et al., 1995). Thus, the ocean bottom EM study is considered a sensitive tool to probe temperature, the presence of melt, hydrogen (water) content, and anisotropy in the upper mantle beneath the ocean floor.

In this paper, we will first show our ocean bottom EM observations from the Philippine Sea. Secondly, the MT impedance tensor will be estimated at each observation site. The MT impedance tensor will be corrected for the effect of topography and one-dimensionality will be examined using the Rho$^+$ algorithm (Parker and Booker, 1996). Then, the one-dimensional (1-D) conductivity structure beneath the Philippine Sea will be estimated at each observation site. Effect from two dimensionalities on the 1-D conductivity structure and the robustness of the solutions will also be examined. Finally, we will interpret the 1-D conductivity structure. The conductivity structure near the spreading axis of
the Mariana Trough will be used to discuss the melting process beneath the spreading axis related to water content. The results from the off-axis locations will be examined with respect to tectonic setting and crustal age difference.

2. Ocean bottom EM observation and data analysis

We conducted an ocean bottom EM array jointly with a broadband seismic array as a part of the Ocean Hemisphere Project, Japan (Kawakatsu et al., 1998). One of the aims of this experiment is to reveal the large-scale upper mantle structure beneath the Philippine Sea. Our EM observations were based on Ocean Bottom Electro-Magnetometers (OBEMs). Six OBEMs were deployed along a line crossing the Philippine Sea from NW to SE during the Dai-5 Kaikou-maru cruise in November, 1999; two OBEMs in the northern West Philippine Basin, two in the northern Parece Vela Basin, and two in the central Marina Trough (Fig. 1 and Table 1). Two types of OBEMs were used and we call them type-A and -B hereafter (Fig. 2). The type-A OBEM is made of three glass-spheres with a geomagnetic field measurement resolution of 0.1 nT, which has also been used in the MELT experiment at the southern East Pacific Rise (Evans et al., 1999). The type-B OBEM has been developed during the Ocean Hemisphere Project and has two glass-spheres with a geomagnetic field measurement resolution of 0.01 nT. For about 8 months, both types of OBEMs measured two horizontal components of the electric field and three components of the geomagnetic field at 1-min intervals. All the OBEMs were recovered during the Shintatu-maru cruise in July 2000 and fairly high-quality data were obtained with the following exceptions: (1) The OBEM3 data are not useful, because the OBEM3 had been flooded when it was recovered and recorded data only for 1 month. (2) The OBEM1 data show bad electric field data for about 50 initial days. (3) The OBEM2 data have a data gap of 12 days.

The raw time series data were cleaned up through the following procedure. First, we removed the drifts using a cubic function applied to the data with a time window length of 3 days. The electric field data show much larger drifts than geomagnetic field data, which are mainly due to electrodes. Secondly, the unusual noise spikes in the electric field were carefully edited; i.e., the abnormal signals were picked out manually and then interpolated by appropriate values. Although the electric field data are contaminated by some noise spikes, the

![Fig. 1. Locations of the observation sites (solid circles with their site names).](image1)

![Fig. 2. Photographs of (a) type-A Ocean Bottom Electro-Magnetometer (OBEM) and (b) type-B OBEM.](image2)
geomagnetic field data are found to be very high quality. Thirdly, the OBEM’s clock was corrected by measuring the time difference between the clocks of each OBEM and the GPS before the deployment and after the recovery. This correction was based on an assumption of linear time drift. Since all the OBEMs had been placed by free fall, each component was transformed into local Cartesian coordinate system with $x$, $y$, and $z$ axes pointing to the geomagnetic north, east, and downward directions, respectively. The tilt data and the absolute value of each component (obtained from the geomagnetic field data) are used for transformation. The OBEM1 data is an exception, because the tilt value is more than that of the measurement range of $8.5^\circ$ and no tilt data are available for transformation. For the OBEM1, the three axes were rotated so that declination and inclination at the observation site coincide with those given by the International Geomagnetic Reference Field (IGRF; IAGA Division V Working Group VMOD, 2005). Finally, we removed signals of tidal components by a least squares method.

We estimated the MT impedance tensor, which is a transfer function from magnetic field to electric field variation, as a function of period. Five seafloor MT impedances with jackknife error bars are obtained from original time series data using the robust remote reference method (Chave and Thomson, 1989). The apparent resistivity and its phase calculated from the impedance tensor of OBEM1 are shown in Fig. 3, for example. All the data show relatively small error bars between 500 and a few tens of thousand seconds in period. Once the MT impedance is obtained, the electric field can be predicted from the magnetic field. The coherences between observed and predicted electric field were used to check the reliability of the MT impedances.

We corrected the observed MT impedance for the effect of topography using flattening surface 3-D modeling (FS3D; Baba and Seama, 2002) and the correction equation of Nolasco et al. (1998), which is the most appropriate for topographic correction (Matsumo et al., in press). Following Nolasco et al. (1998), horizontal electric and magnetic fields distorted by seafloor topography ($E$ and $B$) and without topographic distortions ($E_m$ and $B_m$) are represented by

$$E = E_m + CE,$$

$$B = B_m + DE,$$

where $C$ and $D$ are $2 \times 2$ complex tensors to represent electric and magnetic topographic effects including both galvanic and inductive distortions. Then, the topographic correction equation is

$$Z_c = (I - C)(I - Z_o D)^{-1} Z_o,$$

where $I$ is the identity tensor, $Z_o$ an observed impedance tensor, and $Z_c$ is a corrected impedance tensor. For this correction, we first calculate the electric and magnetic fields using FS3D forward modeling in two cases that are with seafloor topography and with flat-lying seafloor. Then, an observed impedance tensor is corrected from these electric and magnetic fields through this correction equation. A conductivity structure, which needs to be assumed for the calculation, is taken as a uniform half-space of $100\, \Omega\cdot m$. The area for each calculation was taken as a square, $6400$ km on a side, which covers both land and ocean, because Heinson and Constable (1992) showed that the electromagnetic coast effect is of paramount importance in modeling oceanic MT data. The area is discretized into numerical rectangular blocks whose side length varies; it is $1$ km near the center (the observation site) but it becomes larger as it gets farther from the center. After topographic correction, the apparent resistivities for the diagonal impedance tensor elements become much smaller than ones for the off-diagonal elements, showing one- or two-dimensionality compared to ones before the correction (Fig. 3). The apparent resistivity and its phase (Fig. 4) are calculated from the determinant average of each impedance tensor after the topographic correction.

We tested whether or not the apparent resistivity and its phase data are consistent with the modeling assumption of one-dimensionality using the Rho+ method.

### Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Water depth (m)</th>
<th>Instrument</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBEM1</td>
<td>16°34.4′N, 144°41.7′E</td>
<td>3259</td>
<td>Type B</td>
<td>Bad E field data for 50 days</td>
</tr>
<tr>
<td>OBEM2</td>
<td>17°47.2′N, 143°24.5′E</td>
<td>4082</td>
<td>Type A</td>
<td>Data gap of 12 days</td>
</tr>
<tr>
<td>OBEM3</td>
<td>20°12.9′N, 140°46.0′E</td>
<td>4604</td>
<td>Type A</td>
<td>Not useful (flooded)</td>
</tr>
<tr>
<td>OBEM4</td>
<td>22°33.6′N, 138°07.3′E</td>
<td>5102</td>
<td>Type A</td>
<td></td>
</tr>
<tr>
<td>OBEM5</td>
<td>25°00.0′N, 135°08.3′E</td>
<td>5245</td>
<td>Type B</td>
<td></td>
</tr>
<tr>
<td>OBEM6</td>
<td>27°11.4′N, 132°25.0′E</td>
<td>5431</td>
<td>Type A</td>
<td></td>
</tr>
</tbody>
</table>

Table 1

Memo of each observation site
algorithm (Parker and Booker, 1996), which gives the minimum possible RMS misfit model the same as the D+ algorithm (Parker, 1980). All the OBEM data after topographic correction passed it at the 95% confidence level, although the OBEM2 data before the topographic correction failed this test. This failure is due to the fact that the OBEM2 was located very close to a marked topographic feature of the West Mariana Ridge (remnant arcs), and any 1-D structural model cannot explain the OBEM2 data before the topographic correction.

The 1-D electrical conductivity structure beneath each observation site (Fig. 4) is estimated to fit the determinant average of each MT impedance tensor using Occam’s inversion (Constable et al., 1987), which gives a smooth conductivity model. For the Occam’s inversion, both the first and second derivatives of roughness are minimized with the RMS misfit of 1.0 and the coincidence of the two models supports the interpretation over the depth range. The separation of the two models in the deeper part suggests that the acceptable limit of the depth range is about 400 km (Fig. 4).
Fig. 4. The apparent resistivity (top), phase (middle), and 1-D conductivity structural profiles (bottom) of each OBEM site. The observed apparent resistivity and phase with error estimates are calculated from the determinant average of each magnetotelluric impedance. The error bars are 1σ.D. The lines are based on the conductivity structural models, which are obtained by Occam’s inversion (Constable et al., 1987). Occam’s inversion gives smooth profiles in two ways: first derivative roughness (solid lines) and second derivative roughness (dashed lines). Dashed arrows in the OBEM1 profile indicate a low conductivity zone. Arrows in the OBEM2, OBEM4, OBEM5, and OBEM6 profiles show peaks of high conductivity. See text for detail.

Although each 1-D electrical conductivity structure was obtained by inversion using the determinant average of each MT impedance tensor after the topographic correction, a model at each site, which is 1-D electrical conductivity structure (Fig. 4) below 3-D seafloor topography and land–ocean distribution (the same area for the topographic correction), is well supported by the data; the model impedance explains all four elements of the observed MT impedance at each site, as one example shown in Fig. 3. Moreover, we re-calculated the topographic effects using the resultant 1-D electrical conductivity structural model instead of the simple 100 Ω m oceanic crust and mantle model. But, these two corrected MT impedance, using the different conductivity structural models, become almost the same within the error bars. This is probably because the topographic effects are weakly coupled with the underlying oceanic crust and mantle structure as suggested by Nolasco et al. (1998) and because the correction equation of Nolasco et al. (1998) is robust to a resistivity structure assumed for the correction (Matsuno et al., in press).

3. Results

The results of the 1-D conductivity inversion for each observation site (Fig. 4) indicate common and different features among the sites as follows.

(1) The structure of the OBEM1 site is quite different from the other sites. Following a moderate high at shallow depth, the OBEM1 conductivity profile shows distinct low at a depth of 50–150 km (dashed arrows in Fig. 4) and then a gradual increase in the deeper part.

(2) The conductivity structural profiles of the OBEM2, OBEM4, OBEM5, and OBEM6 sites show a similar pattern. For all the sites, a high conductivity peak at intermediate level (arrows in Fig. 4) follows the lowest conductivity values at shallow depth. In the deeper part, the conductivity values increase with depth.

(3) The depth of the high peak in each conductivity profile is 80 km for the OBEM4 site, 100 km for
the OBEM5 and OBEM6 sites, and 200 km for the OBEM2 site.

(4) The conductivity profiles of the OBEM5 and OBEM6 sites are almost identical.

We performed a simple 2-D inversion of all the data along the OBEM observation line to justify our results from 1-D model at each site. As pointed out in a previous section, all impedance tensors showed one- or two-dimensionality after a topographic correction. This means that 1- and 2-D inversion of observed impedances will give consistent conductivity-depth profiles for each OBEM site, if lateral variations of conductivity are gradual. Conversely, there will be significant discrepancy between profiles estimated by 1- and 2-D inversion, if there is a sharp lateral variation of conductivity and the observation site is located close to its boundary. The 2-D electrical conductivity structure beneath the observation line (Fig. 5) is estimated to fit the off-diagonal elements (Fig. 6) of the MT impedance tensor after the topographic correction using the data space Occam’s inversion (DASOCC inversion; Siripunvaraporn and Egbert, 2000). The strike of the 2-D electrical conductivity structure is not parallel to the regional strike at each site, which was estimated from the MT impedance tensor after the topographic correction using the method of Groom and Bailey (1989); the strike of the 2-D electrical conductivity structure is assumed to be N43°E, while the regional strikes are N17°E, N36°W, N19°W, N25°E, N43°E, at OBEM1, OBEM2, OBEM4, OBEM5, and OBEM6, respectively. Furthermore, the number of the present available data sets is limited and its coverage is sparse (only five sites along the observation line of 1700 km length). Thus, the 2-D electrical conductivity structure itself is not suitable for interpretation, but it is useful to check effect from two dimensionalities on the 1-D conductivity structure and to justify our results from 1-D model at each site.

A conductivity-depth profile for each OBEM site was obtained from the inverted 2-D profile and was compared with each conductivity profile from 1-D inversion. This comparison (bottom in Fig. 5) shows two similar-
Fig. 6. Off-diagonal elements of apparent resistivities and phases at the OBEM1 site. Observations (circles) with error bars of 1 S.D. are compared with calculations from a model (solid lines). The $x'$ and $y'$ axes are parallel and perpendicular to the observation line, respectively.

Fig. 7. 1-D Occam’s inversion results, with first derivative roughness at each OBEM site for RMS values varying from 0.9 to 1.3. The dashed line shows a preferred misfit level; the profile is shown in Fig. 4.

Fig. 7. 1-D Occam’s inversion results, with first derivative roughness at each OBEM site for RMS values varying from 0.9 to 1.3. The dashed line shows a preferred misfit level; the profile is shown in Fig. 4.

4. Discussions

The results of the 1-D conductivity structure are well conformed to the tectonic setting and the crustal age beneath each site. The OBEM1 site is only 20 km away from the spreading axis and the crustal age beneath the OBEM1 site is estimated at 1 Ma using the vector geomagnetic anomaly data obtained from the surface geophysical survey (Iwamoto et al., 2002). In comparison to OBEM1, the other sites are located far from the spreading axis. Crustal ages of the other OBEM sites are reported as follows. The crustal age beneath the OBEM4 site is placed at 21 Ma corresponding to the geomagnetic anomaly 6A results (Okino et al., 1999). The DSDP sites 445 and 446 near the OBEM5 site show a basement age of $59.0 \pm 3$ and $56.5 \pm 2$ Ma, respectively (Ozima et al., 1980). Furthermore, the geomagnetic anomaly 24
A potential temperature of 1300°C is used for these calculations. The estimation of conductivities in the presence of different hydrogen contents is based on the Nernst–Einstein relation following previous analyses (Karato, 1990; Lizarralde et al., 1995), even though this is still a hypothesis as there are no published laboratory measurements on this work. A potential temperature of 1300°C is used for these calculations. The result indicates the reduction of hydrogen contents at intermediate depth beneath the OBEM1 site (Fig. 8). These results suggest that the extraction of water from minerals such as olivine through melting (Karato, 1986; Hirth and Kohlstedt, 1996) may explain the low conductivity values of the OBEM1 profile. The melting initiates at a depth of nearly 250 km where the trend of the OBEM1 conductivity profile becomes different from that of the conductivity profile calculated for an isotropic olivine mantle with a constant hydrogen content (Fig. 8). Although the resolution of our result is not high enough, the presence of this low conductivity region is robust in depths of 50–150 km as we have examined (Fig. 7), indicating that the melting begins at a depth deeper than at least 150 km. This depth is significantly greater than that of the typical MORB source region (~115 km; Hirth and Kohlstedt, 1996), which is probably due to higher water content in back-arc regions (Karato and Jung, 1998).

The OBEM4, OBEM5, and OBEM6 sites are located far from spreading axis, and their conductivity profiles show a similar pattern; a high conductivity peak or a change in conductivity gradients exists at mid-level. The depth of the peak or the gradient change shows a relationship between depth and crustal age beneath each site. The OBEM4 site has a younger crustal age (21 Ma) and shows a shallower depth for the high conductivity peak (80 km) compared to those of the OBEM5 and OBEM6 sites (around 60 Ma and 100 km). The OBEM5 and OBEM6 sites have similar crustal ages and their structural profiles are almost identical, suggesting that crustal age is the main parameter for the conductivity structure. The whole evidence supports a relationship between crustal age and the depth of the high conductivity peak or the conductivity gradient change; the peak depth increases as the age becomes older. The relationship is well related to the geothermal model of Parsons and Sclater (1977), suggesting that the age dependency of the peak depth is explained by the thermal structure in terms of lithospheric cooling, possibly with the presence of partial melt. Temperature change is a primary parameter for the conductivity value. In the geothermal model of Parsons and Sclater (1977), the isotherms run deeper and the thermal gradient becomes gentler as the mantle gets older. The depth of the high conductivity peak beneath the OBEM4, OBEM5, and OBEM6 sites coincide with the depth of the 1300°C isotherm calculated from Parsons and Sclater (1977). Further, the steep conductivity gradient of the OBEM4 profile and the gentle conductivity gradient of the OBEM5 and OBEM6 profiles qualitatively agree with the gradient change with age of the model of Parsons and Sclater (1977). Moreover, partial melt may be required for the OBEM4 site to explain the high conductivity peak, which is the robust
feature and is different from those of the other sites (Fig. 7). A high conductivity peak cannot be produced only by the thermal structure associated with the lithospheric cooling alone, but by the limited depth range that partial melt can exist. The limited depth range occurs because the thermal gradient is small below the partial melt region while the pressure increases linearly with depth. The compositional boundary model for the base of an oceanic plate can be a candidate, but the difficulty of this model is that another mechanism is required to explain the age dependency of the peak depth.

5. Conclusions

Our study is the first attempt to investigate the large-scale features of the electrical conductivity distribution in the mantle beneath the Philippine Sea back-arc basins by 1-D inversion of magnetotelluric data from five seafloor stations. The observed tensor impedance at each site has been shown to be well explained by a 1-D model with 3-D effects of seafloor topography and land-ocean contrast. Further, a comparison between 1-D model and the simple 2-D inversion model justified the 1-D treatment at four sites (the OBEM1, OBEM4, OBEM5, and OBEM6 sites). Considering the crustal age of each site, geodynamic processes in the upper mantle, and effects controlling the mantle conductivity by temperature and fluid contents, the following conclusions have been obtained by interpretation of the inversion results.

(1) The structure nearly beneath the spreading axis of the Mariana Trough (the OBEM1 site) probably reflects the upwelling dynamics operating beneath the spreading axis and shows distinct low conductivity structure at depths of 50–150 km. These low values are comparable with that of olivine with low hydrogen content, implying that (1) the melting process extracts water from minerals such as olivine, and (2) the depth of melt beginning in the Mariana Trough is deeper than that of the typical MORB source region (∼115 km; Hirth and Kohlstedt, 1996). Although these interpretations are based on one observation site, it is suggested that further ocean bottom EM study has the high potential to investigate the amount of hydrogen (water) content and melt in upwelling dynamics operating beneath the spreading axis.

(2) The off-axis conductivity profiles (the OBEM4, OBEM5, and OBEM6 sites) show the existence of a high conductivity peak or conductivity gradient change at middle depth level, and the depth level increases with the crustal age. We are the first to show the relationship between depth level and crustal age in back-arc basins and it indicates that the conductivity structure is well related to the geothermal model of Parsons and Sclater (1977), suggesting that the high conductivity peaks are explained by a temperature gradient change, possibly with the presence of partial melt.

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