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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 dimensionalities 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 under 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_2O-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 SO2 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