— Reviews —

Recent progress of the Electro-Magnetic survey to investigate Earth's interior

Takafumi Kasaya[1*], Tada-nori Goto[2], Kiyoshi Baba[3], Masataka Kinoshita[1], Yozo Hamano[1], Yoshio Fukao[1]

During the past five years, the electro magnetic (EM) team of the Japan Agency for Marine Science-Technology (JAMSTEC) has conducted many observations to investigate the crustal and mantle structure in pursuit of various scientific aims in collaboration with other universities and institutes. Around the Nankai subduction zone, we constructed a crustal and regional resistivity model, and detected the low resistivity zone with subduction. Moreover, we developed new geophysical survey tools––the small ocean bottom electro magnetometer (OBEM) and the deep-towed DC resistivity survey system—to investigate the shallow crustal structure. We also conducted an ocean bottom EM array study in the Philippine Sea and other areas to investigate the mantle structure using long-term OBEMs, thereby obtaining high-quality EM data.

Keywords : Resistivity structure, Ocean bottom electro magnetometer (OBEM), Marine deep-towed DC resistivity survey system

---

Received 18 February 2009 ; Accepted 6 August 2009

1 Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
2 Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University
3 Earthquake Research Institute, University of Tokyo

Corresponding author :
Takafumi Kasaya
Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
2-15, Natsushima-cho, Yokosuka, 237-0061, Japan
+81-46-867-9337
tkasa@jamstec.go.jp

1. Introduction

Electrical resistivity (conductivity) is very important parameter to investigate the earth interior because electrical resistivity is sensitive to the existence of the water in the earth. The Japanese EM community began development of the ocean bottom equipment in the late 1970s (e.g. Segawa et al., 1981; Segawa et al., 1982; Hamano et al., 1984). A practical OBEM with three glass spheres was completed in the 1990s, providing geomagnetic field measurement resolution of 0.1 nT. In 2001, an instrument of the subsequent generation with a geomagnetic field measurement resolution of 0.01 nT was equipped with two glass spheres, and was improved to reduce the power comsunption of electrical circuit. These equipments was used for the Mantle Electromagnetic and Tomography (MELT) experiments at the southern East Pacific Rise (Baba et al., 2006) and for array observations in the Philippine Sea conducted by the Ocean Hemisphere Project (Seama et al., 2007).

During the past five years, JAMSTEC-EM team has conducted many observations to investigate the crustal and mantle structure in pursuit of various scientific aims, in collaboration with universities and institutes (Fig. 1). Moreover, we have developed new geophysical survey tools that are appropriate for particular survey targets. In this paper, we introduce the developed EM equipment and the recent progress of the JAMSTEC EM team.

2. Development of small OBE(M) and the structure survey around the earthquake zone

Investigation of the megathrust seismogenic zone is extremely important because generation of earthquakes is inferred to be related to the existence of water. To investigate the cause of the large earthquake generation, JAMSTEC has promoted the integrated research project of deep scientific drilling using D/V Chikyu in the Kumano area of Nankai Trough. Many seismic surveys have been conducted around

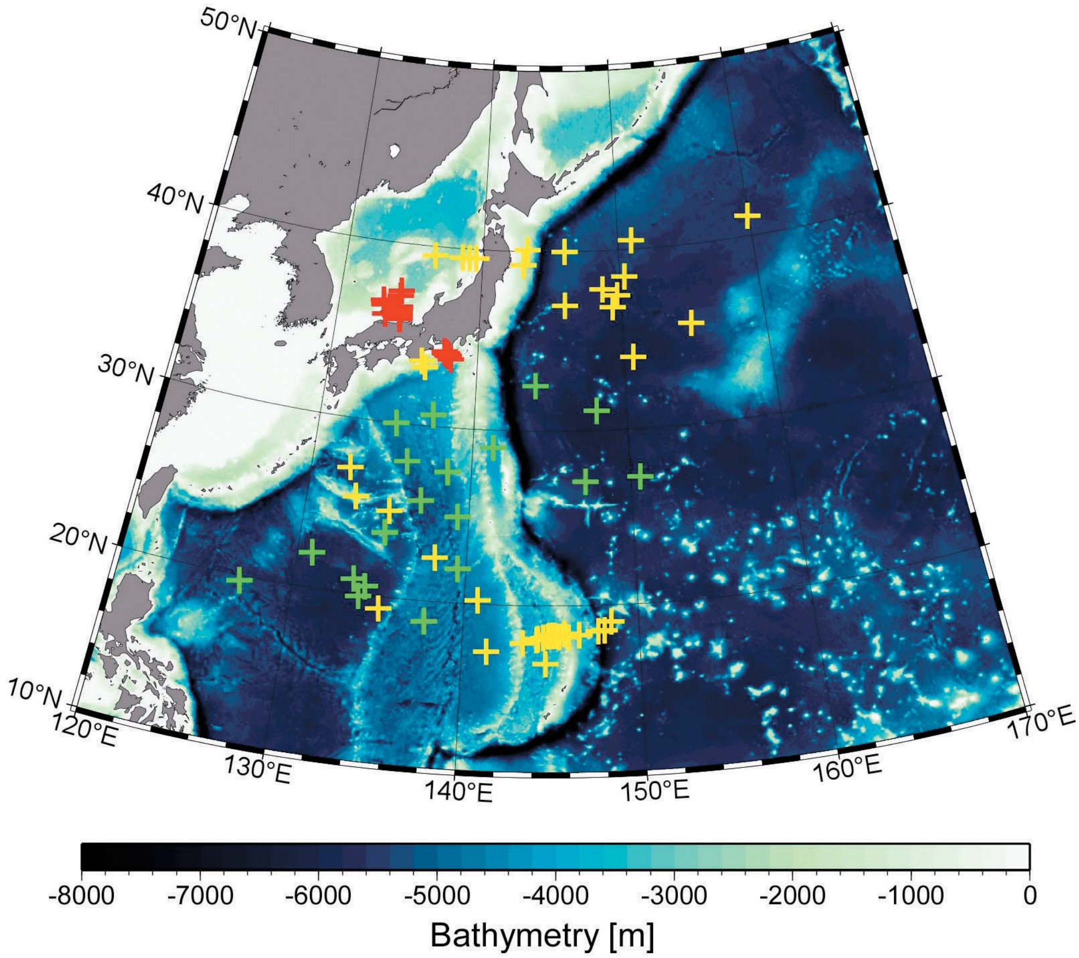

Fig. 1 All EM sites near Japan. Red crosses show Ocean Bottom Electro-Magnetic (OBEM) sites surveyed using new small OBEMs and OBEs. OBEM sites surveyed by the Stagnant Slab Project are shown as green crosses. Yellow ones show EM sites that were corrected by related project.

this area, For example, Park et al. (2002) reported details of spray faulting which branches upward from the plate-boundary interface. In the Kumano area, EM work was also conducted using two long-term OBEMs and nine high-sampling OBEMs (Fig. 1). Kasaya et al. (2005) compiled a resistivity image of the Philippine Sea Plate using both marine and land EM data. The salient results are a variation in the plate's resistivity with subduction. Figure 2 portrays the final resistivity model deduced using an inversion technique. The plate's resistivity clearly decreases to about 10 Ω-m with subduction. Kimura et al. (2005) reported details of the crustal structure around the trough axis. They inferred a pathway of fluid along the spray fault based on the existence of the low-resistivity zone within the accretionary prism.

To obtain an image of the structure around the subduction zone, it is necessary to obtain EM data in the frequency range of a few to hundreds of thousands of seconds. A suitable OBEM system, however, did not exist at the time of the Nankai experiment. For that reason, we decided to develop an OBEM and OBE system with a high sampling rate. It has a folding-arm system to facilitate assembly and recovery operations. Concepts of our developed OBEM and OBE system are miniaturization, a high sampling rate, easy assembly and recovery operations, and low costs of construction and operation.

Electric circuit used for each system is contained in the pressure glass spheres. The fluxgate magnetometer of the OBEM system is mounted outside the glass sphere (Fig. 3-a). The salient characteristic of our system is its arm-folding mechanism, which facilitates and simplifies our onboard operations. Consequently, we can carry out recovery operations using a small boat. In fact, a small fishing boat was used for recovery operations in Turkey (Fig. 3-b).

Each OBEM and OBE system can use common exterior equipment and an acoustic system. We used an acoustic release system that had been already used by JAMSTEC for Ocean Bottom Seismography (OBS). Our acoustic system accommodates the frequency of a Super Short Base Line (SSBL) system of JAMSTEC vessels, which make it easy for us to detect its position in the sea or on the seafloor. Kasaya et al. (2006) and Kasaya and Goto (2009) reported details of the new system along with field data. These new OBEM and OBE systems have been used around the off Tokai, off Tottori, off Sanriku areas, and in Turkey. Deployment and recovery operations have been

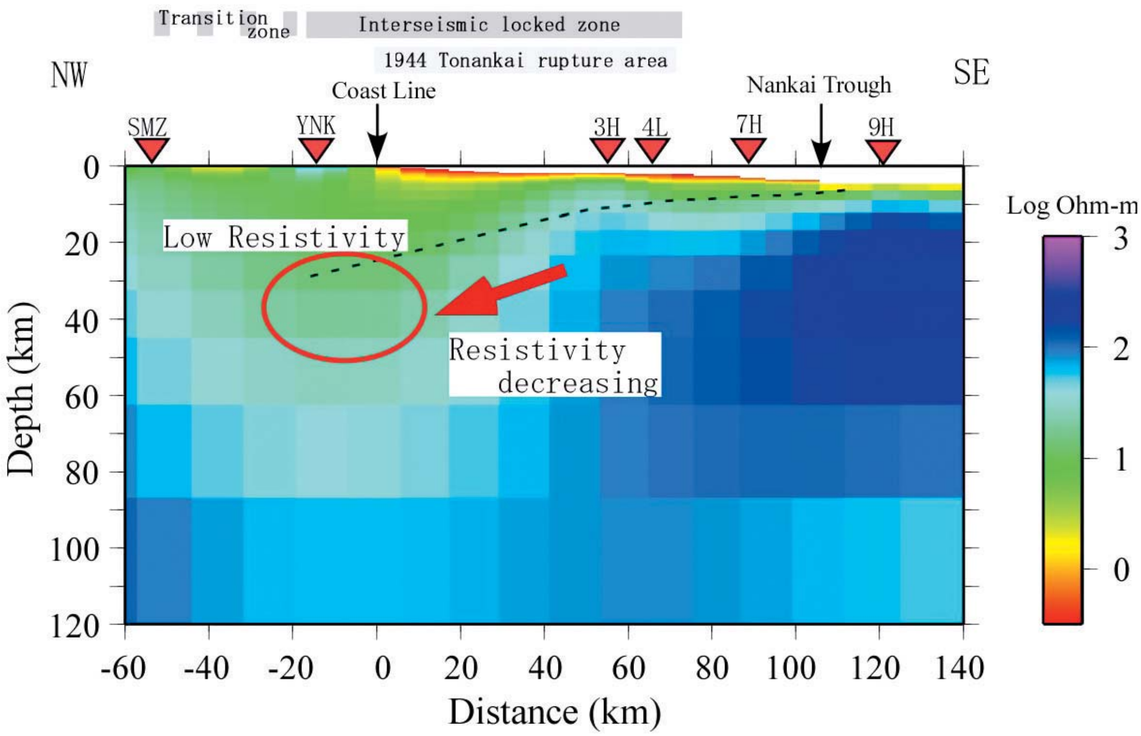

Fig. 2 Resistivity model across the Nankai Trough and Kii Peninsula. A dashed line shows the plate boundary. Triangles show the horizontal position of observation sites used for the inversion procedure. Interseismic locked and transition zone were estimated geothermal data (Hyndman et al., 1995). After Kasaya et al. (2005).

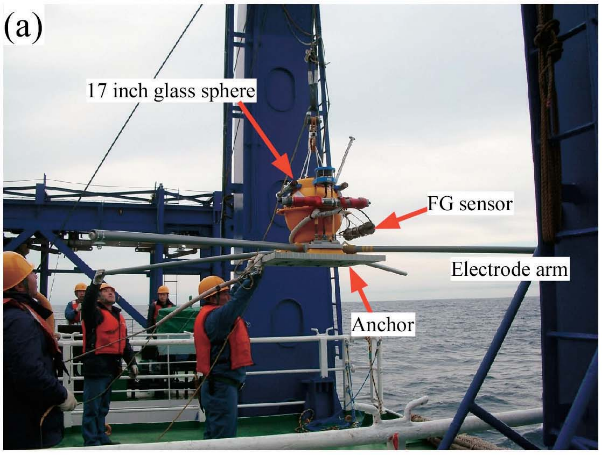

Fig. 3 (a) Deployment of the developed OBEM instrument. (b) Photograph of the recovery operation using a small fishing boat.

conducted at 33 sites: all equipment was recovered. We will show an example of the MT result dedeuced off Western Tottori prefecture. In this experiment, the OBEMs recorded 40 days EM data with 8 Hz sampling rates. MT response was estimated by the robust remote reference method (RRRMT) developed by Chave et al. (1987). Kasaya and Goto (2009) described the details of this observation and data analysis. Figure 4 presents the MT response (apparent resistivity and phase) calculated by the time series of a site at the depths of 230 m. The time series at shallow depth tend to disturb because of the strong sea current. However, the estimated MT response has sufficient quality. This result shows that the exterior design of our small OBEM is robust for the seabottom current.

3. Deep structure survey

In addition to small OBEMs, we have long-term OBEMs for deep mantle surveys, which are the same specifications that were originally developed at the Earthquake Research Institute, University of Tokyo (Seama et al., 2007). Figure 5 portrays a long-term OBEM with two pressure glass spheres that enclose electric circuits, fluxgate magnetometers, and batteries. The Japanese EM community has conducted many EM experiments using OBEMs of these types (e.g. Toh et al., 2006). We also have joined some projects to investigate the deep mantle structure using these OBEMs. In this section, we present a summary of deep mantle survey projects.

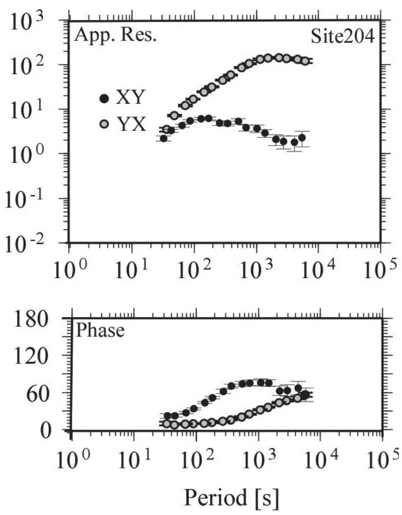

Fig. 4 Apparent resistivity and impedance phase calculated using the time series data obtained off Tottori prefecture. After Kasaya and Goto (2009).

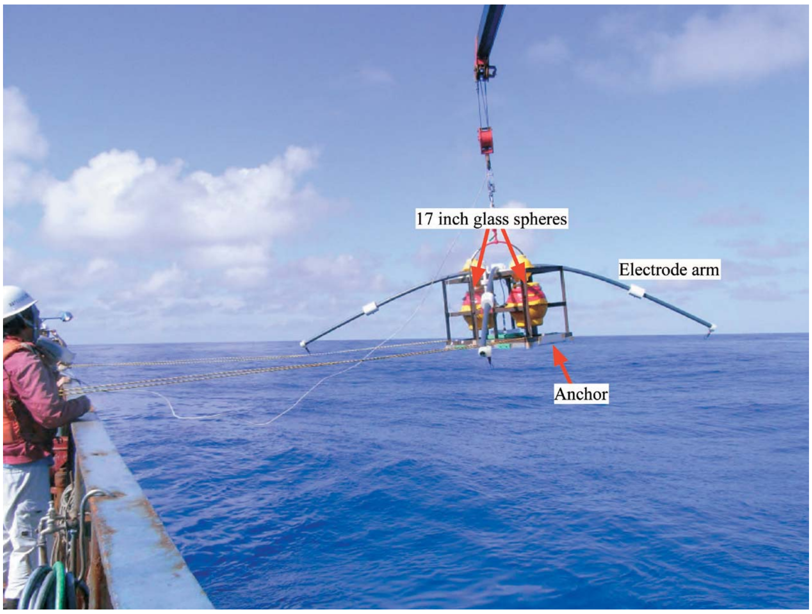

Fig. 5 Photograph of a long-term OBEM system.

During the past five years, we have conducted an ocean bottom array study in the Philippine Sea as a part of the Stagnant Slab Project (Shiobara et al., 2009). Many OBEMs and broadband ocean bottom seismometers (BBOBSs) were used in this field study. All OBEMs were recovered and time series data were obtained perfectly among the data acquisition at all 17 sites (Fig. 1). We conducted four deployment and recovery cruises from October 2005 to December 2008 because the nominal battery life time is one year. The three years' data consisting of one-year observation were obtained at seven sites. Figure 6 shows an example of the three years' time series data set collected at T14 site (see Fig. 1) using long-term OBEMs in the Philippine Sea by this project. As a result of the time series analysis, high-quality MT responses were available for construction of 2-D and 3-D structures.

In the central Mariana area, two seafloor MT experiments were conducted in 2001–2002 and 2005–2006. These were collaborative researches with domestic and international institutes and JAMSTEC has resourced the projects with the OBEMs (Fig. 1). The projects aim to image electrical conductivity structure of the upper mantle and then support discussion of the respective dynamics in the system of oceanic-subduction, arc volcanism, and back-arc spreading systems. A 2-D conductivity model was obtained by Baba et al. (2005) using data corrected in the first experiment (Fig. 7). The second experiment arranged high-density linear array using 47 instruments: the largest experiment in the history of marine EM research. The data are now under analysis by the research group.

Petit-spot, an intra-plate volcanism found in the northwestern Pacific, is also a target of seafloor MT surveys. Geochemical and geological evidence indicate that the source of the petit-spot melt is likely in the asthenospheric depth (Hirano et al., 2006), which is the most sensitive zone for marine MT. An MT experiment using six OBEMs was conducted in 2005 and consecutive observations using three OBEMs were conducted in 2007–2008. Research is on going toward elucidation of the condition and distribution of partial melting associated with the petit-spot activity.

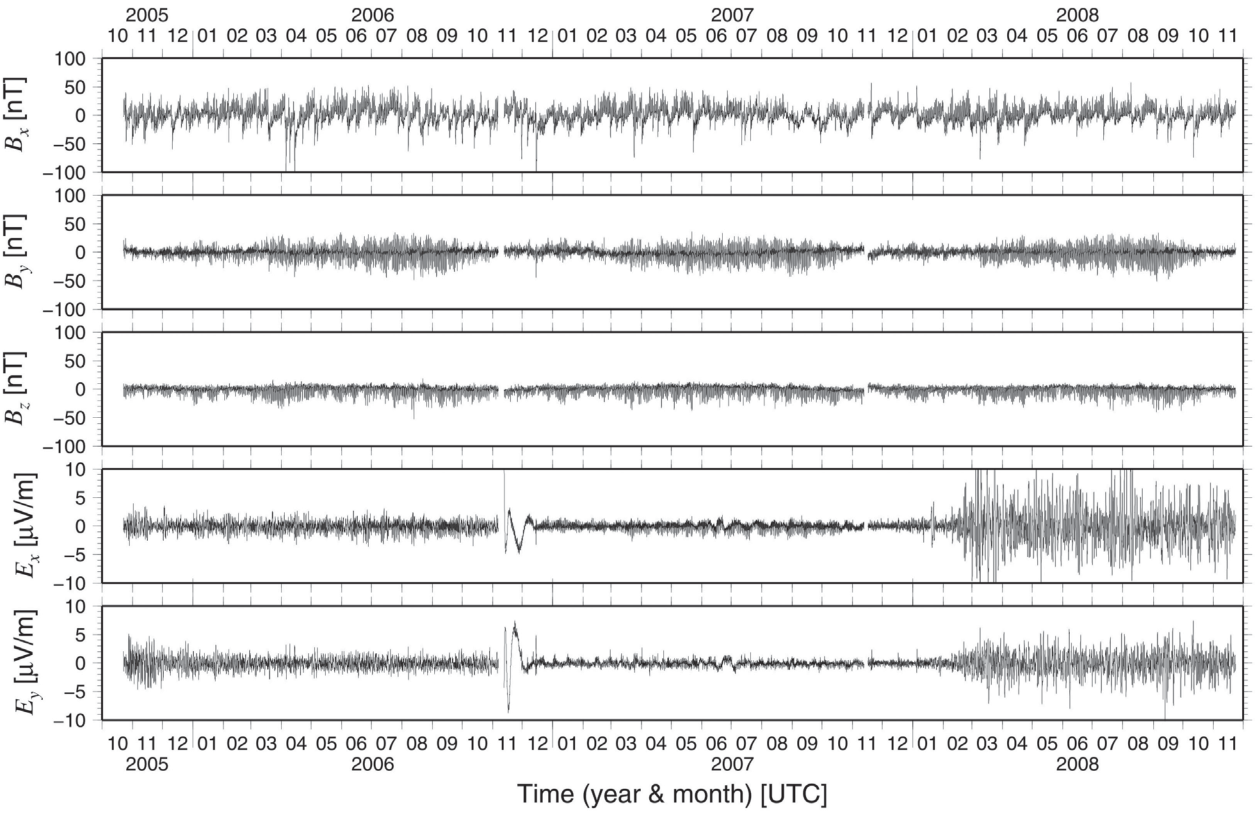

Fig. 6 An example of the time series data set collected at T14 site using long-term OBEMs in the Philippine Sea by the Stagnant Slab Project. Three components of the magnetic field and horizontal two components of the electric field are plotted. x, y, and z are geomagnetic north, east, and vertical directions, respectively. Linear trend of the magnetic field and trend longer than about three days for the electric field are removed.

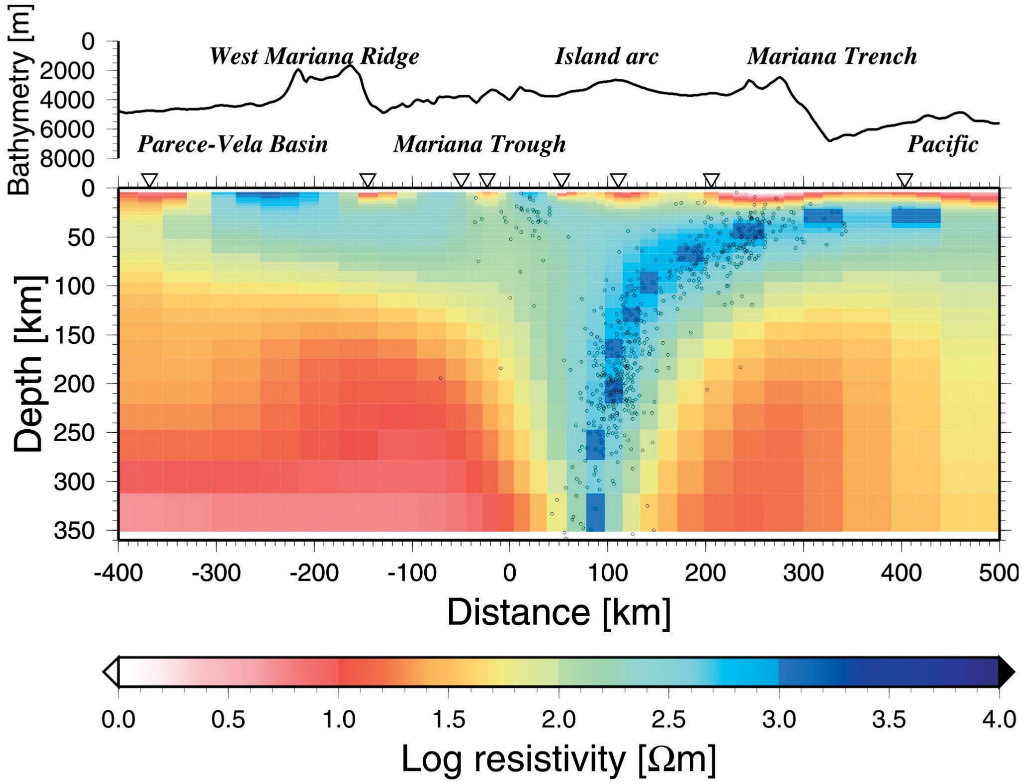

Fig.7 Two-dimensional model of the upper mantle electrical conductivity beneath the central Mariana area. Inversed triangles indicate the OBEM site locations. Dots are hypocenters. Bathymetric profile along the survey line is plotted on the top. After Baba et al. (2005).

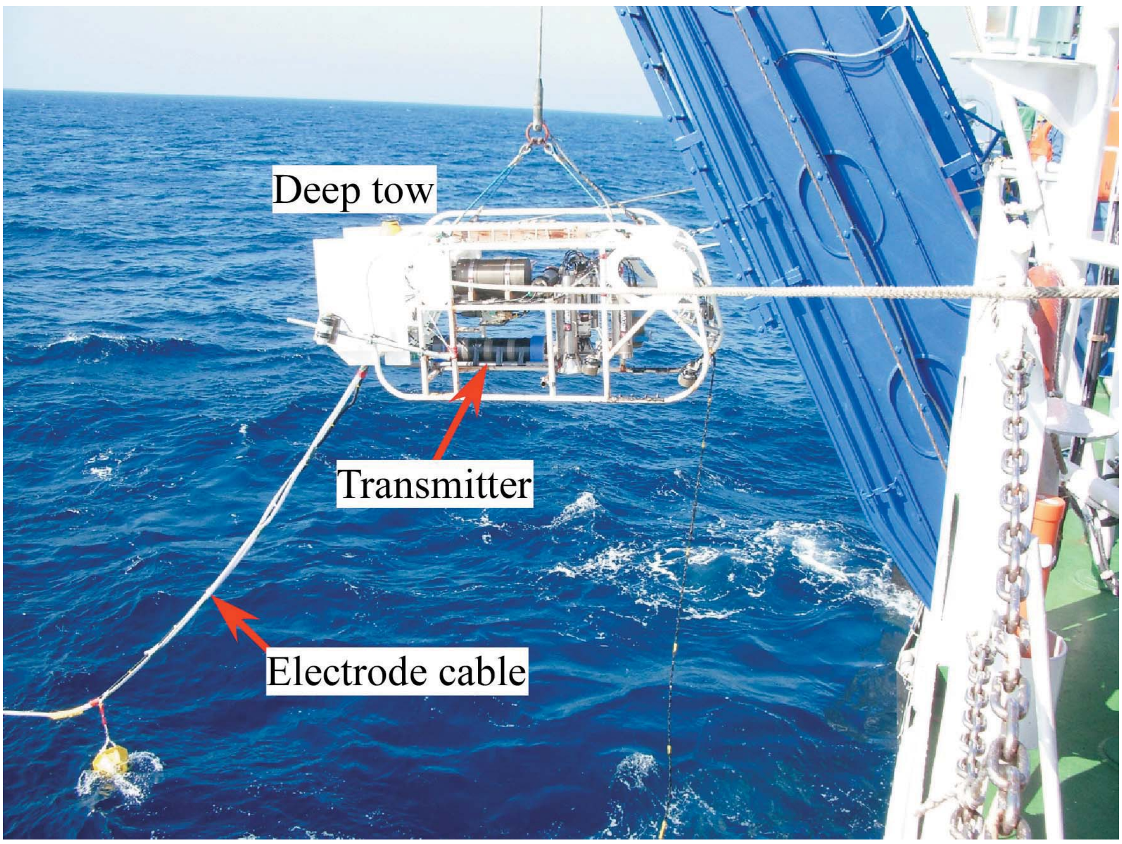

Fig. 8 Photograph of a marine deep-towed DC resistivity survey system: MANTA.

4. Marine deep-towed DC resistivity survey system

It is difficult for natural source MT method to sense the structure shallower than a hundred meters in the deep sea. Therefore, we must use other survey methods used with the control source. We developed a new deep-towed marine DC resistivity survey system to detect details of the shallow structures with depth of a hundred meters. Our system, with a transmitter and a 160-m-long tail with eight source electrodes and a receiver dipole, is towed from a research vessel near the seafloor (Fig. 8). This transmitter is added on the frame of the 6000 m class Deep-towed system of JAMSTEC. The maximum output power of the transmitter is 0.8 kW with maximum voltage of 72 V p-p and current of 44 A p-p. Numerical calculations show that the electrode configuration of our marine DC resistivity survey system can image the top surface of the methane hydrate layer effectively (Goto et al., 2008).

A survey was conducted out off Joetsu (Fig. 1), where outcrops of methane hydrate are observed (Goto et al., 2008). We obtained DC resistivity data along a profile ca. 3.5 km long, and detected high apparent resistivity values, which defy explanation by normal sediments below the seafloor. Particularly in areas with methane hydrate exposure (see Fig. 7 of Goto et al., 2008), anomalously high apparent resistivity was observed. We interpret these high apparent resistivities to be attributable to the methane hydrate zone below the seafloor. Marine DC resistivity surveys can serve as a new tool to image sub-seafloor structures within methane hydrate zones. This system is also used as a transmitter of the control source survey. We already succeeded that our OBE system detect the signal from a DC resistivity system during same cruise, from which data are now being analysed.

5. Summary

A great progress has been made in our EM data acquisition technique and development of geophysical survey instruments during the past five years. We obtained long-term EM data with certainty, and have obtained data related to important subsurface resistivity structures. It is particularly expected that the newly developed OBE(M)s and DC resistivity survey system will provide information about shallower structures. However, some data analysis tasks remain to be solved. Future studies will examine development of new analytical techniques: advanced 2D structural analysis, 3D analysis, and so on. We also seek collaboration with other science teams to clarify the earth's interior structure.

Acknowledgments

We appreciate the extensive support offered by the respective captains, ships' crews, and marine technicians of all vessels. We are grateful to Dr. Ichiki for EM data acquisition and many helpful discussions related to instruments and scientific interpretation. We are also thankful to Dr. Suetsugu and Dr. Nagao for reviewing. The OBEMs and OBEs were carefully manufactured and modified by Tierra Technica and CloverTech Inc., respectively. We thank Mr. Okabe for many useful ideas related to the arm holding mechanism. We also thank Dr. Suyehiro and Prof. Mikada for their helpful comments and support for OBEM and OBE development. These OBEM operations were supported by JAMSTEC internal budget and the Ministry of Education, Science, Sports and Culture, Grant-in-Aid. Several figures were created using GMT, which was produced by Wessel and Smith (1998).

References

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

Baba, K., A.D. Chave, R.L. Evans, G. Hirth, R.L. Mackie (2006), Mantle dynamics beneath the East Pacific Rise at 17°S: Insights from the Mantle Electromagnetic and Tomography (MELT) experiment, *J. Geophys. Res., 111(B02101)*, doi:10.1029/2004JB003598.

Goto, T., T. Kasaya, H. Machiyama, R. Takagi, R. Matsumoto, Y. Okuda, M. Satoh, T. Watanabe, N. Seama, H. Mikada, Y. Sanada, and M. Kinoshita (2008), A marine deep-towed DC resistivity surevey in a methane hydrate area, Japan sea., *Exploration Geophysics, 39*, 52-59.

Hamano, Y., T. Yukutake, J. Segawa, T. Asaoka, H. Utada, I. Nakagawa and Y. Sasa (1984), Seafloor measurement of natural electric field by use of newly developed instrument, *Proceedings of Conductivity Anomaly Research Symposium*, 259-265 (in Japanese).

Hirano, N., E. Takahashi, J. Yamamoto, N. Abe, S.P. Ingle, I. Kaneoka, T. Hirata, J. Kimura, T. Ishii, Y. Ogawa, S. Machida, and K. Suyehiro (2006), Volcanism in response to plate flexure, *Science, 313*, 1426-1428.

Hyndmann, R. D. and K. Wang (1995), Thermal constraints on the seismogenic portion of the southwestern Japan subduction thrust, *J. Geophys. Res., 100*, 15373-15392.

Kasaya, T., T. Goto, H. Mikada, K. Baba, K. Suyehiro and H. Utada (2005), Resistivity image of the Philippine Sea Plate around the 1944 Tonankai earthquake zone deduced by Marine and Land MT surveys: *Earth Planets Space, 57*, 209-213.

Kasaya, T., T. Goto, and R. Takagi (2006), Marine electromagnetic observation technique and its development –For crustal structure survey-, *BUTSURI-TANSA, 59*, 585-594 (in Japanese with English abstract).

Kasaya, T. and T. Goto (2009), A small OBEM and OBE system with an arm folding mechanism , *Exploration Geophysics, 40*, 41-48.

Kimura, T., Y. Ashida, T. Goto, T. Kasaya, H. Mikada, Y. Sanada, T. Watanabe And K. Yamane (2005), Crustal resistivity structure around the Nankai subduction zone, *BUTSURI-TANSA, 58*, 251-262 (in Japanese with English abstract).

Park, O. J., T. Tsuru, S. Kodaira, P. R. Cummins, and Y. Kaneda (2002), Splay fault branching along the Nankai subduction zone., *Science, 297*, 1157-1160.

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

Segawa, J., T. Yukutake, Y. Hamano, T. Kasuga, and H. Utada (1981), Sea floor measurement of geomagnetic field using newly developed ocean bottom magnetometers: *J. Geomag., Geoelectr., 34*, 571–585.

Segawa, J., T. Yukutake, Y. Hamano, and H. Utada (1982), A new model of ocean bottom magnetometers: *J. Geomag., Geoelectr., 35*, 407–421.

Shiobara, H., K. Baba, H. Utada, and Y. Fukao (2009), Three-year Deployment of Ocean Bottom Array to Probe the Stagnant Slab Beneath the Philippine Sea, *EOS, Trans. AGU, 90(9)*, 70-71.

Toh, H., K. Baba, M. Ichiki, T. Motobayashi, Y. Ogawa, M. Mishina, and I. Takahashi (2006), Two-dimensional electrical section beneath the eastern Japan Sea, *Geophys. Res. Lett., 33(22)*, L22309, doi:10.1029/2006GL027435.

Wessel, P. and W. H. F. Smith (1998), New improved version of Generic Mapping Tools released: *EOS Trans. Am. Geophys. U., 79(47)*, 579.