Journal of Applied Geophysics 100 (2014) 23–31

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A new marine magnetotelluric measurement system in a shallow-water environment for hydrogeological study ☆

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ARTICLE INFO

Article history:
Received 18 June 2013
Accepted 11 October 2013
Available online 22 October 2013

Keywords:
Seafloor electromagnetic exploration
Marine magnetotellurics
Shallow water
Coastal area
Seawater/freshwater interface

ABSTRACT

We have developed a new marine magnetotelluric (MT) measurement system that can reduce noises caused by sea wave motions and can be applied to measurements under very shallow seawater areas, such as a coastal region with a sea depth of 10 to 100 m. The difficulties of geophysical exploration in shallow water and coastal areas include (1) fishery activity, (2) limitations of survey vessel size, and (3) motion noise caused by sea waves. In order to overcome these difficulties, we selected a MT method that uses natural EM fields without transmitting an electric current in seawater, which enables the method to be used in areas with active inshore fisheries. In addition, the developed marine MT system is very short, which reduces motion generated by sea waves, and compact, which enables light-draft small survey boat operation. We conducted offshore data acquisition using a new MT measurement system and an onshore MT survey at the Horonobe coastal area, Hokkaido, Japan. High-quality data were successfully obtained in both onshore and offshore field surveys. Two-dimensional (2D) inversion for field data from onshore to sea bottom reveals that a quaternary sedimentary layer of a few hundred meters in thickness, which was determined by well logging to be a freshwater layer, extends horizontally offshore for several kilometers under the sea. The results obtained herein demonstrate that the newly developed marine MT measurement system can be used to clarify the geoelectrical structures of brackish/fresh groundwater distributions and in coastal areas.

1. Introduction

The geological information of coastal areas is important because of the high concentration of economic and social activities in these areas. For example, the importance of the saline/freshwater distribution in coastal areas has been increasingly recognized in groundwater utilization for municipal, industrial, and agricultural purposes (Mitsuhata et al., 2006).

In addition, coastal areas have been considered as candidate repository sites of high-level radioactive waste (HLW) (e.g., the nuclear waste created by the reprocessing of spent fuel) (Tanaka et al., 2003). The basic national policy of Japan is to isolate HLW underground at a depth of at least 300 m in a stable geologic formation. Coastal areas are identified as candidate repository sites for several reasons, such as transportation and logistical advantages for shipping, the lower hydraulic gradient of groundwater flow compared with inland areas, and the general lack of habitation areas downstream of the groundwater flow. However, seawater intrusions exist in the ground of coastal areas (Mitsuhata et al., 2006). The fresh/saltwater boundary in the ground can move depending on the sea level over long periods of time, e.g., thousands to tens of thousands of years (Ito et al., 2010; Tanaka et al., 2003). Furthermore, the subsurface of coastal areas may contain fossil seawater that was trapped during sediment formation. These physical and chemical changes in groundwater may affect subsurface facilities (Tanaka et al., 2003). Therefore, evaluating brackish/fresh groundwater distributions and hydrological structures in coastal area is essential (e.g., Marui, 2003; Marui and Hayashi, 2001).

The hydrology of coastal areas and related groundwater systems has been investigated extensively, for example, offshore of New Jersey, North America (Hathaway et al., 1979) and offshore of Surinam, South America (Groen et al., 2000). In addition to these fundamental studies, geoscientific investigations, which seamlessly image subsurface structure from land to sea, are important in order to clarify the entire hydrological system beneath a coastal area that involves both onshore and offshore regions (Fig. 1). Therefore, in Japan, several national and private research organizations have been conducting research and development in order to describe the geological structures and hydrological systems of coastal areas (Hama et al., 2007; Sugihara, 2009; Tokiwa et al., 2013). For example, several geoscientific studies, including geological, geochemical, and hydrological investigations, have focused on groundwater behavior associated with internal rocks and geological formations, including both saline and freshwater distributions (Ikawa et al., 2012; Kozai

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http://dx.doi.org/10.1016/j.jappgeo.2013.10.003

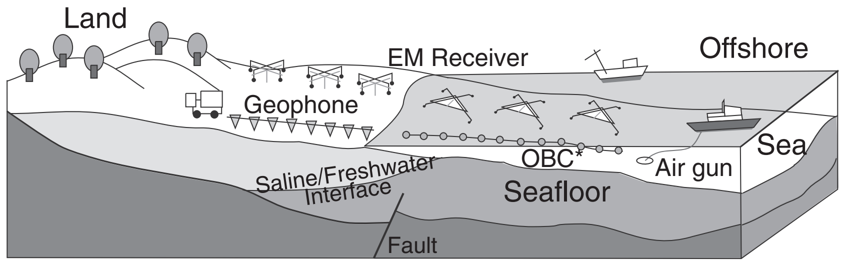

Fig. 1. Sketch of geophysical explorations of a coastal area. Geophones and ocean bottom cables (OBCs) for seismic exploration and receivers for electromagnetic (EM) field measurement.

et al., 2013). We have also been investigating geophysical methods for seamlessly evaluating geological structures from land to sea under a nuclear waste repository research project funded by the Ministry of Economy, Trade and Industry (METI) of Japan in the Horonobe coastal area since 2007.

The Horonobe coastal area, which is located along the northwestern coast of Hokkaido Island (Fig. 2), is part of a sedimentary coastal basin, which is composed of poorly compacted Neozoic sand-, silt-, and mudrocks (e.g., Koshigai et al., 2012). In this area, the gradient of the seafloor is small, e.g., the sea depth is approximately 60 m, even 10 km from shoreline. In order to comprehend the subsurface hydrological and geological structure, not only seismic and/or borehole logging methods but also geoelectrical methods, such as direct current electric and electromagnetic (EM) methods, are important because these methods can provide resistivity information related to saline/fresh groundwater (Fig. 1). Furthermore, EM methods are more suitable than the direct current electric method for geoelectrical investigation of HLW geological disposal because some EM methods can be used to investigate deep geoelectrical structure at depths of approximately 10 km using low-frequency EM signals.

Both onshore (e.g., Nabighian, 1991) and offshore (e.g., Constable, 1990, 2010), EM methods have been developed and successfully applied in commercial exploration and academic research for the past few decades. Although there has been significant progress, especially in deepwater (water depths greater than approximately 300 m) EM exploration (e.g., Chave et al., 1991; Constable and Srnka, 2007; Constable et al., 1998; Hoversten et al., 1998; Kasaya and Goto, 2009; Kaya et al., 2013; Key, 2011; Key et al., 2013), only a few results and reports of EM surveys in shallow water (water depths of less than approximately 300 m) and/or coastal regions (e.g., Andréis and MacGregor, 2008; Hoversten et al., 2000; Mittet and Morten, 2013; Weiss, 2007) have been presented. Moreover, very little research and development has been conducted (e.g., Yoshimura et al., 2006) in sea areas with water depths ranging from 5 to 100 m, which is referred to herein as very shallow water.

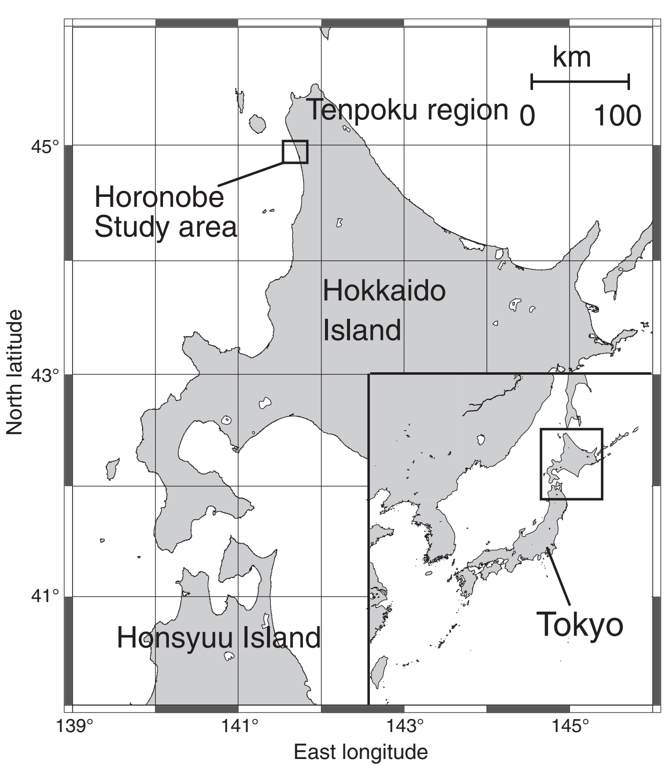

Fig. 2. Map of Hokkaido Island and location of the study area.

From a practical point of view, the difficulties of EM exploration in very shallow water and in coastal areas lie in (1) fishery activity, (2) limitations of the survey vessel size, and (3) motion noise caused by sea waves (Fig. 3) (Fournier and Reeves, 1986; Kinsman, 1965), especially for frequencies from 10^{-2} to 10^{0} Hz (period: 1 to 100 s) (e.g., Webb, 1998; Webb and Crawford, 2010). Under these conditions, the MT method is suitable because the MT method simply observes natural EM fields without transmitting any electric current in water. Therefore, the MT method does not negatively impact fishery activity in coastal areas.

However, the MT method requires the measurement of EM signals typically in the frequency range from 10^{-3} to 10^{4} Hz (Vozoff, 1991), including 10^{-2} to 10^{0} Hz, which are subject to contamination by motion noise due to sea waves (Fig. 3). In addition to motion noise, very shallow water at coastal areas makes it difficult to operate deep-draft survey ships having adequate payloads for EM survey equipment. For example, in the Horonobe coastal area, the sea depth is approximately 10 m at a distance of 1 km from the shoreline. In order to overcome these difficulties, we have developed a new marine MT measurement (ocean bottom electromagnetometer, OBEM) system for MT data acquisition in very shallow water, such as coastal regions. The new marine MT measurement system is very short in order to reduce motions caused by sea waves and is compact in order to allow light-draft small survey boat operation.

We began our research by conducting a preliminary hardware test and data acquisition examination using a synthetic signal generated by a controlled source at test facilities and conducted field experiments involving MT data measurement at the coastal area in Horonobe during 2010 and 2011. We also conducted onshore geophysical investigations, including seismic reflection and onshore MT surveys. Using both onshore and offshore MT data simultaneously, we performed 2D inversion in order to estimate a 2D resistivity model that is orthogonal to the shoreline. In addition to these geophysical explorations, we also conducted a 1000-m-deep drilling and well logging on land near the coastline of Horonobe field to obtain detailed geological information on the area. Resistivity is a function of porosity and pore fluid resistivity. Geological and hydrological interpretation based solely on the resistivity obtained by EM methods is difficult. Therefore, all geoscientific information obtained by various investigations described above have been interpreted in order to clarify the geological and hydrological structure under the Horonobe coastal region.