A semi-airborne TEM (GREATEM) survey and its applicability to geo-hazards

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Abstract

A semi-airborne TEM survey method, or a grounded electrical-source airborne transient electromagnetics (GREATEM), was exploited to mitigate natural disasters such as volcanic eruptions and tsunamis. The method was designed to survey deep electric resistivity structures in inaccessible areas such as rugged mountains. We applied GREATEM to active volcanoes such as Mt. Aso and Mt. Bandai, and also coastal areas such as Kujukuri and northernmost part of Awaji Island. Comparison of the GREATEM resistivity values with those of ground-based transient electromagnetics data, repeated GREATEM survey results at the same and different flight heights, and lithologic descriptions indicates that GREATEM can successfully identify underground structures as deep as ~800 m in rugged mountainous areas at a flight height of 100–200 m. In Mt. Aso, an active volcanic region (Naka-Dake crater) was mapped as a low-resistivity zone from the surface to a depth of 100 m. This low-resistivity zone extended to the west-north-west, implying future volcanic activity in this area. Therefore, it was found that the GREATEM method is useful for surveying deep structures in large, inaccessible areas, such as volcanic provinces. As for the mitigation of tsunami hazards, it is important to delineate underground features in coastal areas (including both on land and offshore), whereas limited information has been acquired due to the lack of suitable survey methods. In the Kujukuri alluvial coastal plain, it was found that the GREATEM can survey resistivity structures to a depth of 300–350 m in coastal areas where shallow water prevails. In conclusion, the GREATEM is applicable to survey deep magma activity in active volcanoes and also to survey underground structures in coastal areas in a quick and cost-effective way.

Keywords: airborne geophysics, electrical resistivity, Aso, Kujukuri

1. Introduction

Airborne geophysics is now used in many fields of investigations, covering geo-engineering, environmental observations, mineral and hydrocarbon explorations and more. The method is particularly useful for surveys of inaccessible areas such as rugged mountains and coastal areas covering both land and sea.

In view of the great potential of airborne geophysics and in order to mitigate natural disasters such as volcanic eruptions and large landslides, we have developed a semi-airborne TEM survey method, or a grounded electrical-source airborne transient electromagnetics (GREATEM). The method was first applied to active volcanoes such as Mt. Aso (Ito et al., 2014), Mt. Bandai (Mogi et al., 2009) and others. It was then used for surveys for construction of long underground tunnels in mountainous areas (Okazaki et al., 2011). In order to test the applicability of the GREATEM method to other inaccessible areas, we have challenged to survey coastal areas covering both land and sea such as the Kujukuri coastal plain (Ito et al., 2011; Abd Allah et al., 2013) and Awaji Island (Abd Allah et al., 2014).

This paper introduces some topics of our experience, especially survey results at Mt. Aso (Ito et al., 2014) and the Kujukuri coastal plain (Ito et al., 2011) and shows the usefulness of the GREATEM technology to survey underground structures at inaccessible areas.

2. GREATEM system

The GREATEM system uses a grounded electrical dipole source 2–3 km in length as the transmitter and a three-component magnetometer in the towed bird as the detector (Mogi et al., 1998; Ito et al., 2011; Okazaki et al., 2011) (Fig. 1). With a grounded source, a large moment source can be applied and a long transmitter-receiver distance used, yielding a greater depth of investigation. Other advantages include a small effect of flight altitude and the possibility of high-altitude measurements. Mogi et al. (1998) illustrated some theoretical transient responses of magnetic fields in the air for horizontally layered structures and noted several features of the GREATEM response, such as the depth of investigation, effect of measuring height, and source–receiver distance. Mogi et al. (1998) also indicated the advantages of the system for investigating deep structures to a depth of more than 1000 m and the possibility of identifying resistivity structure responses from heights of 100–500 m. To realize the method, we overcame two main problems: monitoring and filtering the motion noise of the receiver and cancelling the natural magnetic field variation and cultural noise without stacking in the time domain data. We installed a high-accuracy fiber-optic gyro (Japan Aviation Electronics Industry, JCS7401) as an attitude sensor to monitor the pitch and roll of the sensor in the bird, and manufactured an electromagnetic receiver (induction coils) that can detect three components of the magnetic field. A three-component magneto-impedance (MI) sensor was installed to detect azimuth direction. These attitude, magnetic, and directional sensors were installed on gimbals in the bird. The data acquisition system, consisting of a 16-bit analog-to-digital (AD) converter which digitizes at a rate of 80 μs, was first installed in the helicopter cabin with a high-precision global positioning system (GPS; NovAtel, GPS-702) synchronized with the same type of GPS in the transmitter. This system was designed to analyse full wave data in the time domain for investigating deep to shallow subsurface resistivity structures. Note that the latest GREATEM system was further improved using a 24-bit AD converter towed in a container as shown in Fig. 1.

3. A case study at a mountainous area

3.1 Aso volcano

Aso Volcano is located in central Kyushu, southwest Japan, and has an oval caldera measuring about 18 × 25 km (EW × NS) (Fig. 2). Geological studies have revealed that the caldera was formed by four major explosive eruptions with devastating pyroclastic flows that took place between approximately 270 and 90 ka. Post-caldera central cones formed soon after the last caldera-forming eruption (90 ka) and have produced large volumes of fallout tephra and lava flows. Most of the eruptions in historical time have been characterized by basaltic to basaltic-andesite ash emission with periodic strombolian and phreatic to phreatomagmatic activities at Naka-Dake, one of the youngest cones (Fig. 2).

3.2 Survey results of Aso volcano

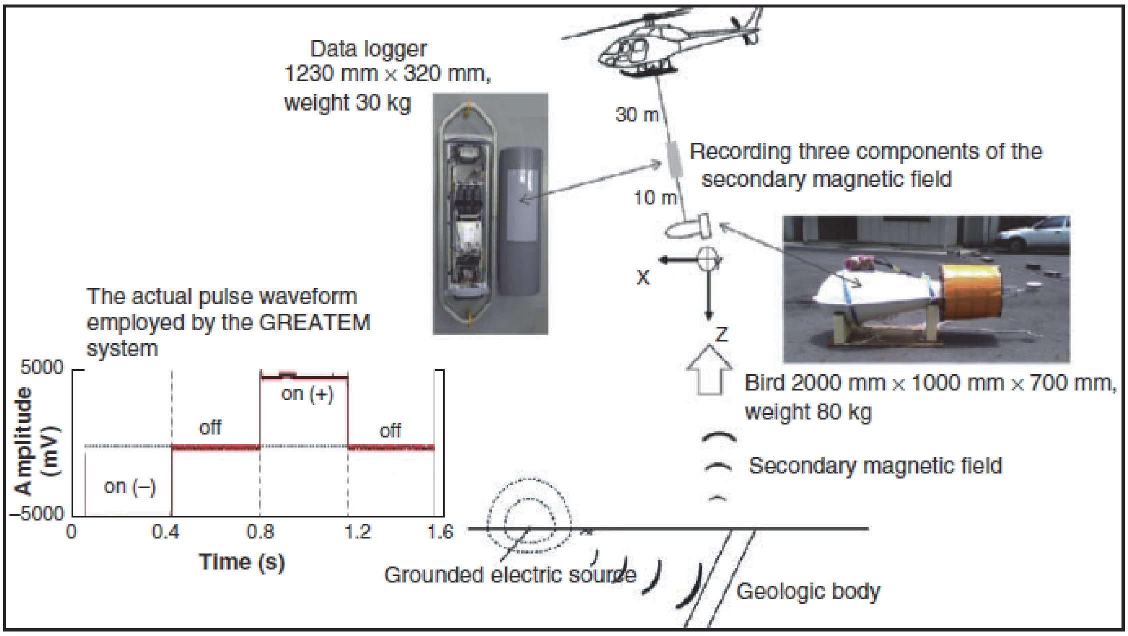

Fig. 1 Overview of the GREATEM system. The towed bird contains the three-component magnetometer, gyro, directional MI sensor and GPS sensor. The data logger has a 24-bit AD converter, SSD memory, and a high-precision clock synchronized with the transmitter-control clock in the towed container. The secondary magnetic field induced in accordance with the ground resistivity is recorded during current ‘on’ and ‘off’ times.

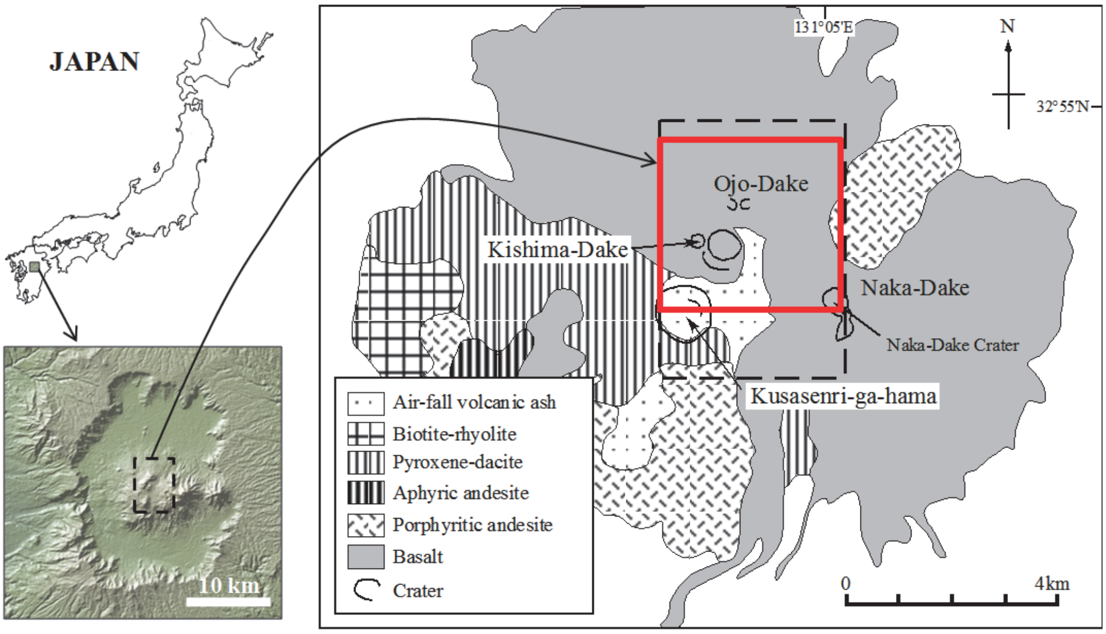

Fig. 2 The locations of Aso Volcano and the GREATEM survey area. Dashed and red rectangles are the flight area and the survey area shown in Fig. 3, respectively.

Fig. 3 shows resistivity maps at depths of 10 and 100 m using data obtained at a height of 100 m. The overall resistivity distributions in both maps are similar. A low-resistivity zone of < 20 Ωm exists in the Naka-Dake Crater. In this area, hot fluid is usually trapped in the crater lake and hydrothermal alteration is dominant underneath, which explains the low resistivity. This result is concordant with the ground-based controlled-source magnetotelluric (CSMT) result of Handa and Tanaka (1999), who reported a low-resistivity zone of < 10 Ωm in and around the Naka-Dake Crater at depths of 100–400 m. Handa and Tanaka (1999) attributed the low resistivity to the existence of hydrothermal fluids rich in ionized particles. The GREATEM data newly revealed that the low-resistivity zone extends to the west-northwest toward Kishima-Dake, which suggests that hydrothermal fluids also extend in the same direction. This low-resistivity zone is also vaguely shown in Handa and Tanaka's (1999)

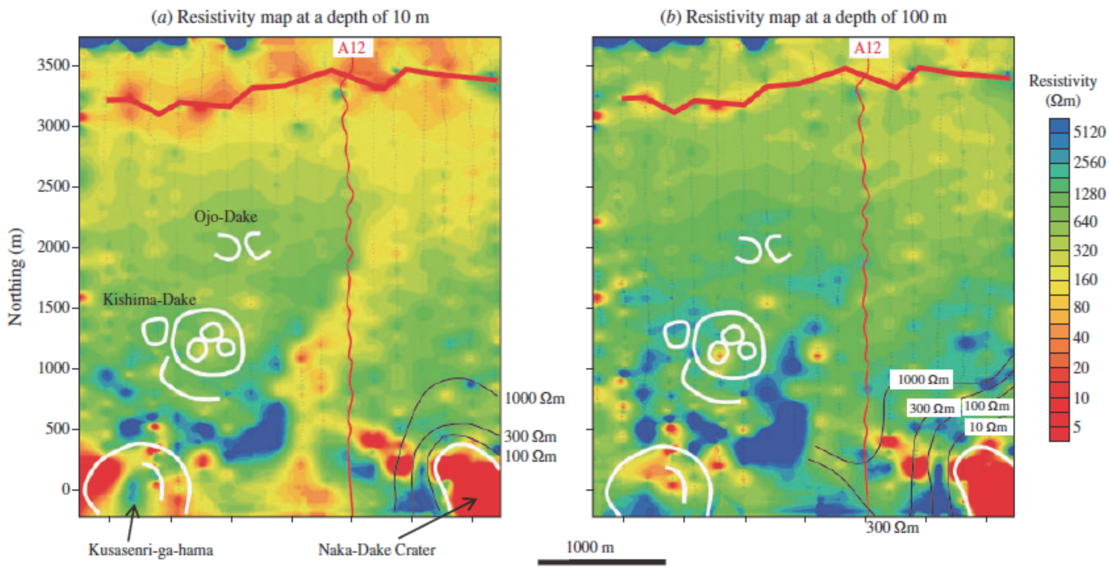

Fig. 3 Resistivity maps at depths of 10 m (a) and 100 m (b) using data from a flight height of 100 m in 2004. The thick red line indicates the transmitter cable (electrical source). The location of flight line A12 (thin red line) is shown for reference. White lines indicate the craters. Resistivity contours (a) and (b) are those at ground surface and at 1000 m elevation (corresponding to ~100–250 m depth) in Handa and Tanaka (1999), respectively.

resistivity maps at 800 and 1000 m in elevation. Handa and Tanaka (1999) also mentioned that the low-resistivity zone tends to expand when volcanic activity is intense in the Naka-Dake Crater. Therefore, the newly found low-resistivity zone to the west-northwest of the Naka-Dake Crater is a place where future volcanic activity might occur because of the possible existence of hydrothermal fluids.

Conversely, there are no low-resistivity zones at the other craters at a depth of 100 m (Fig. 3b). This concurs with the CSMT result of Handa and Tanaka (1999) and also with the magnetotelluric result of Asaue et al. (2005). Asaue et al. (2005) reported resistivity-depth profiles from the surface to 4000 m depth in and around Kusasenri-ga-hama and showed a resistivity of > 100 Ωm at ~100 m depth in Kusasenri-ga-hama. The low-resistivity zone in the western part of Kusasenri-ga-hama at a depth of 10 m (Fig. 3a) probably reflects the fact that the area is a wetland. High-resistivity (> 2000 Ωm) areas are distributed sporadically, especially to the south of Kishima-Dake. These areas are mostly outside the craters, where rock mass deformation has been less intense and therefore high resistivity is likely. The low-resistivity belt along the electrical source (Fig. 3a) resulted from a rapid decrease in the magnetic response due to the proximity of the transmitter and receiver, which leads to an erroneous fitting at the sampling rate used.

4. A case study at a coastal area

4.1 Kujukuri coastal plain

The Kujukuri coastal plain, Boso Peninsula, southeast Japan (Fig. 4) was selected for our study. It is one of the longest coastal plains in Japan measuring 60 km in length and 10 km in width. This area is suitable for our first attempt because the seawater is shallow and adequate resistivity data from previous investigations were available (Mitsuhata et al., 2006; Uehara et al., 2007; Hayashi et al., 2009). Mitsuhata et al. (2006) applied three types of grounded-source resistivity surveys: audio-frequency magnetotelluric, transient electromagnetic, and small loop-loop EM measurements. They revealed resistivity features to a depth of ~500 m on the landward side and the existence of deep fossil saline water underneath. Uehara et al. (2007) applied electric resistivity measurements along a land-seafloor crossing line and determined the resistivity structure to a depth of 40 m both on the land and sea sides.

4.2 Survey results of Kujukuri coastal plain

As shown in Fig. 5, resistivity structure to a depth of 300–350 m was obtained. The resistivity structure shows that low resistivity of less than 1 Ωm prevails beneath both land and sea. Landmass with higher resistivity (~3–10 Ωm), herein called high-resistivity landmass, exists to a depth of ~50 m between the shore and ~300 m landward from the sea. The thickest high-resistivity landmass resides in K-Line, which lies almost along a river (Fig. 4b), therefore this landmass corresponds to either thick sand deposits, less saline groundwater mass, or both.

Using electric resistivity measurements, Uehara et al. (2007) showed high-resistivity landmass of 3–100 Ωm exists to a depth of 30 m beneath the

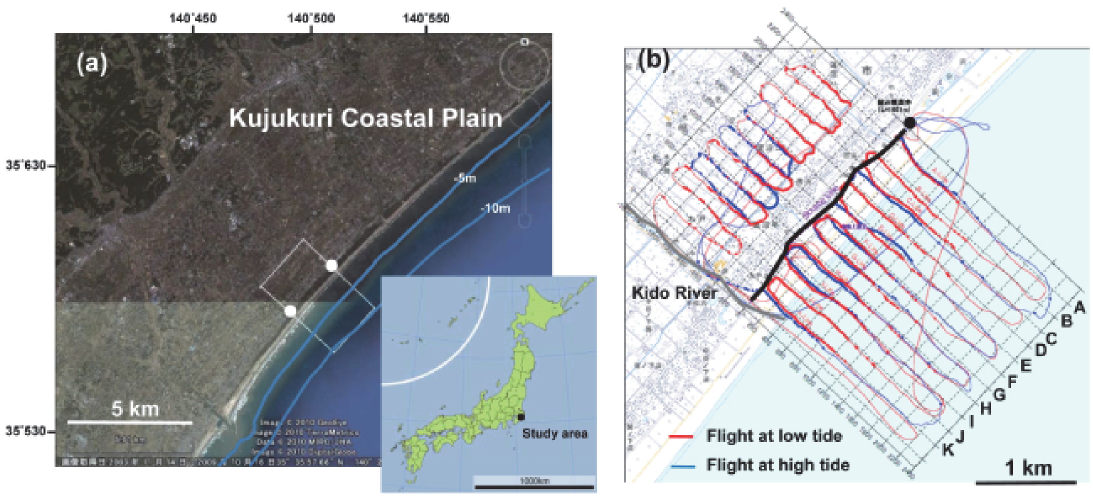

Fig. 4 (a) Location of survey area in the Kujukuri coastal plain with 5-m bathymetric contours. White dots denote the places where current dipole electrodes were placed. (b) Survey area and flight lines. The thick black line indicates the transmitter cable, which was placed 300–400 m inland and parallel with the coastal line. Meaningful data were obtained along flight lines with a thicker color. A black dot indicates the wellbore site in Hayashi et al. (2009).

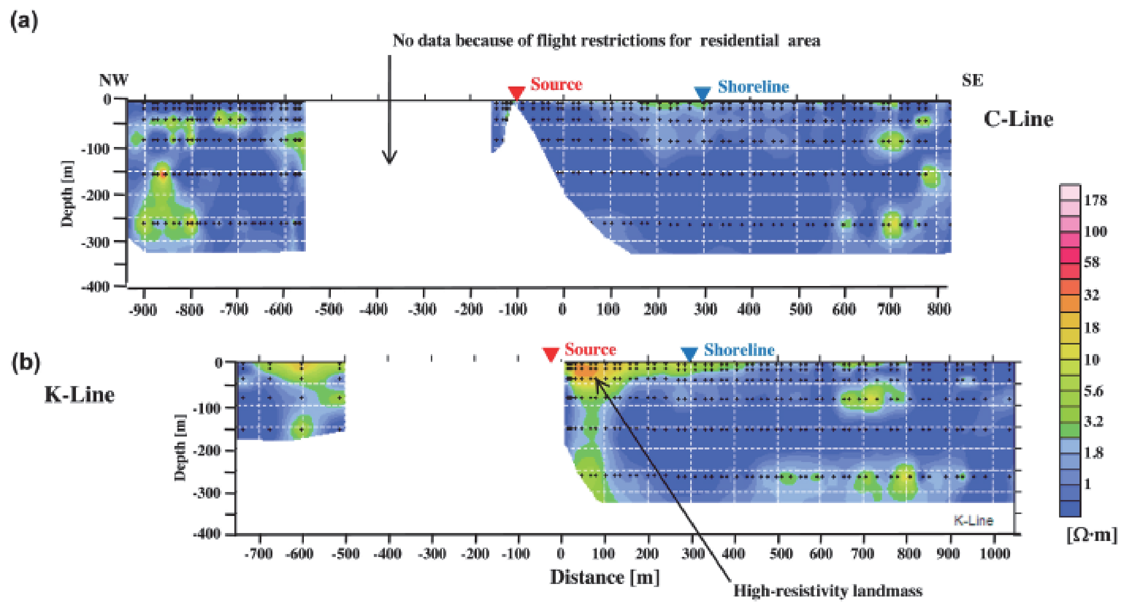

Fig. 5 Resistivity profiles along flight lines C (a) and K (b) at low tide.

beach, and low resistivity (less than 2 Ωm) prevails below the bottom of the high-resistivity landmass and adjacent sea bottom. This corresponds well with our results (Fig. 5), although the resolution of GREATEM is much lower than the electric resistivity method.

Mitsuhata et al. (2006) applied three different-scale electromagnetic measurements on land. Their results show that on the land side a high-resistive surficial zone about 30 m thick (sandy ridge) is underlain by a low resistive (~1 Ωm) zone, which was thought to be caused by seawater intrusion. They also showed that a surficial low-resistive structure (salt marsh) exists behind the sandy ridge. These features are also recognized in our study, assuring the credibility of our method.

Hayashi et al. (2009) reported wellbore logging data from 30 m to 1660 m in depth adjacent to our study site (Fig. 4b), which shows that a low resistivity zone of 1–2 Ωm comprised of Quaternary siltstone resides from 30 m to at least 1000 m in depth. This also is in good agreement with our data.

The reason the electrical source was set 300–400 m inland was to obtain the highest quality data beneath the shoreline. This goal was achieved as evidenced by a clear signal beneath the shoreline (Fig. 5).

Although the method employed here has some limitations in that it is impossible to delineate the resistivity structure directly beneath the source (Fig. 5) and data quality becomes worse according to the distance from the source, the GREATEM system has the capability to determine underground resistivity structure to greater depths and more safely than conventional airborne electromagnetics.

5. Conclusions

Two case studies of the GREATEM were shown. In the case of Mt. Aso, it was shown that the GREATEM can map resistivity in detail to a depth of ~100 m and can assess magmatic activity. We also showed that the GREATEM can map resistivity to a depth of ~800 m and the reliability of the method by comparison of the repeated GREATEM surveys at different flight heights of 100 m and 200 m (See Ito et al., 2014). Therefore the method is useful to survey deep resistivity structure at rugged mountainous areas, which can be applied to assess future volcanic activities and/or large landslides in mountainous areas.

In the case of the Kujukuri coastal plain, we could map resistivity to a depth of ~300–350 m beneath a shoreline in a quick and cost-effective manner, which can be used to unravel geological and geomorphological history in coastal areas (such as to detect tsunami deposits), and to plan to make safer development in coastal areas.

In conclusion, the GREATEM method can be used to mitigate geo-hazards by mapping a place where future geo-hazards might occur and it is especially useful for surveying inaccessible areas.

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