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Temporal changes in electrical resistivity at Sakurajima volcano from continuous magnetotelluric observations

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ABSTRACT

Continuous magnetotelluric (MT) measurements were conducted from May 2008 to July 2009 at Sakurajima, one of the most active volcanoes in Japan. Two observation sites were established at locations 3.3 km east and 3 km west–northwest of the summit crater. At both observation sites, the high-quality component of the impedance tensor (Zyx) showed variations in apparent resistivity of approximately ±20% and phase change of ±2°, which continued for 20–180 days in the frequency range between 320 and 4 Hz. The start of the period of changes in apparent resistivity approximately coincided with the start of uplift in the direction of the summit crater, as observed by a tiltmeter, which is one of the most reliable pieces of equipment with which to detect magma intrusion beneath a volcano. A 2D inversion of MT impedance suggests that the resistivity change occurred at a depth around sea level. One of the possible implications of the present finding is that the degassed volatiles migrated not only vertically through the conduit but also laterally through a fracture network, mixing with shallow groundwater beneath sea level and thereby causing the observed resistivity change.

1. Introduction

The monitoring of subsurface magma is an essential approach in terms of predicting volcanic eruptions and contributing to hazard mitigation. Daily imaging of the location, volume, and physical properties (e.g., pressure and gas fraction) of subsurface magma enables predictions not only of eruption timing, but also its location, duration, and degree of explosivity.

Geodetic measurements (strain, tilting, and GPS) are currently the most practical methods with which to investigate changes in subsurface magma, because such data are sensitive to subtle pressure changes and have high temporal resolution. For example, at Sakurajima volcano, Japan, Vulcanian-type eruptions are routinely predicted in advance by up to 1 day based on data from a strainmeter and tiltmeter installed in a tunnel at the volcano (e.g., Ishihara, 1990; Iguchi et al., 2008a,b). However, it is generally difficult to predict an eruption over the coming weeks or months. In addition, some eruptions occur without significant ground deformation.

It is a promising procedure to monitor changes in subsurface structure as an indicator of changes in subsurface magma. Previous studies have used seismic methods to investigate changes in structure beneath active volcanoes and geothermal areas (e.g., Foulger et al., 1997; Nishimura et al., 2000; Miller and Savage, 2001; Foulger et al., 2003; Gerst and Savage, 2004; Yamawaki et al., 2004; Nishimura et al., 2006). A recent study of temporal change in seismic structure (4D tomography) beneath Etna volcano, Italy, clearly imaged change in the structure of Vp/Vs ratio (Patanè et al., 2006). The authors attributed the change in Vp/Vs to subsurface magma movement and corresponding degassing of volatiles. Another approach involves using seismic noise records to monitor seismic structure, as reported by Brenguier et al. (2007, 2008). Based on the premise that long-term averaging of seismic noise produces a random source field, the authors imaged changes in seismic velocity at Piton de la Fournaise volcano, Reunion Island. These recently developed seismic methods have given rise to the possibility of monitoring magma movement and predicting eruptions, although such approaches require a dense seismometer network.

The monitoring of electrical resistivity structure also shows promise in terms of imaging subsurface magma, because magma

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(melt) and degassed volatiles (if mixed with groundwater) are highly conductive. Indeed, repeated DC electrical measurements revealed a significant resistivity change coincident with the 1986 eruption of Izu-Oshima volcano, Japan, from which the movement of subsurface magma was inferred (Yukutake et al., 1990; Utada, 2003). At Miyake-jima volcano, Japan, significant resistivity change was observed before the formation of a crater in 2000, interpreted to represent disturbance of the hydrothermal system (Zlotnicki et al., 2003). Because these pioneering studies used DC electrical measurements with a few receivers, the temporal resolution (several weeks to months) or the spatial resolution (hundreds of meter) beneath the observation line are relatively coarse. In the present study, we provide the first results of long-term (over 1 year), continuous magnetotellurics (MT) observations of an active volcano using the natural electromagnetic source field. Because MT impedance is stable and has high temporal resolution (Eisel and Egbert, 2001; Hanekop and Simpson, 2006; Kappler et al., 2010), the MT technique is suitable for monitoring subsurface resistivity structure.

2. Observations

Continuous MT observations were carried out at Sakurajima volcano, which is one of the most active volcanoes in Japan. Sakurajima is located in southern Kyushu, and its summit is ~1100 m above sea level. The volcano is located in the southern part of the 20 × 20 km Aira caldera (Fig. 1), which emitted 100 km^3 of eruption products during an event 22,000 years ago (Aramaki, 1984). Since 1955, eruptions have occurred mainly at the summit crater (Minami-dake). Volcanic activity is characterized by Vulcanian eruptions (~8000 explosions in the past 50 years), effusive eruptions, and continuous ash emissions. Showa crater, which is located 500 m east of the Minami-dake summit crater, started to erupt in June 2006 after lying dormant for 58 years. Activity at Showa crater gradually replaced that at Minami-dake, with eruptions becoming increasingly vigorous: 548 explosions were recorded in 2009. The magma volume presently emitted from Sakurajima is in the order of 0.001 km^3/year (Iguchi et al., 2008a,b).

In 2008, we established two continuous MT observation sites at locations 3.3 km east of Showa crater (KURMT) and 3 km west–northwest of the crater (HARMT) (Fig. 1). This paper is the first report of long-term continuous MT measurements performed with the aim of investigating the relationship between volcanic activity and resistivity change, although MT observations were previously carried out for 6 weeks at Ruapehu volcano, New Zealand, to investigate the relationship between earthquakes and resistivity change (Hanekop and Simpson, 2006). Naturally occurring geomagnetic fields and induced earth electric currents in the frequency range of 320–0.0005 Hz were measured using Phoenix MTU5 systems. Sampling frequencies were 2400 Hz (1 s every 4 min), 150 Hz (16 s every 4 min), and 15 Hz (continuous), from which high-frequency variations were removed using an anti-aliasing filter. The electrodes were buried at 30 cm depth at spacings of ~20 m; the contact resistance between electrode and soils was maintained below 3000 Ω. The observation sites were visited approximately weekly for maintenance of the apparatus (e.g., changing batteries, sweeping away volcanic ash, and checking that cables had not been disconnected as a result of animal activity) and for collecting the time series data stored on a 4 GB CompactFlash card. The MT time series during eruptions contain

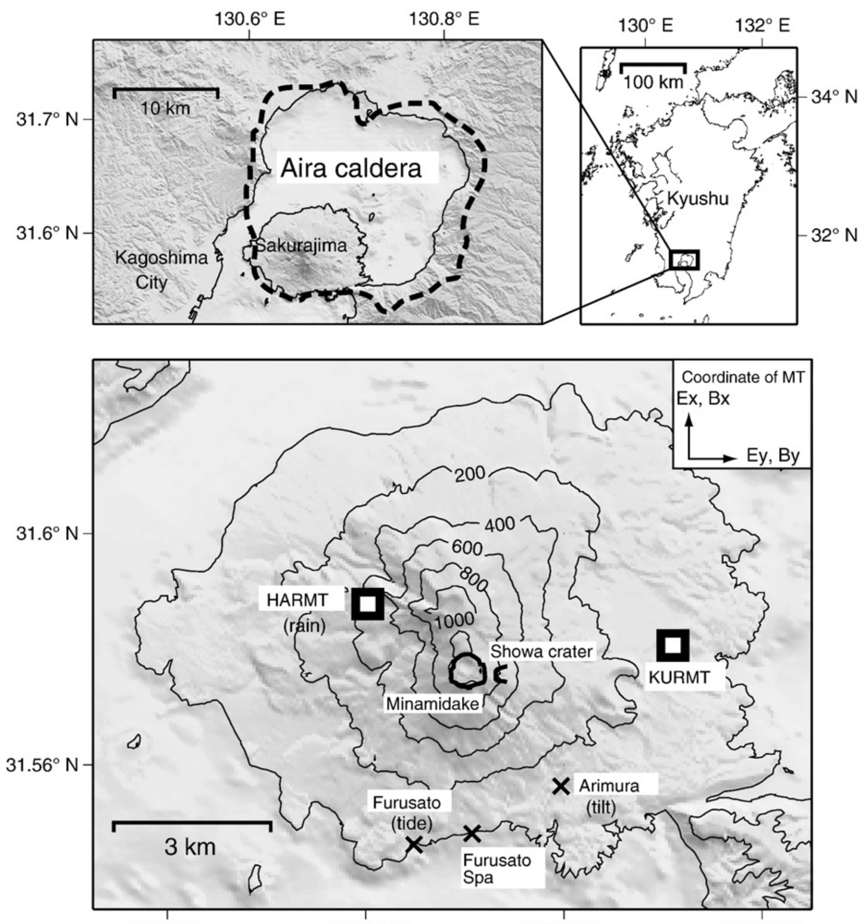

Fig. 1. Locations of sites of continuous MT measurements at Sakurajima volcano (squares) and sites of other geophysical/geochemical observations (crosses; see Section 5).