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A preparation zone for volcanic explosions beneath Naka-dake crater, Aso volcano, as inferred from magnetotelluric surveys

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ABSTRACT

The 1st crater of Naka-dake, Aso volcano, is one of the most active craters in Japan, and known to have a characteristic cycle of activity that consists of the formation of a crater lake, drying-up of the lake water, and finally a Strombolian-type eruption. Recent observations indicate an increase in eruptive activity including a decrease in the level of the lake water, mud eruptions, and red hot glows on the crater wall. Temporal variations in the geomagnetic field observed around the craters of Naka-dake also indicate that thermal demagnetization of the subsurface rocks has been occurring in shallow subsurface areas around the 1st crater. Volcanic explosions act to release the energy transferred from magma or volcanic fluids. Measurement of the subsurface electrical resistivity is a promising method in investigating the shallow structure of the volcanic edifices, where energy from various sources accumulates, and in investigating the behaviors of magma and volcanic fluids. We carried out audio-frequency magnetotelluric surveys around the craters of Naka-dake in 2004 and 2005 to determine the detailed electrical structure down to a depth of around 1 km. The main objective of this study is to identify the specific subsurface structure that acts to store energy as a preparation zone for volcanic eruption. Two-dimensional inversions were applied to four profiles across the craters, revealing a strongly conductive zone at several hundred meters depth beneath the 1st crater and surrounding area. In contrast, we found no such remarkable conductor at shallow depths beneath the 4th crater, which has been inactive for 70 years, finding instead a relatively resistive body. The distribution of the rotational invariant of the magnetotelluric impedance tensor is consistent with the inversion results. This unusual shallow structure probably reflects the existence of a supply path of high-temperature volcanic gases to the crater bottom. We propose that the upper part of the conductor identified beneath the 1st crater is mainly composed of hydrothermally altered zone that acts both as a cap to upwelling fluids supplied from deep-level magma and as a floor to infiltrating fluid from the crater lake. The relatively resistive body found beneath the 4th crater represents consolidated magma. These results suggest that the shallow conductor beneath the active crater is closely related to a component of the mechanism that controls volcanic activity within Naka-dake.

1. Introduction

Volcanic explosions represent the phenomenon by which thermal or mechanical energy accumulated within the volcano is released from the crater over a very short period of time. In addition to magmatic explosions, phreatic or phreatomagmatic explosions may occur if the magma heats or comes into contact with the groundwater. To obtain a better understanding of volcanic explosions, it is important to investigate the preparation zone for explosions where thermal or mechanical energy is accumulated, and to determine the state of the magma, heat, or groundwater that house the accumulated energy.

Aso volcano is located in the central part of Kyushu Island, southwestern Japan (Fig. 1). Naka-dake is the summit of the central cone complex, situated in a large oval-shaped caldera of 25 km by 17 km in area. Over the past 70 years, all of the volcanic events within Aso volcano have originated from the 1st crater of Naka-dake, and all conform to the following eruptive pattern. During a quiet period, the crater becomes filled with hot, acidic water. As the crater bottom is heated by deep-level thermal energy, it gradually dries up and a red glow is seen on the crater wall or bottom. Subsequently, vents open and emit ash, sometimes accompanied by phreatic eruptions. The activity then progresses to a Strombolian eruption stage, after which the activity declines and the crater bottom again fills with water (e.g. Ono et al., 1995a; Sudo et al., 2006). Although each stage is of different duration, the nature of this cycle of activity was recognized 70 years

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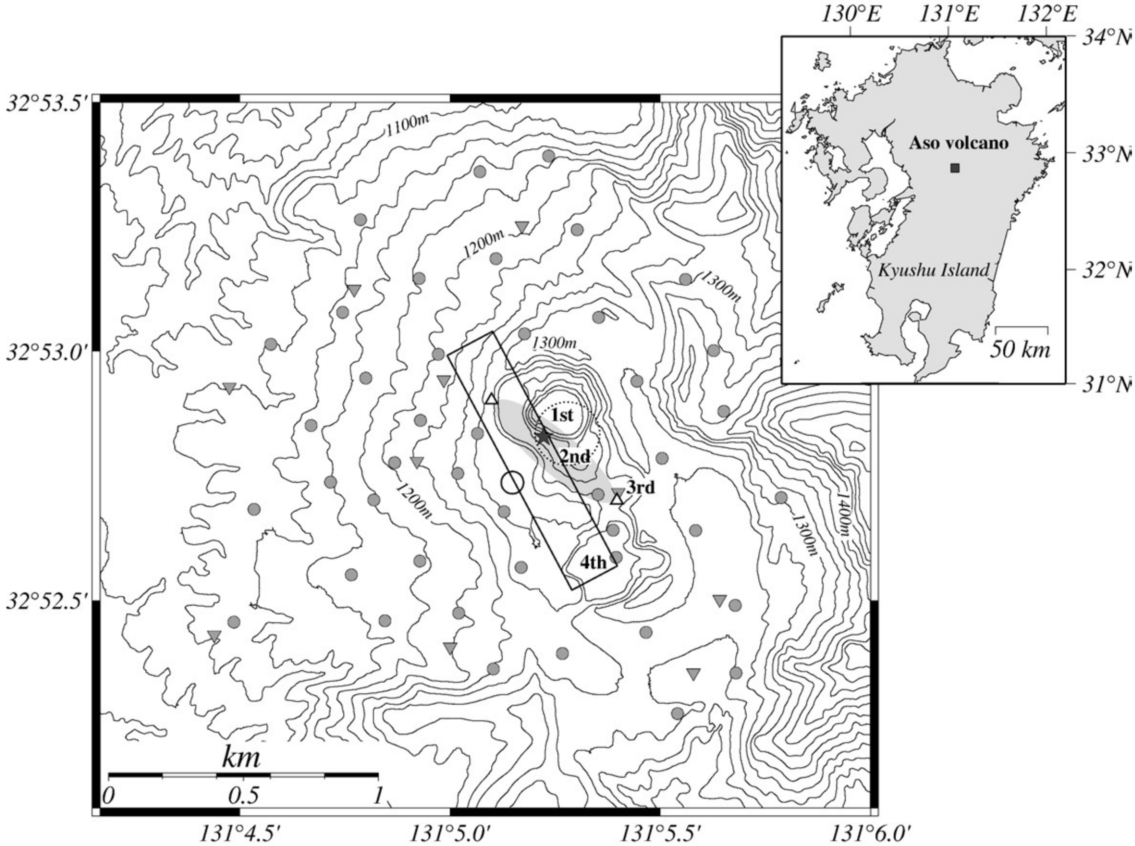

Fig. 1. Location of Aso volcano (inset) and topographic map of the Naka-dake craters, showing the 1st to 4th craters. Circles indicate audio-frequency magnetotelluric (AMT) sites surveyed in 2004 and 2005. Inverted triangles represent some of the wide-band MT sites surveyed in 1999 (Hashimoto et al., 2002). The star denotes the location of an equivalent source inferred from temporal variations in the geomagnetic field (Tanaka, 1993). The rectangle and open circle represent the source region of the LPTs estimated using a tensile crack model (Yamamoto et al., 1999) and an isotropic point-source model (Kawakatsu et al., 2000), respectively. The source region of the SPTs (Mori et al., in press) and two point sources of continuous tremors (Takagi et al., 2006) are shown by a dotted circle and open triangles, respectively. The shaded area represents the apparent epicenters of the continuous tremors (Takagi et al., 2006). The calculated depths are 1–1.5 km for the LPT point source, about 300 m for the SPT source, and shallower than the SPT source for the continuous tremor source. The upper edge of the crack model is located at a depth of about 300 m.

ago when modern volcanology observations were first initiated in the area (Namba, 1936); such cycles have been observed repeatedly over periods of at least several tens of years. The present-day activity is also considered to be part of a cycle. No remarkable volcanic activity was observed at Naka-dake between 1995 and 2000; however an increase in activity has been observed since 2000, including a reduction in the level of the crater lake, mud eruptions, tremors, and red glows with temperatures above 500 °C.

Researchers from Kyoto University have recorded geomagnetic total intensities in the area of the Naka-dake craters since the late 1980s (Tanaka, 1993). During eruptive activity in 1989–1990, a thermally demagnetized zone was inferred southwest of the 1st crater at a depth of 200–300 m (star in Fig. 1), where interaction between groundwater and superheated water vapor or volcanic gases is considered to take place, thereby enabling efficient heat transfer. Recent temporal variations in the geomagnetic fields also suggest the supply of heat to the crater bottom. A decreasing trend in geomagnetic intensity has been observed at a site on the southern side of the 1st crater since 1998, reaching −20 nT by 2004 (Aso Volcanological Laboratory, 2004). The temporal pattern of the observed geomagnetic variations is consistent with a thermal demagnetization model in which gradual heating is assumed immediately below the 1st crater. The location of an equivalent point source is similar to that inferred during the 1989–1990 eruptive period.

Electromagnetic (EM) soundings are widely used to investigate the subsurface structure of volcanoes because of their sensitivity to saline fluids and high-temperature melts (e.g. Ingham, 1992; Müller and Haak, 2004; Manzella and Zaja, 2006). Sensitivity to conductive clay minerals is an additional important property of EM soundings in volcanic and geothermal contexts for the delineation of zones of hydrothermal alteration (e.g. Wright et al., 1985; Pellerin et al., 1996; Ogawa et al., 1998; Matsushima et al., 2001; Nurhasan et al., 2006). Many electric and electromagnetic surveys have been undertaken around the Naka-dake craters at Aso volcano. Tanaka et al. (1981) conducted seven vertical electric soundings using a Schlumberger array, reporting a heterogeneous resistivity structure around the craters and low resistivity of several tens ohm meters below the surface, although sounding depth was approximately 100 m because of the limitation of the array length. Handa et al. (1998) carried out magnetotelluric (MT) surveys at 200 sites in and around the Aso Caldera over the period from 1983 to 1987. The authors' two-dimensional (2-D) forward modeling across the caldera revealed a low-resistivity layer of 10 Ωm beneath the Naka-dake craters. This layer was interpreted as a geothermal system associated with volcanic activity; however, the authors used just four frequencies: 10,200 Hz transmitted from an Omega station and three lower resonant frequencies of the Schumann resonance (7.8, 14.1, and 20.4 Hz). A controlled-source MT method was also applied around the craters during the period 1989–1990 (Handa and Tanaka, 1999), using 11 frequencies ranging from 7.8 to 5120 Hz. In this case, the authors presented a 2-D resistivity section across the Naka-dake craters and identified a very-low-resistivity zone (<1 Ωm) beneath the craters; however, their 2-D model was based on trial-and-error forward modeling, and the sounding depth was 500 m at most. A wideband MT survey (Hashimoto et al., 2002) and a time domain electromagnetic