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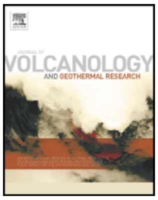

Hydrothermal system beneath the crater of Tarumai volcano, Japan: 3-D resistivity structure revealed using audio-magnetotellurics and induction vector

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ABSTRACT

Audio-magnetotelluric (AMT) measurements were recorded in the crater area of Tarumai volcano, northeastern Japan. This survey brought the specific structures beneath the lava dome of Tarumai volcano, enabling us to interpret the relationship between the subsurface structure and fumarolic activity in the vicinity of a lava dome. Three-dimensional resistivity modeling was performed to achieve this purpose. The measured induction vectors pointed toward the center of the dome, implying the topographic effect. However, estimation of the topographic effect showed that the measured vector was not explained only by this effect. This suggested that the distribution of induction vectors still held information of the subsurface structure and could be helpful in determining the geometry of 3-D bodies. The 3-D modeling was based on a quasi-one-dimensional layered structure that included topography. The final model revealed that the andesitic lava dome is characterized by comparatively low resistivity (50 Ωm), and that two conductive bodies (50 and 1–5 Ωm) are present beneath the lava dome. The shallower of these conductors is interpreted as an aquifer, such as a buried crater lake. The deeper, extremely conductive body corresponded to a convecting zone containing rising hydrothermal fluid. The shallower aquifer critically controls the temperature and chemical components of the fumarolic gasses. High-temperature gas supplied from deeper part that encounters the shallow aquifer loses its water-soluble components and heat, resulting in weak and low-temperature fumaroles. In contrast, most of the gas, which ascends outside the area of the shallower aquifer, is released as high-temperature fumaroles. This study provides an insight that the shallow aquifer in the crater area plays a significant role in the property of fumaroles at the volcanic surface.

1. Introduction

The three-dimensional (3-D) resistivity structure beneath an active volcano can provide information about the location and transport path of volcanic fluids, because the resistivity of rocks is effectively varied by the existence of fluids, hydrothermal alteration and temperature. The distribution and behavior of volcanic fluids such as magma, volcanic gas, and hydrothermal fluids are unique to each volcano. For example, understanding the phreatic explosions that result when magma contacts a shallow aquifer (e.g., Kagiyama et al., 1999) requires data on the position and volume of the aquifer. Investigating the 3-D resistivity structure of a volcano can identify the depth and position of such aquifers, contributing to our understanding of hydrothermal condition beneath volcanoes.

Fumarolic activity of Tarumai volcano, located in northeastern Japan, has been constant on and around a lava dome that formed in the crater area during the 1909 eruption. Fumaroles occupy an area approximately 500 m in diameter. Fumaroles located on the southern part of the dome emit particularly high-temperature gases that reach 600 °C (Sapporo District Meteorological Observatory, 2004), suggesting that they degas directly from magma. The temperature of other fumaroles, however, is below the boiling point of water. Such spatial differences in fumarolic temperature may be a function of the subsurface structure beneath the fumaroles. Taking this assumption into consideration, audio-magnetotelluric (AMT) soundings were conducted at densely spaced sites to delineate the 3-D resistivity structure of the subsurface.

This paper treats electrical resistivity as a parameter that reflects the 3-D subsurface structure. MT soundings have been successfully used at many volcanic and geothermal areas to reveal hydrothermal convection systems and magma reservoirs (e.g., Matsushima et al., 2001; Aizawa et al., 2008; Kanda et al., 2008). MT soundings have also been used to locate volcanic fluid paths (e.g., Nurhasan et al., 2006). Such studies have generally analyzed MT data using inversions and assuming a two-dimensional (2-D) structure. The 2-D assumption, however, can be a problem when investigating volcanoes because of the effect of surface topography. The topographic effect on MT data is quite different between 2-D and 3-D topography (Nam et al.,

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2007); thus using a 2-D assumption for 3-D topography can provide misleading results in the resulting resistivity model. Another problem is determining the strike of a 2-D structure. Techniques for estimating an electromagnetic 2-D strike, such as Groom–Bailey′s decomposition (Groom and Bailey, 1989) and the phase-tensor technique (Caldwell et al., 2004), commonly do not yield a consistent 2-D strike direction. This indicates that the assumption of 2-D structure is not appropriate for such study areas. Three-dimensional analyses overcome such problems. As a result of improved computing technology, the computing time for 3-D numerical modeling has recently decreased, and 3-D forward modeling is now widely used. However, 3-D forward modeling that incorporates surface topography remains uncommon (e.g., Mogi and Nakama, 1993; Müller and Haak, 2004), and few studies of the 3-D resistivity structure of volcanoes have used a numerical inversion technique (e.g., Jones et al., 2008). This has been caused by working cost to obtain denser measurements for 3-D modeling and long duration to calculate the response including surface topography. The AMT soundings that target shallow structure, however, can be measured by comparatively lightweight instruments and require only a few hours per a station. As the computation time has been shortened practical level, 3-D modeling is now becoming more popular than before. Such a 3-D modeling should be applied proactively to volcanic areas. To obtain the knowledge of 3-D subsurface structure, this study applied 3-D resistivity modeling to AMT data for the crater area of Tarumai volcano.

In this study, the induction vector is used in the modeling as well as the ordinary impedance tensor, aiming for fleeing the static shift. We show the usefulness of the induction vector in 3-D modeling with steep topography. Based on our resistivity model, structural control of fumarolic activity around the lava dome is discussed.

2. The lava dome of Tarumai volcano and its surroundings

Tarumai is an active andesitic volcano located in southwestern Hokkaido, northeastern Japan. It is one of several volcanoes that formed along the southeast wall of Shikotsu caldera, which formed approximately 30 ka (Katsui, 1963). The lava dome, one of the most obvious features of Tarumai, is located beside a pyroclastic cone in the summit crater area. As recorded in historical descriptions of past eruptions (Ishikawa et al., 1972), such a dome was generated and destroyed at least twice. The present dome formed during the 1909 eruption, which was the most recent magmatic eruption. The present dome formed as a result of magma squeezing through a vent (Yokoyama, 2004). Some phreatic eruptions after the 1909 event partly fractured the dome, forming two fissures that trend NE and NW (Fig. 1).

Volcanic gas emission around the lava dome is conspicuous. In recent decades, volcanic gas from the A crater and B fumaroles has had extremely high temperature (up to 600 °C), whereas temperatures at other fumaroles have been below the boiling point of water (Sapporo District Meteorological Observatory, 2004). Such temperature contrasts over short distances are probably related to hydrothermal activity beneath the dome. Aoyama et al. (2004) and Aoyama (2006) suggested that hydrothermal water beneath the volcano may have contributed to a low-frequency earthquake swarm that was triggered by the 2003 Tokachi-oki earthquake (Mw 8.0) beneath the volcano, after which gas emission took place at the B fumaroles (e.g., Terada et al., 2004).

Resistivity investigations focusing on the structure beneath the lava dome have been conducted (Watanebe et al., 1984; Sapporo District Meteorological Observatory, 1999). A dipole–dipole resistivity survey by Watanebe et al. (1984) showed that the resistivity decreases monotonously with depth, and the resistivity structure beneath the lava dome has almost the same structure as that beneath the southern part of the crater area at several hundred meters depth. A later study (Sapporo District Meteorological Observatory, 1999) confirmed that finding and also identified a resistivity structure consisting of four layers. These investigations, however, were based on DC resistivity sounding that assumed a horizontally layered structure (1-D analysis) and did not include the top of the dome. A 3-D analysis with denser AMT measurements will offer new insight into the subsurface structure in the crater area of Tarumai volcano.

3. AMT survey and data processing

Audio-frequency magnetotellurics measures electromagnetic variation of the audio-frequency band (approximately 1 to 10^4 Hz). Using this frequency band provides information on the resistivity structure to depths of a few kilometers. Fig. 1 shows the distribution of the AMT measurement sites in the crater area of Tarumai. For the 3-D analysis, measurements were made on a grid at approximately 200-m spacing. Time-series data for the electric and magnetic fields were collected using the MTU-5A system manufactured by Phoenix Geophysics, Ltd. (Canada). Pb–$PbCl_2$ electrodes and induction coils were used to measure two horizontal components of the electric fields and three components of the magnetic fields, respectively. Time-series data were collected for a few hours at each site and then transformed to power spectra using a Fourier transformation. The remote reference technique (Gamble et al., 1979) was applied for eight AMT sites for which time-series data had been simultaneously measured at the site 290, locating about 2 km north from the study area (Fig. 1b). Remote site is generally placed at great distance where the noise is incoherent with that in the survey area, in order to reduce bias in response function. Given the skin depth corresponding to the AMT band, although the distance of 2 km in this study might be too close, the results of processing improved quality particularly in frequency ranges around 50 and 2000 Hz. The sites A30 and A40 were processed with each other. In spite of close range between these sites, the remote reference process was effective in the same frequency ranges. The other 10 sites, which did not have any remote data, were compelled to process by single site. The apparent resistivity, impedance phase, and induction vectors were calculated from the MT impedances, which were derived from the power spectra at each frequency, at each site.

The apparent resistivity trend was approximately the same at all sites, decreasing as frequency decreased (Fig. 5). Although such behavior might suggest a simple layered structure, the real part of the induction vectors pointed toward the northeastern part of the dome at a frequency range above 100 Hz (Fig. 2), implying the presence of a conductor within or below the dome. In order to estimate the dimensions of the structure, phase tensors were calculated (Caldwell et al., 2004). Fig. 2 shows the distributions of the phase tensors for each frequency. The major axis of the phase tensors was concentrated toward the center of the lava dome at 1000 and 100 Hz, but lacked any discernable trend at other frequencies. The skew angle (β) of the phase tensors was large ($>10°$), indicating the existence of strong 3-D structures. This indicated that 3-D analysis would be more suitable than 1-D or 2-D analysis for modeling the structure of the study area.

4. Three-dimensional forward modeling

4.1. Model setting

Three-dimensional forward modeling based on AMT data was performed to reveal the resistivity structure beneath the crater area, including the lava dome, using a part of wideband-MT data which was measured in another survey (Yamaya et al., 2005). Induction vectors could not be obtained for wideband-MT sites because only the electric field was measured.

The MT responses were calculated using the 3-D numerical modeling code developed by Fomenko and Mogi (2002). The modeling scheme is based on a finite-difference staggered grid of non-uniformly sized rectangles. Using a staggered grid yields highly accurate results, even for irregular grids. This decreases both the number of cells and