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Short communication

Possibility of effective magma degassing into groundwater flow systems beneath Unzen volcanic area, SW Japan, inferred from the evaluation of volcanic gas fluxes using electrical conductivity structures

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ABSTRACT

The mass and heat budget of volcanic gases released from magma is critical to understanding a number of volcanic activities, including the ease with which magma can ascend. Due to its elevated temperature and salinity, the crustal electrical conductivity in a groundwater flow system increases through the addition of hydrothermal fluids which are produced by mixing of volcanic gases with meteoric-origin water. Therefore, the spatial extent of high electrical conductivity regions within groundwater flow systems may be used to evaluate the mass flux of volcanic gases to the systems. The present study attempts to estimate the mass flux of volcanic gases beneath the Unzen volcanic area in Southwest Japan, by developing a simple flow model of hydrothermal fluids and applying this model to the electrical conductivity structure of the area. The estimated mass flux of volcanic gases ($10^{4.8 \pm 0.3}$ t/yr) yields results for CO_2 flux ($10^{3.1 \pm 0.3}$ t/yr) and magma input rate ($10^{0.1 \pm 0.3}$ million m^3/yr) that are consistent with those estimated by geochemical and geodetic observations. This suggests that volcanic gases are steadily released from magma into the overlying groundwater flow system beneath the area, and that effective degassing may be one of the factors controlling the relatively effusive style of recent volcanism at Unzen volcano.

1. Introduction

Volcanic areas commonly develop hydrothermal systems, in which circulating hydrothermal fluids are a mixture of meteoric water and volcanic gases released from magma (Henley and Ellis, 1983). The transport of heat and mass within these systems is of great interest, because the degassing of magma and the dissipation of volcanic gases control the ease of magma ascent and the explosive potential of a volcano (Eichelberger et al., 1986; Jaupart and Allégre, 1991; Shinohara and Kazahaya, 1995; Kagiyama, 2008). In addition, hydrothermal activity may be controlled by the influx of hydrothermal fluids (e.g., Ingebritsen et al., 2010; Todesco et al., 2010; Matsushima, 2011). Hydrothermal fluids have high salinity and temperature, causing significant rock alteration. This leads to high electrical conductivity (E.C.) of pore waters and rock matrices (e.g., Keller and Rapolla, 1974; Revil et al., 2002; Komori et al., 2013). Therefore, the distribution of E.C. anomalies can provide quantitative constraints on the dissipation of volcanic gases into a groundwater flow system (e.g., Aizawa et al., 2009; Rinaldi et al., 2011).

Unzen volcanic area is situated in a volcanotectonic depression in the Shimabara Peninsula, SW Japan (Ohta, 1973; Chida, 1979, Fig. 1a). N–S extension has formed Unzen Graben, defined by E–W trending faults (Hoshizumi et al., 1999). The recent stage of Unzen volcano (0–0.15 Ma) is characterized by relatively effusive volcanism, e.g. lava-dome formation with minor dome-collapse pyroclastic flows, and hot spring/fumarolic activities (Ohta, 1973; Nakada et al., 1999). Kagiyama et al. (1999) proposed that effective magma degassing into the groundwater flow system may induce the observed phenomena, including temporal changes of the chemical composition of fumaroles, and volcanic tremors after earthquake swarms. Srigutomo et al. (2008) conducted extensive TDEM surveys, and found an E–W trending high-conductance region (or a thick high E.C. region) at the western part of Shimabara Peninsula, as shown in Fig. 1b and c, on the basis of one-dimensional (1-D) inversion. This region is located above the epicenter of an earthquake swarm that occurred during the 1990–1995 eruption (Umakoshi et al., 1994), and also above the path of magma traveling from a western deeper pressure source to an eastern shallower source, inferred from geodetic surveys (e.g., Ishihara, 1993; Kohno et al., 2008). Based on these facts, the authors considered that the high conductance was due to discharge of volcanic gases from magma beneath the area.

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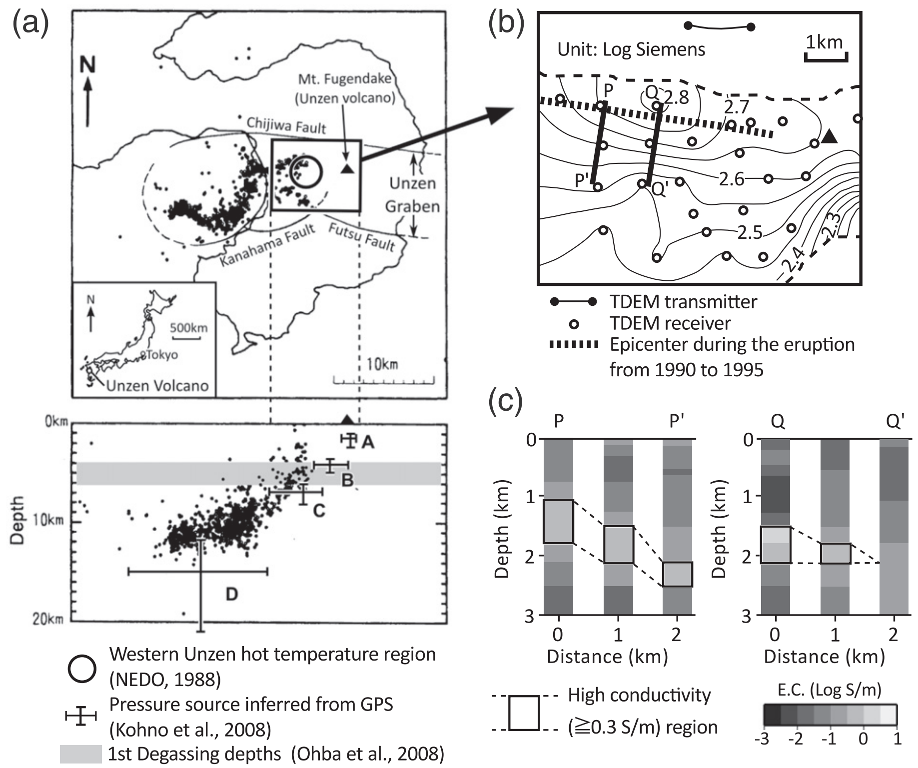

Fig. 1. Unzen volcano, SW Japan. (a) Precisely-estimated hypocenters during the 1990–1995 eruption and the location of Unzen volcano (modified after Umakoshi et al., 1994). During the eruptive event, magma moved from the deep source to the shallower one, as inferred from geodetic surveys (e.g., Ishihara, 1993; Kohno et al., 2008). (b) Conductance distribution, obtained from TDEM surveys (Srigutomo et al., 2008). The high conductance region corresponds to the epicenter during the eruptive events. (c) 1-D electrical conductivity structure of Srigutomo et al. (2008), along the lines P–P′ and Q–Q′.

The present study develops a simple model for the dissipation of volcanic gases into the systems, and attempts to evaluate their mass fluxes using the E.C. structure of Unzen volcanic area. The estimated flux is then compared to the other geophysical and geochemical studies to assess the possibility of effective magma degassing and its influence on volcanic activity.

2. Conceptual model

2.1. Fluid flow model at Unzen volcanic area

The western part of Shimabara Peninsula had about 10 sites for the geothermal exploration drilled by NEDO (1988). A high temperature region (greater than 200 °C) was found at a depth of a few km (Fig. 1a); this region corresponds to the high conductance zone from Srigutomo et al. (2008). This suggests that fluids are maintained at high temperature within the high conductance zone. Ohsawa et al. (2002) and Ohsawa (2006) conducted chemical composition and isotopic analyses of hot springs and fumaroles, and showed that the liquid-dominated hydrothermal fluids (thermal waters) are maintained at a temperature of 300 °C beneath the western part of the peninsula. These are thought to originate from NaCl-type deep fluids derived from deeply-seated magma. The authors also showed that most of the hydrothermal fluids are discharged laterally outwards within the shallow part of the peninsula, following the groundwater flow driven by meteoric water. Further, Ohba et al. (2008) postulated that Unzen volcano has a three-stage degassing system, indicated by temporal variations in the chemical composition of the volcanic gases during the 1990–1995 eruption. The authors inferred that the first degassing occurred through the depth interval of 6–4 km; these depths correspond to two pressure sources B and C, inferred from leveling and GPS data (Kohno et al., 2008, Fig. 1a).

On basis of all the abovementioned evidence, the following simple dissipation model of volcanic gases may successfully describe the Unzen volcanic area, as shown in Fig. 2a. Volcanic gas is released from the magma at the first-degassing depths, and ascends along E–W trending fragile sections; mixing with meteoric water may occur during its ascent, to form the thermal water. This thermal water forms the high temperature region at the shallow part, and is moving laterally according to a groundwater flow driven by the injection of the thermal water and rainfall precipitation.

Corresponding to this simple model, the E.C. structure also suggests the lateral dissipation of the volcanic gas. Fig. 1c shows the 1-D E.C. structures along the lines P–P′ and Q–Q′. The part enclosed by a rectangle represents a high E.C. region greater than 0.3 S/m. The high E.C. region extends toward the relatively shallower part near the high conductance center; with increasing distance from the center, the region extends downward. The region along the line Q–Q′ is not extending as great a width as that along the line P–P′. The present study used the above two distributions of the high E.C. region for estimation of the volcanic gas flux.

Simplified model assumptions

In many instances, volcanic and geothermal areas may experience large amounts of precipitation, and a significant proportion of meteoric water can infiltrate the subsurface, contributing to the groundwater flow system. Under such conditions, forced convection, resulting from the mass of infiltrating water, is the predominant driver behind subsurface fluid flow (Holzbecher and Yusa, 1995). The present study therefore assumes that forced convection is a dominant factor controlling the flow regime of the whole area (i.e., recharge-driven advection), compared to buoyancy-driven convection. According to NEDO (1988), temperatures of all the boreholes penetrated into the depths of 1000–1400 m were significantly below vaporization curves. In addition, thermal waters have neutral pH, and contain mainly Cl, HCO_3^-, and Na^+, with minor quantities of SO_4^{2-} and other ions (NEDO, 1988; Ohsawa