Magma ascent beneath Unzen Volcano, SW Japan, deduced from the electrical resistivity structure

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Received 2 August 1997; received in revised form 17 June 1998; accepted 10 September 1998

Abstract

The resistivity structure of Unzen Volcano has been revealed by extensive magnetotelluric surveys since the first eruption on November 17, 1990. This structure comprises a highly resistive surface layer, a low-resistive second layer at several hundred meters depth, interpreted as a water-saturated layer, a resistive third layer, and a low-resistive fourth layer at 10 km depth, possibly related to the deep magmatic activity. The structure has influenced the volcanic activity of Unzen. This activity was characterized by a series of dramatic changes in eruption type: a minor phreatic eruption on November 17, 1990; phreatic eruptions after February 12, 1991, preceded by several weeks of volcanic tremor; phreatomagmatic eruptions after April 9, and dome effusion beginning May 19, 1991. This paper presents a hypothesis in which the top of the magma column rose about 20 m/day, reached the base of the water-saturated layer at the end of January, 1991, and approached the upper boundary of this layer on April 9. Thus, the temporal change of eruption type and associated phenomena are systematically explained by an interaction between magma and groundwater contained in the saturated layer. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Unzen Volcano; magma rising process; resistivity structure; magma–water interaction

1. Introduction

Unzen Volcano is a complex of many lava domes, located in Shimabara Peninsula, Kyushu, Japan (Fig. 1). After the seismic swarm under Tachibana Bay and the western part of Shimabara Peninsula from the end of 1989, and volcanic tremor from July 1990, phreatic eruptions occurred at Jigokudani Crater and Kujukushima Craters, near the summit of Fugen-Dake on November 17, 1990 (Fig. 2). The eruption followed 198 years of dormancy. This eruption was essentially phreatic, because no fresh, high-temperature juvenile products were found, and a mud eruption was observed at Jigokudani Crater (Ohta, 1993). However, a high concentration of magmatic volatiles such as H₂ was detected just after the eruption by Hirabayashi et al. (1992), suggesting a potential magmatic contribution to the apparently non-magmatic eruption. This possibility is also supported by isotopic composition of H₂O and CO₂ in volcanic gas (J. Hirabayashi, pers. commun.). The ash emission stopped within a few days and only fumarolic activity continued at Kujukushima Crater, with a...
gradual decrease of the temperature. However, this activity was followed by a new stage of volcanic activity from the end of January 1991 (Table 1). First, volcanic tremor was observed beneath the summit area, and a mud eruption was reactivated at Jigokuato Crater. Then, from February 12, phreatic eruptions started at the newly-opened Byobuiwa Crater, 200 m west of Jigokuato Crater (Fig. 2). This eruption was only mildly explosive, although ash was continuously emitted. However, after April 9, explosive phreatomagmatic eruptions, with cock’s-tail jets, frequently occurred at Jigokuato Crater. A lava dome appeared at the bottom of Jigokuato Crater on May 19, and from the end of May, Merapi-type pyroclastic flows occurred frequently. Explosive eruptions occurred on June 8 and 11.

Why did such changes of eruption type occur? What parameters control the eruption type? What kinds of phenomena should be expected with rise of the magma? How fast was the tip of the magma rising from deep in the Earth, before the eruption? These questions establish an interesting theme, pursued in this paper. Taking the last question first, several workers have estimated the speed in the pre-eruptive stage of the present Unzen activity (Kagiya et al., 1991, 1992; Nakada et al., 1995).
These resulting estimates are around 10–20 m/day, on the basis of result of magnetotelluric (MT) resistivity sounding, petrological considerations and other geophysical observations.

The evolution of changing styles in the present activity strongly suggests that groundwater is an important factor in solving the problems given above. This paper presents a hypothesis in which the top of the magma column rose about 20 m/day. With this hypothesis, it shows that the temporal changes of eruption type and associated phenomena can be systematically explained by an interaction between magma and groundwater at several hundred meters depth beneath the Unzen volcanic area.

### 2. Resistivity structure beneath Unzen volcano

Electrical resistivity is one of the most useful methods to examine the thermal process taking place inside volcanoes, because the electrical resistivity of the ground highly depends on the temperature and the concentration of water and volcanic gas in the...
permeable porous medium that usually composes the volcanic edifice. The resistivity structure around Fugen-Dake was established by VLF (Very Low Frequency) and ELF (Extremely Low Frequency) MT surveys in December 1990, just after the first eruption (Kagiya et al., 1991). The results, presented in Fig. 3, indicates that a low-resistivity layer—interpreted to be a water-saturated layer—is found at 400 to 500 m above sea level throughout the Fugen-Dake area, beneath a highly resistive surface layer. Beneath the Jigokuato Crater, on the other hand, the low-resistivity layer is very shallow, only a few hundred meters deep. This zone has a resistivity of about 1 $\Omega$ m. Kagiya et al. (1991, 1992) suggested that the regional near-surface resistivity layer corresponds to a thick volcanic complex of porous lava block, while the extremely-low-resistivity layer reflects a hydrothermal zone just beneath the summit craters. The distribution of the apparent resistivity by VLF-MT (Fig. 2) indicates that this low-resistivity zone is limited to within several hundred meters from Jigokuato Crater. Since the self-potential of the
active area increased during several months before the dome appearance (Hashimoto et al., 1993; Hashimoto and Tanaka, 1995), the upper boundary of the low-resistive hydrothermal system is considered to have grown by the continuous supply of volcanic gas from depth to the water-saturated layer before the eruption.

To reveal the deeper structure, ULF Ultra Low Frequency-MT and VLF, ELF-MT surveys have been carried out at 62 sites by the 'electromagnetic research group' at Unzen, between June 1991 and December 1994 (Kagiyma et al., 1992; Utada et al., 1994). The resistivity structure at site UZ3, on the western flank of Fugen-Dake, is presented in Fig. 4; beneath the resistive surface layer and the conductive second layer as mentioned above, a more resistive third layer and a conductive fourth layer are found at 1 and 30 km below sea level, respectively. However, the last value includes much error due to the inaccuracy of impedance response at longer periods. Resistivity structures at UZ9, UZ14 and UZ43 in Fig. 4 have similar features, but the depth of the upper boundary of the deep conductive layer is around 10 km below sea level. The results obtained from other sites indicate that the resistivity structure around Unzen Volcano is expressed by a simple four-layer structure similar to the case of Fig. 4, and that the depths to the bottom of the second layer and to the surface of the fourth layer are roughly estimated as 1 ± 0.5 and 10 ± 3 km below sea level, respectively. This result provided two implications of volcanological importance (Fig. 3; Kagiyma et al., 1992; Utada et al., 1994):

1. There probably exists a well-developed water-bearing layer beneath the Unzen volcanic area, at from several hundred meters to a few kilometers depth, which is detected by MT survey as a widespread low-resistivity layer.

2. At roughly 10 km below sea level is another deep crustal conductor, possibly related to the deep magmatic activity such as a partial melted region or a water-rich layer which facilitates melting.

3. Magma ascent and associated phenomena

The growth rate of the lava dome was estimated as follows. On May 20, a lava dome was first observed at the bottom of Jigokudani Crater with a height of 30–40 m, while no dome existed there on May 18. Thus the average growth rate was initially about 15–20 m/day (Kagiyma et al., 1991). Also, Terai (1991) observed the appearance of the dome on May 19, with the growth rate 24 m/day. These data suggest an initial growth rate of about 20 m/day. However, the rise rate of the top of the magma column before the dome forming stage is not well known.

Here we examine a simple model of magma ascent. Letting the rise speed of the top of the magma column be constant at 20 m/day throughout the pre-dome stage, we examined the relation of the calculated position of the top of the magma and the observed phenomena. The magma column reached the bottom of Jigokudani Crater, 1200 m above the sea level, on May 19, 1991. The height of the column top is calculated for each proceeding stage (Fig. 5): working backward in time, the top was 400 m above the sea level on April 9, when the phreatomagmatic eruption started, at 0.7 km below sea level on February 12, when the phreatic eruption started at Byobuwa Crater, and at 1.1 km below sea level on January 25, when the volcanic tremor reappeared. Fig. 5 demonstrates that these values are quite close to the depth of the upper or lower boundaries of the water-saturated layer (shallow low-resistive layer). From this correlation, we may imagine an important role of magma and groundwater interaction in controlling the eruption types.

Before the first eruption in November 1990, changes in seismicity were observed (Table 1). Though it is not clear if the vertical rise speed of magma before November 1990 is the same as assumed above, using this method allows the level of magma for each event of Table 1 to be calculated as follows (Fig. 5): 5.2 km below sea level on July 4, 1990, when volcanic tremor was firstly observed; 7.3 km on March 5, 1990, when the seismic activity increased within Shimabara Peninsula; 9.3 km on December 11, 1989, when the earthquake swarm firstly occurred in Shimabara Peninsula; and 9.7 km on November 21, 1989, when earthquake swarm firstly occurred beneath Tachibana Bay. According to the leveling survey by Ishihara (1993), three different point sources were suggested for the subsidence movement after the dome extrusion; approxi-
Fig. 5. Calculated depth of the top of the magma column vs. volcanic activity. Approximately 1.5 km deep beneath the summit, 5.0 km deep, 3 km west of the summit and 7.0 km deep, 5 km west of the summit, respectively. The shallowest hypothetical source locates within the water-saturated layer, and the two deeper sources are close to the level of the magma in July and March 1990, respectively. The hypocentral depths of the earthquakes under Tachibana Bay and in the western part of Shimabara Peninsula are around 10 km of depth (Umakoshi et al., 1994), close to the level of the magma at the end of 1989 from a simple calculation given above.

Based on these results, we propose the following hypothetical scenario for the appearance of some precursory phenomena and changes in the eruption type (Fig. 6). Associated with the seismic swarm in 1989, magma at about 10 km began to rise, and volcanic gas released from the magma reached and heated the water-saturated layer and caused the volcanic tremor in July 1990 (Fig. 6b). The continuous supply of volcanic gas generated a growing hydrothermal system beneath Fugen-Dake, increasing vapor pressure at various groundwater layer depths, and finally resulted in the phreatic eruption of November 17, 1990 (Fig. 6c). This idea is supported by the detection of magmatic gas components at the very beginning of the activity (Hirabayashi et al., 1992). Vapor pressure greatly increased when the magma column reached the bottom of the water-saturated layer (Fig. 6d), which caused more intense volcanic tremor, mud eruptions, and phreatic eruptions at the end of January to February 1991. This idea is supported by several kinds of observational evidence: (a) Shimizu (1992) estimated the depth of the volcanic tremor during this stage from 0.5 to 0.5 km above sea level, which is within the water saturated layer, (b) Nakada et al. (1995) pointed out that juvenile glass was included in the ash sampled after the end of February, and its proportion increased with the time, and (c) an increase in thermal energy release rate from active craters was detected by analysis of continuous video-recording of the fumarolic plume from several MW to several hundred MW after the eruption on February 12 (Kagiyama and Masutani, 1996). On April 9, 1991, magma approached the upper boundary of the water-saturated layer (Fig. 6e) and caused a phreatomagmatic explosion. After that, magma continued to rise and a lava dome appeared at the bottom of Jigokuato Crater on May 19, 1991 (Fig. 6f). The dome continued to build until it became unstable at the end of May, when pyroclastic flows frequently occurred at the eastern flank of Fugen-Dake. Two remarkable explosive events occurred on June 8 and 11. The negative pressure sources of the crustal deformation associated with these explosions
were determined at depths consistent within the water-saturated layer (Shimizu, 1992). This evidence suggests that the deformation was caused by sudden pressure release of steam or volcanic gas created by an interaction of magma and the groundwater.

4. Conclusions

The resistivity structure of Unzen Volcano has been revealed by the extensive MT survey carried out since December 1990, just after the first eruption occurred. This subsurface structure can be represented by a four-layer model: surface high-resistive, second low-resistive, third resistive, and fourth low-resistive layers. The second low-resistive layer is interpreted as a porous layer saturated with groundwater, while the deep conducting layer is assumed related to deep magmatic activity. The current activity of Unzen Volcano has been characterized by a series of dramatic changes in eruption type, in related anomalous phenomena, and in shifts the location of active vent. The phreatic eruption from February 12, 1991, was preceded by volcanic tremor since the end of January 1991; phreatomagmatic eruption on April 9, 1991, and f) dome appearance on May 19, 1991.

Fig. 6. Schematic illustration of magma rising process: (a) earthquake swarm in November 1989, (b) volcanic tremor in July 1990, (c) phreatic eruption on November 17, 1990, (d) phreatic eruption on February 12, 1991, (e) phreatomagmatic eruption on April 9, 1991, and (f) dome appearance on May 19, 1991.
eruption followed on April 9, and dome effusion commenced on May 19, leading to frequent pyroclastic flows. These changes, and the times of their occurrence, can be qualitatively explained by the hypothesis that magma at about 10 km depth began to rise at a rate of about 20 m/day in November 1989, when the first earthquake swarm activity took place. With a rate of rise about constant, the magma column reached the bottom of the saturated layer at the end of January, and approached the upper boundary of this layer on April 9. Thus, the present study indicated that the low-resistive, water-saturated layer plays a critical role in generating precursory phenomena and in controlling the eruption type, through interactions between magma, juvenile gas, and groundwater.

Acknowledgements

The authors would like to thank Prof. K. Ohta, Shimabara Earthquake Volcano Observatory, for his kind support and encouragement to our research, and to H. Shimizu, S. Nakada, Y. Tanaka, T. Hashimoto and J. Hirabayashi for their valuable discussion. The manuscript was critically reviewed by Prof. B. Voight, Pennsylvania State University. This work was partly supported by the Grant-in-Aid for Scientific Research (No.04640398, T. Kagiyama; No.05680359, T. Kagiyama; No.03306009, K. Ohta; No.04302020, K. Ohta) from the Ministry of Education, Science, Sports and Culture Japan (Monbusho).

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