Continuing deflation by fumaroles at Kuju Volcano, Japan

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[1] A phreatic eruption occurred at Kuju Volcano in October 1995. We deployed an EDM network around the active craters of the volcano just after the eruption. Slope distances of the survey lines in the northern network have tended to contract, whereas those in the southern one extended. The maximum contraction observed in the northern network was 70 cm over 6 years. A spherical volume decrease just beneath a fumarolic area called Iwoyama 700 m north of the new craters is a plausible model for these changes in slope distances. A noteworthy feature is that over 6 years after the phreatic eruption ended, the deflation rate is still approximately linear. We also estimated the thermal energy discharge by fumaroles in the geothermal field as 120 MW with the plume-rise method before the phreatic eruption. Jinguuji and Ehara [1996] also estimated the energy discharge of the fumaroles as approximately 100 MW just before the phreatic eruption.

2. Summary of Kuju Volcano and Previous Studies

[4] Kuju Volcano consists of 20 lava domes and cones, located in the central part of Kyushu Island, Japan (Figure 1). One of the most active geothermal fields around Kuju Volcano is Iwoyama, situated on the northeastern flank of Mt. Hossho, where sulfur used to be mined.

[5] Figure 1 shows the Iwoyama geothermal fields that consist of 4 fields named A, B, C and D. A, B and C were pre-existing field, while the D field is a group of new vents that were opened by the phreatic eruption of 1995. The highest temperature fumaroles are in C field, between 250–350°C.


[7] A second ash eruption occurred on the 18th December 1995. The gross volumes of the ash ejected by the first and the second eruptions were estimated as approximately 2 × 10^4 m^3 and 5 × 10^3 m^3, respectively [Nakada et al., 1996]. There was no ash ejection after Feb 1996. Hatae et al. [1997] detected up to 0.32 wt% content of vesiculated glass shards in the ash of the second eruption.

[8] Kagiyama [1981] estimated the energy flux of the fumaroles in the geothermal field as 120 MW with the plume-rise method before the phreatic eruption. Jinguuji and Ehara [1996] also estimated the energy discharge of the fumaroles as approximately 100 MW just before the phreatic eruption.

3. EDM Survey and Results

[10] No ground deformation observation had been carried out at Kuju Volcano before the phreatic eruption in 1995. Figure 1 shows the EDM network that was constructed after the phreatic eruption, aiming to detect ground deformation associated with the phreatic eruption and to monitor magma movements. The first measurement was carried out 4 days after the eruption. The network was extended to the south of the new craters 6 months later.
We have made atmospheric corrections using only the pressure and temperature at the measurement point because of the difficulty of access to the reflectors. The accuracy of a measurement depends on the elevation difference and the distance between a reflector and a measuring site. The errors in the northern network (P283, HSS, IOY2, KJW) are in the range of 3 ppm, because the lines are short. The slope distances of the lines from CJB2 and the southern network (AKG, HNK, HSZ, K4, K5, K6) are over 3 km, giving errors in the range of 0.5–1 cm. However, these errors are quite small compared with the observed deformation. We measured each line 50–80 times within 10 minutes with a DI-3000 (Leica) and took the average.

The maximum deformation was observed in the line (SGM-HSS) that contracted approximately 70 cm in 6 years. All the lines connecting to HSS contracted more than 50 cm. It means that HSS has moved northeastward at least several tens of cm since October 1995.

Almost all the lines in the northern network (SGM, P283, HSS, IOY2, KJW) contracted except for P283-IOY3 (Figure 2a). In contrast, all the lines in the southern network extended (Figure 2b). As a first approximation, it looks possible to explain these contractions and extensions by assuming a deflation source beneath Iwoyama. Thus, we applied a spherical Mogi deflation model, as described in the next section.

Almost all the lines changed rapidly in the first three months. deformation rates of the lines (SGM-HSS, IOY-HSS) in this period were \(-1.18\) and \(-1.27\) mm/day, respectively. Thereafter, the trends were approximately linear. The deformation rates at the same lines decreased to \(-0.29\) and \(-0.26\) mm/day, respectively. It was often impossible to measure in winter because of snow or frozen prisms. Thus, there is less data than for the other seasons. We analyzed slope distances without removing seasonal changes, because they were small compared to the main changes.

4. Analysis of the Deformation

The Mogi model successfully explains the ground deformation at various volcanoes [e.g. Mogi, 1958; Dvorak...
et al., 1983; Nishi et al., 1999]. It is reasonable when discussing the volumetric change and source depth to use the Mogi model as a first approximation. We located a best-fit Mogi deflation source using least squares by the grid search method, assuming an elastic half medium. We used the deformation change between the dates of 11th October 1997 and 11th December 2001, a period during which the slope distance changed approximately linearly. Figure 3 shows the contour map of average residual displacement versus Mogi source position. Table 1 shows the fitting parameters of the Mogi source. The possible range of the center of deflation is shown in Table 1. Figure 3 shows the error as a color variation from red to orange.

To check for movement of the Mogi source, we calculated a deflation source for three different sections of the whole period. Although the first section has large errors because of the lack of data, the variation in position of the deflation sources was always within the standard error. Therefore, significant movement of the deflation source did not occur after the phreatic eruption.

Figure 4 shows the relation between observed line length changes, and the Mogi model calculated changes. The correlation coefficient is 0.89, showing that the Mogi model explains the broad features of the deflation. The differences between the Mogi model and the observation data may arise from topographic effects and from the source having a significant size.

The deflation source is located beneath the south end of the pre-existing C geothermal field (Figure 1). The depth of the source is about 600 m from the surface. There remains a possibility that the source is shallower than the 600 m shown in the vertical distribution map of Figure 3. The elevation of the lowest point of the EDM network is 844 m (a.s.l.). Consequently, the grid mesh was limited to

![Figure 2b](image_url)

**Figure 2b.** Slope distance changes near Kuju in Southern Network.

![Figure 3](image_url)

**Figure 3.** Map of average residual strain versus horizontal and vertical source position. Unit is meter. The origin is set on P283.

![Figure 4](image_url)

**Figure 4.** Observation data versus the Mogi model calculated value for total length change on each line over Oct. 13 1997–Dec. 11 2001.

### Table 1. Best Fitting Range for a Mogi Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>500 ± 250 m East from P283</td>
</tr>
<tr>
<td>Y</td>
<td>1100 ± 100 m South from P283</td>
</tr>
<tr>
<td>Z</td>
<td>500–800 m above sea level</td>
</tr>
<tr>
<td>Delta V</td>
<td>1.4–3.0 × 10^6 m³</td>
</tr>
</tbody>
</table>
an elevation of 800 m. We will improve the calculation method by accounting for topography in future work.

[19] Sudo et al. [1998] described how the alignment of the new vents shows a left lateral relationship. For this reason, we also attempted to fit the observation data with a left lateral fault model [Okada, 1992] beneath the new vents. However, we could not find a good correlation. The observed alignment might arise from an old fault.

5. Deflation Source and Continuing Deformation

[20] What is the cause of the continuing deformation? It is often thought that magma movements cause the ground deformation around volcanoes. However, in the case of Kuju, we propose that the continuing deformation is due to an increase of the discharge of the geothermal fluid from the fumaroles since the eruption. Firstly, there was only a very small magmatic involvement in the eruption, which was dominantly phreatic. The gross volume of the ash, at most approximately $3 \times 10^6 \text{ m}^3$ [Nakada et al., 1996], was very much less than the amount of water discharged as is described in a later section. Furthermore, no ash ejection has been observed since February 1996, although contraction and extension of the slope distances have continued.

[21] The deflation Mogi source is located near the C field, which is the most active fumarolic field in this area before the phreatic eruption in 1995. After the phreatic eruption, the D field was stronger than the C field for several years, but now the C field is the strongest again (The steam temperature is about 300°C). We also observed that the rate of deflation seemed to correlate with gas emission from the fumaroles. This suggested that the deflation was due to the loss of fluid from the geothermal system. In this case, the slope distance change will be proportional to the volume change, i.e. to the net mass lost from the system.

[22] In order to confirm the proposal, we intend to consider the relation qualitatively between the temporal change of the fumarole and slope distance with a simple model. Let us here consider a deflating geothermal reservoir, which is discharging geothermal fluid. Temporal change of the volume caused by the outflow of the fluid is expressed as follows,

$$\Delta V = Q \Delta t, \quad (1)$$

here $Q$ is the flux of the fluid. $\Delta V$ is the volumetric change of a reservoir. According to the Mogi model, slope distance is proportional to the volume change of the reservoir, so the deformation rate ($\Delta L/\Delta t$) is proportional to the flux of fluid.

[23] (Figures 5a and 5b) show the temporal variation of energy flux from the new vents that opened at the phreatic eruption in 1995 and the contraction rate of the slope distance (SGM-HSS), respectively. The energy flux of these new fumaroles was measured by using the plume rise method [Kagiyama, 1981; Briggs, 1969], which estimates the energy flux of fumaroles using of the photographs or video images. These results are consistent with those of Jinguji and Ehara [1996], who used the maximum diameter method, which estimates energy flux from the visible maximum diameter of fumaroles. We can convert the energy flux into the equivalent weight of the discharged water, assuming the fumaroles discharged a flux of saturated steam at 160°C whose enthalpy was 2.8 MJ/kg.

[24] Although both energy flux and contraction rate were very irregular at first, their general patterns are well correlated, suggesting that the rate of deformation is proportional to the energy flux. Therefore, the continuing deflation means that there is still a net loss of fluid occurring.

6. Discussion

[25] Sakanaka et al. [2001] located an increase in magnetization centered at the south end of the pre-existing geothermal field (C field). This may well represent a thermomagnetic effect from a cooling area. The magnetic source is located in the vicinity of our estimated position of the Mogi model deflation source. The temporal change of the geomagnetic field also shows a linear trend, suggesting both geomagnetic and geodetic observations have monitored the same phenomena. This means that both deflation and cooling occurred in the same shallow geothermal reservoir.

[26] Before the phreatic eruption, this shallow geothermal region was probably pressurized and contained hot water.
After the eruption started the pressure began to drop and the water volume decreased causing deflation. The temperature of the reservoir also dropped, because cold groundwater was supplied from around the geothermal area. Hirabayashi and Ohba [1996] inferred that 60–70% of the steam mass has originated from meteoric water estimated by stable isotope content of water. Thus, meteoric water mixes with the geothermal fluid from a deep source in the shallow geothermal region, and cools and deflates the geothermal reservoir.

[27] Let us here make a crude evaluation of mass balance assuming the observed deflation is due to the deflation of a geothermal reservoir beneath Iwoyama area. The discharged mass over the first three years, estimated from (Figure 5a), amounts to approximately $1.8 \times 10^7$ tons. The corresponding volume of this discharge is uncertain because we do not know the exact conditions in the shallow geothermal reservoir. However, $1.8 \times 10^3$ m$^3$ is a lower limit for the volume, assuming the discharge was originally liquid water at that depth. On the other hand, the decrease in volume of the Mogi source over the first three years was $1 \times 10^8$ m$^3$. Hence, it can be stated that the amount discharged from fumaroles was much larger than that of the volume decrease causing the deformation. This result indicates that most of the discharged fluid has been replaced from a deep source or by groundwater of meteoric origin.

[28] Although the continuing linear deformation trend is one of the main features observed at Kuju, this depression could not last forever because the volume of the geothermal reservoir is finite. As is mentioned in the previous section, Ehara et al. [1981], based on historical records, reported that predominantly phreatic eruptions and intense fumarolic discharges repeat every 60–100 years in Iwoyama area. If the periodicity is mainly controlled by a shallow fluid transfer system, it is probable that the cycle consists of two stages, namely, fluid-recharging and discharging phases before and after a phreatic eruption, respectively. Assuming the discharging phase lasts for half of the period of each cycle and extrapolating the linear trend of deflation rate ($3.3 \times 10^7$ m$^3$/yr), the overall deflation volume of Mogi source will be approximately $1.0–1.7 \times 10^8$ m$^3$ over 30–50 years. This is equivalent to a sphere with a radius of 130–160 m, only a small fraction of the likely geothermal field volume.

[29] If the deformation source region had been known to be associated with the pre-existing geothermal areas, rather than the new vents, it would have reduced the concern about the revival of activity of Kuju Volcano, as it would have suggested the deformation had a fumarolic origin, rather than being a response to magmatic changes. In fact, the deformation network only became adequate to identify the deformation source during the 2nd half of 1996, when it was already becoming apparent that no further eruption would occur.

[30] The deformation measurements we made were thought at the time to be monitoring magmatic changes occurring in Kuju. The explanation that the changes were actually related to geothermal fluids, introduces just one more complexity into the monitoring of active volcanoes.

[31] Acknowledgments. We acknowledge the assistance of the Geological Survey of Japan, who allowed us to use some of their EDM reflectors. We thank Eto, Nishi, and all members of Sakurajima Volcano Observatory for helping this study. We thank the staff of AVL for their assistance throughout this project.

References


