Discharge model of fumarolic gases during post-eruptive degassing of Izu-Oshima volcano, Japan

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The chemical and isotopic compositions were determined for fumarolic gas samples collected between May 1988 and January 1991 from the summit ("A" terrace) and from the south caldera rim of Izu-Oshima volcano, Japan. The contribution of meteoric water and/or seawater to the "A" terrace fumarolic discharges increased as the fumarole temperature decreased. A large contribution of seawater to the fumarolic gas was inferred during the period from December 1988 to May 1989. The fumaroles which first appeared in June 1989 on the south caldera rim discharge the water vapor derived from local meteoric water. The isotopic compositions of water vapor followed a Rayleigh fractionation process; a part of vapor condensed during ascent in a gas conduit.

A scenario for the changes in the discharge system of fumarolic gases at Izu-Oshima volcano is proposed as follows: The proportion of groundwater to the "A" terrace fumarolic gas increased with time as the magma head subsided. The fracture network which formed beneath the caldera during 1986 eruption may have allowed seawater incursion from the coast to the central part of the island. Loss of a large amount of groundwater in the form of vapor from the summit crater may have accelerated infiltration of seawater. The discharge system developed over a wider area as the deeper magma head subsided.

INTRODUCTION

Magmatic gases experience complex processes as they ascend from a degassing magma to the surface. The isotopic composition of water vapor can be affected by several processes; e.g., mixing between magmatic water and meteoric water (e.g., Kusakabe and Matsubaya, 1986), and open system degassing of magma (Taylor, 1986). Monitoring of the isotopic composition of volcanic gases can provide information on the discharge processes of volcanic gases and on magma degassing. In addition, the changes in fumarolic activity, as reflected in the size of fumarole area, temperature and flux of fumarolic gases also provide information on volcanic activity.

The purpose of this paper is to reveal the processes that affected the fumarolic discharge systems of Izu-Oshima volcano by using changes in the fumarolic activity and chemical and

isotopic compositions of the fumarolic gases. This paper presents the isotopic results of the fumarolic gases, and discusses the origin of the fumarolic gases and the discharge mechanism. Changes in sources of the fumarolic gases and fumarolic activities during the post-eruptive degassing were modelled taking subsidence of the magma into account.

ERUPTIVE AND FUMAROLIC ACTIVITY

Izu-Oshima is a volcanic island 110 km south of Tokyo (Fig. 1). This basaltic stratovolcano has a central caldera with a diameter of about 3 km. In the middle of the caldera, there is a summit cone, Mt. Mihara. Recently, Izu-Oshima volcano erupted from the summit crater in a Hawaiian lava-fountaining style from November 15 to 20, 1986. A fissure eruption from the caldera and the northwest flank of the volcano on November 21 followed the first summit erup-

Fig. 1. Location map of fumarolic gas collection sites and fumarolic area of Izu-Oshima volcano.

tion. During the fissure eruption, a large crustal movement occurred forming a northwest trending graben structure (NW-SE), 4 km wide across the whole island (Hashimoto and Tada, 1988). Numerous open cracks also formed in a N30°W direction (Endo *et al.*, 1988). This crustal movement is thought to have been caused by dike intrusion at shallow depths (Hashimoto and Tada, 1988). Slow subsidence of the magma in the conduit was started after the 1986 eruption which was inferred from the repeated gravity measurement at summit (Watanabe *et al.*, 1988).

Figure 2 shows the degassing activity of the volcano depicted by the SO_2 emission rate (Kyushu Univ., 1990) and the fumarolic plume height (JMA, 1990). Lava erupted from the summit during November 15–22, 1986, filling the summit pit crater (diameter 300 m, depth 100 m), and finally overflowing onto the caldera floor. Degassing during the lava lake period (December 1986 to November 1987) was very low in terms of volcanic gas flux (Fig. 2). However, a high temperature fumarole (844°C) formed during this

Fig. 2. Different phase of degassing activity as indicated by SO_2 flux (reproduced from Kyushu Univ., 1990) and the daily maximum fumarolic plume height (JMA, 1990) during the period, November 1986–June 1990. Short, horizontal bars indicate the daily variations of SO_2 flux observed during the 1 week sampling period. Numerical values written in the upper figure show the averaged SO_2 flux during the observational period.

period (February 1987) on a mound in the lava lake, but its temperature gradually decreased (Hirabayashi *et al.*, 1988). At the beginning of June 1987, a new fumarole area with a loop structure (400 m in diameter) formed around the lava lake (Inner loop fumaroles in Fig. 1). A maximum temperature of about 150°C was recorded. Kazahaya *et al.* (1988) reported pre-eruptive increase in the H_2 and CO_2 concentrations of fumarolic gases discharging from the "A" terrace (140°C; location shown in Fig. 1) from mid-October 1987 to mid-November, 1987, using a multigas telemetry monitoring system. Explosive eruptions occurred on November 16 and 18, 1987, as the lava lake rapidly drained back into the conduit. A new pit crater with a diameter of

300 m and depth of 120 m was found at the summit (Yamaoka *et al.*, 1989).

New high temperature fumaroles formed in December 1987, on the "A" terrace by the pit crater (Fig. 1). The active degassing phase started from the bottom of the pit crater in January 1988, after the small eruption on January 26 (Fig. 2). During this active degassing period, a pale blue volcanic gas discharged violently. As shown in Fig. 2, SO₂ emission rates were found to be 430 tons/day on average during the active degassing period (Ohta *et al.*, 1988; Kyushu Univ., 1990). The SO₂ flux decreased to 59 tons/day in March 1990. Fumarolic plume height also lowered at the same time, indicating that the active degassing phase terminated in early 1990 (Fig. 2). Volcanic tremor, which is always found in the active degassing phase, also ceased in March 1990 (JMA, 1990). These changes correlate with the decrease in magmatic activity.

The fumaroles on the south caldera rim first appeared in June 1989, 31 months after the first summit eruption in November 1986. The fumarolic area is 200 m long and 50 m wide (Fig. 1). These fumaroles are characterized by low temperatures (99°C) and weak discharge rates.

SAMPLE COLLECTION

High temperature fumarolic gases discharged on the "A" terrace along open cracks. They were contaminated with air. A pump with a flow controller and a flow meter was used to collect the fumarolic gas samples. Fumarolic gas was slowly pumped at 0.5–1.0 l/min through a condenser cooled with dry ice alcohol or ice water, or a bottle containing an alkali solution. The condensed waters were analyzed for their isotopic composition, while the alkali solution was used to determine the chemical composition of the acid gases, and the isotopic composition of sulfur and carbon.

The analytical results of the fumarolic gases are listed in Table 1. The data (H₂O and CO₂ contents and δD , $\delta^{18}O$ and $\delta^{13}C$) were not corrected for the possible air contamination to the sample because atmospheric H₂O and CO₂ were estimated to be insignificant. The Air/H₂O mole ratio of the fumarolic gases collected on the "A" terrace ranged from 0.4 to 0.6. This was based on the amount of air pumped and the amount of H₂O collected. The proportion of atmospheric H₂O to the sampled water is less than 2%, assuming a maximum humidity of 100% at 25°C. Similarly, the calculated proportion of at-

Table 1. Isotopic and chemical compositions of fumarolic gases collected from "A" terrace, south caldera rim, and west Mt. Mihara

Sample		Collection Date	Temp. (°C)	δD (‰)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	$\delta^{34}S$ (‰)	H ₂ O (%)	CO ₂ (%)	ΣS (%)	Cl (%)
“A” terrace	No. 1	May 1988	636	−30.1	+1.9	−6.4	+1.2	96.5	2.54	0.93	0.024
	No. 2	Aug. 1988	540	−34.8	−1.2	−9.2	+1.2	99.4	0.56	0.043	0.003
	No. 3	Dec. 1988	339	−19.4	+0.9	−8.0					
	No. 3′	Dec. 1988	347	−21.0	+2.4	−7.6	+5.2	99.0	0.97	<0.0001	0.002
	No. 3″	Dec. 1988	340	−17.4	+1.4	−8.3					
	No. 4	Feb. 1989	337	−22.3	+0.8	−10.9					
	No. 5	May 1989	147	−18.8	+0.5						
	No. 6	Dec. 1989	141	−34.2	−2.4						
South caldera rim	No. 7	Jul. 1989	99	−110.0	−19.9	−4.4					
	No. 8	Dec. 1989	99	−87.5	−16.2						
	No. 8′	Dec. 1989	99	−83.0	−14.7						
	No. 9	Jan. 1991	99	−89.6	−10.6						
	No. 9′	Jan. 1991	99	−88.2	−12.2						
West Mt. Mihara	No. 10	Dec. 1989	99	−73.9	−12.7						

Superscripts, ' and '' noted after sample number, indicate samples collected in the same period, but from different fumaroles.

mospheric to sample CO_2 ranges from 0.6 to 3.5%. For the sample collected on the south caldera rim, the Air/ H_2O ratio is much smaller (<0.1), and effect of air contamination on the data is negligible.

ISOTOPIC VARIATIONS AND ORIGIN OF THE VOLCANIC GASES

"A" terrace fumarole

The hydrogen and oxygen isotopic ratios for H_2O in the "A" terrace fumarolic gases (No. 1–6) are shown in Fig. 3. The isotopic compositions of volcanic gases labelled No. 1, 2 and 6 lie on a mixing line between local meteoric water and island arc magmatic water vapor (Kusakabe and Matsubaya, 1986). Sample No. 1 has the highest temperature, CO_2 , S and Cl contents (Table 1) and is closest to magmatic water vapor composition, indicating the highest magmatic contribution. This suggests that the endmember magmatic water of Izu-Oshima volcano has an isotopic composition similar to that of andesitic to dacitic volcanoes in Japan.

The gases labelled No. 3, 3', 3'', 4 and 5 lie above the meteoric-magmatic water mixing line. Hydrogen isotope fractionation between water vapor and water dissolved in co-existing silicate melt enrichs water vapor phase with deuterium (Taylor and Westrich, 1985). Since, water vapor exsolving from magma becomes depleted in deuterium as degassing proceeds (Taylor, 1986), deuterium enrichment in samples No. 3 to 5 cannot be explained by the D/H fractionation during degassing of the magma. An alternative process to explain the isotopic change is addition of seawater as a third component to the meteoric-magmatic water mixture.

The isotopic compositions of water vapor from the "A" terrace lie within the triangle formed by the three endmembers, magmatic water, seawater and meteoric water (Fig. 3). In order to estimate the contribution of each endmember to the sampled gases, the following isotopic compositions were assumed; magmatic water; $\delta\text{D} = -27\text{‰}$ and $\delta^{18}\text{O} = 5.3\text{‰}$, meteoric water; -40‰ and -6.9‰ , and seawater; 0.0‰

Fig. 3. Hydrogen and oxygen isotopic compositions of fumarolic vapors. Open squares show island arc magmatic gases, a; Usu, b; Satsuma Iwojima, c; Kuju Iwoyama, and d; Showa Shinzan (Kusakabe and Matsubaya, 1986). The sample numbers are the same as those listed in Table 1. Arrows indicate the time sequence.

and 0.0‰ , respectively. The δD of magmatic water is the average of Japanese high temperature volcanic gases compiled by Kusakabe and Matsubaya (1986). The $\delta^{18}\text{O}$ value for magmatic water vapor is equal to the $\delta^{18}\text{O}$ of Izu-Oshima basalt (1951 lava; Matsuhisa, 1979), assuming that ^{18}O in magmatic gas is completely equilibrated with volcanic rocks or magma at high temperature (Matsuo *et al.*, 1974). Temporal variation of the calculated contribution from each endmember to the "A" terrace fumarole is shown in Fig. 4.

The contribution of magmatic water was highest in May 1988 (No. 1 in Fig. 3), when the highest outlet temperature of 636°C was measured. The meteoric water contribution increased in August 1988 when temperature decreased to 540°C . A significant seawater component was first detected in December 1988 (No. 3) about one year after the beginning of the active degassing phase (Fig. 2). Seawater continued to be a component of the volcanic gases until May 1989 (No. 5). Although the gas No. 3 (December 1988) contains a large seawater com-

ponent (Fig. 4), the gas is very low in Cl content (Table 1). The low Cl content of this gas is likely due to the deposition of NaCl during vaporization and ascent of seawater to the surface. The fumarolic temperature decreased from 347° to 147°C during the period of seawater entrainment. Finally, in December 1989 (No. 6), the fumarolic gas lost its seawater component, returning to a simple mixture of meteoric and magmatic waters.

Incorporation of seawater into the volcanic gas may be accounted for by examining the groundwater hydrology of Izu-Oshima. Takahashi *et al.* (1987; 1991) reported that a Ghyben-Herzberg's lens of groundwater exists over the seawater aquifer with the water head almost equal to the sea level at least 2 km away from the coast in the western part of Izu-Oshima. At an early stage of the active degassing period, the seawater component was not found in the fumarolic gases indicating that seawater may not always penetrate into the central part of the island. A number of fractures which formed by the crustal deformation during the 1986 fissure eruption (Endo *et al.*, 1988) may have allowed seawater incursion from the coast to the central part of the island.

A possible mechanism of seawater incursion to the central part is deduced as follows: Based on video monitoring, a significant amount of

Fig. 4. Calculated changes in relative proportions of seawater, meteoric water and magmatic water vapor in the "A" terrace fumarolic gases (see text).

steam was emitted from the pit crater during the latter half of the active degassing period (20,000 to 80,000 tons/day as minimum; measured nine times in December 1988, December 1989 and March 1990; Kazahaya, unpublished data). Since meteoric water and seawater may have been the major constituents of the steam during this period (Fig. 4), a large amount of meteoric water and seawater was released from the pit crater as shown schematically in Fig. 5. Loss of a large amount of meteoric water in the form of vapor in the central part could have lowered the hydraulic level of groundwater aquifer, and ac-

Fig. 5. Schematic cross section of Izu-Oshima showing the flow system of volcanic gases, meteoric water and seawater. Black arrows indicate the flow path for the volcanic gas. White arrows represent the direction of seawater movement through the fracture network.

celerated the seawater incursion from coastal region into the central part through the fracture network formed during 1986 crustal deformation period (Fig. 5).

As shown in Fig. 4, the seawater component in the fumarolic gas diminished in December 1989. One possible explanation for the disappearance of the seawater component is the cessation of seawater flow into the central part of this island. Slow subsidence of the magma head gradually occurred during active degassing as well as depression of the magma reservoir. The depression may have caused a compression in the graben, and may have led to the closure of fractures. On the other hand, heating of seawater near the conduit may have precipitated anhydrite in the fracture system (Giggenbach and Sheppard, 1989), which could have closed the fractures. If the seawater contribution to the volcanic gas was 35%, the steam flux was 20000–80000 tons/day, and minimal duration of seawater entrainment was 6 months, then the total flux of the vapor of seawater origin is estimated to be $1.3\text{--}5 \times 10^6$ tons. Therefore, 5000–20000 tons of anhydrite likely precipitated from seawater. The cessation of seawater contribution have occurred as a result of the closure of fractures due either to a depression of the magma reservoir or precipitation of anhydrite.

Fumaroles on the south caldera rim

The fumarole area consists of alternating scoria and wet surge layers deposited about 1200 years ago (Nakamura, 1964). One characteristic feature of the fumaroles is that the gases discharge only from the scoria layers. The porous scoria layers, sandwiched by the non-porous wet surge layers, are inclined 20° up, away from Mt. Mihara, which constrain the volcanic gas discharge in a direction away from the pit crater (Fig. 5). Fumarolic temperature on the south caldera rim was constant at 99°C during the monitoring period (Table 1). Two-phase conditions exist at 99°C and about 1 bar; vapor production is controlled by boiling and condensation.

The isotopic compositions of fumarolic

Table 2. $\Delta\delta$ and F values calculated for both hydrogen and oxygen isotopes (in detail see text)

Location		$\Delta\delta\text{D}$ (‰)	$\Delta\delta^{18}\text{O}$ (‰)	$F(\text{D}/\text{H})$	$F(^{18}\text{O}/^{16}\text{O})$
South caldera rim	No. 7	−43.4	−7.9	0.20	0.23
	No. 8	−20.9	−4.2	0.47	0.46
	No. 8'	−16.4	−2.7	0.55	0.61
West Mt. Mihara	No. 10	−7.3	−0.8	0.77	0.87

The temperature of 100°C is used for the Rayleigh fractionation calculations.

steam from the south caldera rim (No. 7 through 9) have very low δD and $\delta^{18}\text{O}$ values compared to magmatic gas compositions (Fig. 3). This large depletion in heavy isotopes was found for all samples collected from July 1989 to January 1991. The isotopic composition of water vapor in equilibrium with local meteoric water at 100°C was calculated and plotted on Fig. 3 using the temperature dependence of the hydrogen and oxygen fractionation factor determined experimentally by Kazahaya (1986). The measured isotopic compositions of fumarolic gases lie on the equilibrium line for 100°C , indicating that the fumarolic gas was derived from the local meteoric water. However, as shown in Fig. 3, the fumarolic gas samples are more depleted in D and ^{18}O than the water-vapor in equilibrium with local meteoric water. This large depletion in heavy isotopes is likely produced by open system partial condensation of water vapor in the scoria layer.

A model illustrating this process is shown schematically in Fig. 5: According to Takahashi *et al.* (1987), perched groundwaters exist in the caldera. Boiling of perched water, which was heated by volcanic gases, produced a vapor in equilibrium with perched water. This vapor ascends through the porous scoria layers condensing a liquid, and is discharged to the atmosphere at 99°C . During such condensation, the isotopic composition of vapor changes according to a Rayleigh fractionation process;

$$\Delta\delta = \delta_f - \delta_i = 1000(F^{(\alpha-1)} - 1),$$

Fig. 6. Schematic views of fumarolic discharge processes during different degassing periods. White and black arrows indicate the gases mainly composed of magmatic water and groundwater, respectively. a) November 1986 to October 1987: Summit eruption in November 1986 formed a lava lake in the pit crater. Little emission of fumarolic gases was observed. b) January 1988 to August 1988: High temperature fumaroles formed on the "A" terrace. Vapor from these fumaroles was composed of magmatic water and meteoric water. Active degassing from the pit crater began in January 1988. c) December 1988 to June 1989: Isotopic composition of fumarolic vapor shows involvement of seawater. In June 1989, a new low temperature fumarole at the south caldera rim formed as a secondary effect of the eruption. d) December 1989 to March 1990: In December 1989, seawater flow into the conduit ceased, and the active degassing phase terminated in March 1990.

where, δ_i is the isotopic ratio of the initial vapor in equilibrium with perched meteoric water, δ_f represents the final residual vapor which emitted at the south caldera rim, and F is the residual fraction of vapor after condensation in the scoria layer. The value α represents the isotope fractionation factor between liquid and vapor at 100°C.

The δD_i and $\delta^{18}O_i$ values for the initial equilibrated vapor are assumed to be -68‰ and -12.4‰ , respectively. These values were calculated using the isotope fractionation factor at 100°C and the isotopic composition of local

meteoric water. The $\Delta\delta$ values and the calculated F values from the above equation are listed in Table 2 for both hydrogen and oxygen isotopes. For the earliest sample No. 7 (July 1989), the F value is only 0.2, indicating that a small portion of vapor (20%) emitted to the atmosphere and 80% of the initial vapor condensed in scoria layers. The F value increased from 0.2 for sample No. 7 (July 1989) to 0.5–0.6 for sample No. 8 (December 1989). This suggests that the flow path (scoria layer) became heated with time.

In January 1991, the $\delta^{18}O$ value of vapor

(No. 9) increased by about 4‰ compared to the initial value measured in December 1989. This increase is unlikely to be due to oxygen isotope exchange reaction of fumarolic gases with the surrounding rocks, because the fumarolic temperature is too low (99°C) for the oxygen isotopic exchange to take place. This "shift" is probably due to an increased contribution of the magmatic vapor in the boiling aquifer.

The fumarole area at west Mt. Mihara (Fig. 1) gradually became enlarged during 1989. However, its temperature remained constant at 99°C. The isotopic composition of water from this fumarole (No. 10) plots closer to those of fumaroles located on the south caldera rim (Fig. 3). Therefore, the fumarolic gas from the west Mt. Mihara probably has a similar origin to the south caldera rim fumaroles. The *F* value of about 0.8 estimated for sample No. 10 is the highest (Table 2) indicating only 20% of the vapor condensed in the fumarolic conduits. This fumarole is located on Mt. Mihara and closer to the pit crater where a higher subsurface temperature is expected. This is consistent with a smaller degree of vapor condensation.

CHANGES IN THE DISCHARGE SYSTEM OF VOLCANIC GAS DURING SUBSIDENCE OF MAGMA IN THE CONDUIT

The isotopic changes of the two fumarolic systems (the "A" terrace and the south caldera rim) can be related to magma movement. We present here a scenario to account for the change in the fumarolic activity and change in the fumarolic gas sources during subsidence of the magma in the conduit. Slow subsidence of the magma appears to have started just after the termination of the first phase of eruptive activity which begun in November 1986. This inference is based on the gravity decrease observed at the summit (H. Watanabe, personal comm., 1992).

Yamaoka *et al.* (1989) presented a model for the November 1987 eruption based on seismic observations. After the summit lava-fountaining terminated in November 1986, most of the molten lava remained in the pit crater even after

the magma subsided in the conduit (Fig. 6a). During the slow subsidence of the magma, an open space filled with pressurized volcanic gas formed. The explosive eruption in November 1987, which destroyed the bottom of the pit crater, may have been induced by accumulation of gas. The pooled lava in the crater then rapidly drained back into the magma conduit forming a pit crater again.

Before the explosive eruption of November 1987, changes in fumarolic activity were observed. A loop-shaped line of fumaroles (Fig. 1, Inner loop fumaroles) was discovered in June 1987. On November 10, 1987, 6 days before the explosion, a new line of low temperature fumaroles (60–99°C) developed outside the first line (Fig. 1, Outer loop fumaroles). Growth of the pressurized gas pocket may have induced extensional deformation of the crust below Mt. Mihara forming new loop-shaped fractures around the summit area. The new fractures may have acted as discharge paths of the fumarolic gases. Since the temperature of the new fumaroles is low, the fractures may not directly be connected to the gas pocket (Fig. 6a). During gas monitoring in the summit area, three hydrogen sensors placed around the lava lake detected spike-shaped release of hydrogen to the atmosphere two weeks before the explosion on November 16, 1987 (Kazahaya *et al.*, 1988). The release of hydrogen occurred at the same time as the formation of the outer fumaroles, which indicates that the opening of the new fractures was due to an increase in gas pressure in the conduit.

Initially, the groundwater dominated over seawater in the aquifer below the caldera because no seawater component was detected in the fumarolic gases collected in the early stage of active degassing. New fracture network that developed during 1986 eruption allowed the seawater incursion from the coastal region to the central part (Fig. 6a).

After the November 1987 explosion and formation of the new pit crater, open cracks (width 10–30 cm) formed parallel to the wall of the pit crater on the "A" terrace. High temperature volcanic gas discharged from these cracks (Fig.

6b). The highest proportion of magmatic vapor was calculated (Fig. 4) for the gas discharging from the "A" terrace in May 1988. Subsequently, the contribution of groundwater to the fumarolic gases increased in August 1988. Slow subsidence of the magma enlarged the gas pocket in the conduit which allowed inflow of a large amount of groundwater vapor into the gas pocket. For this reason, a large amount of groundwater discharged from the pit crater (Fig. 6b).

The continued vaporization of groundwater may have accelerated seawater invasion from the coastal region to the central part of the island through fractures that formed during 1986 eruption. A large seawater contribution was inferred in the fumarolic gases from the "A" terrace in December 1988 on the basis of isotopic changes. This may indicate that the magma head had subsided low enough to allow greater amounts of vaporized seawater to flow into the conduit (Fig. 6c). Seawater vaporization continued until May 1989.

As the magma head subsided, new fumaroles on the south caldera rim formed. The magmatic gas discharge continued heating and evaporating the perched groundwater (Fig. 6c). The vapor thus generated then ascended through the permeable scoria layers to the surface at the south caldera rim. This interpretation explains why a new fumarolic system was formed on the south caldera rim after a major magmatic activity weakened. The fumarole of the west Mt. Mihara was also activated by similar process.

The seawater contribution to the "A" terrace fumarolic gas almost disappeared in December 1989. The cessation of vaporization of seawater may be due to closure of the fracture systems either by compression of the crust, or by precipitation of anhydrite. The subsidence of the magma head led to a decrease in magmatic activity by March 1990 (Fig. 6d).

SUMMARY

The isotopic composition of the water vapor in fumarolic gases has allowed inferences to be

made on the discharge mechanism for degassing at Izu-Oshima volcano. The isotopic results of the "A" terrace gas show that the water vapor in the fumarolic gases is composed of three different components; magmatic water, meteoric water and seawater. The proportion of each component changed with time. The gas from the south caldera rim was produced by boiling of perched groundwater. The isotopic composition of this vapor can be explained by partial condensation of water vapor in the conduits.

A slow subsidence of the magma head can explain the changes in sources of the fumarolic gases observed at the "A" terrace and formation of the new discharge system on the south caldera rim.

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