Degassing process of Satsuma-Iwojima volcano, Japan: Supply of volatile components from a deep magma chamber

Kohei Kazahaya, Hiroshi Shinohara, and Genji Saito

Geological Survey of Japan, AIST, 1-1-1 Higashi Tsukuba, Ibaraki 305-8567, Japan

Satsuma-Iwojima volcano continuously releases magmatic volatiles from the summit of Iwodake, a rhyolitic lava dome. The temperature of fumaroles is high, between 800° and 900°C, and the water-rich composition of volcanic gases has not changed essentially over the past 10 years. Sulfur dioxide flux measured by COSPEC is almost constant with an average of 550 t/d since 1975. The present volcanic gas is likely degassed from a rhyolitic magma whose composition is similar to that erupted in 1934, 2 km east of Satsuma-Iwojima. Comparison of silicate melt inclusions and volcanic gas compositions indicates that the magma degassing pressure is very low, implying magma-gas separation at a very shallow level. The mass rate of magma degassing is estimated at 10 m^3/s using the volatile content of the magma and the fluxes of magmatic volatiles. The rhyolitic parental magma is volatile-undersaturated in the deep magma chamber, as suggested by melt inclusion studies. Magma convection in a conduit, driven by the density difference between higher density degassed and lower density non-degassed magmas, explains the high emission rate of magmatic volatiles released at shallow depth from such a magma chamber, that is gas-undersaturated at depth. Model calculations require the conduit diameter to be greater than 50 m as a necessary condition for convection of the rhyolitic magma. Long-term convective degassing has resulted in the rhyolitic magma in the deep chamber to become depleted in volatile components. The melt-inclusion studies indicate that the rhyolitic magma responsible for discharging the present volcanic gas has been degassed during the long degassing history of the volcano and is now supplied with CO_2-rich volatile components from an underlying basaltic magma. The total volcanic gas flux over 800 years requires degassing of 80–120 km^3 of basaltic magma.

1. Introduction

A number of passively degassing volcanoes emit large quantities of magmatic volatiles without eruption, i.e., Etna (Allard, 1997), Stromboli (Allard *et al.*, 1994) and Izu-Oshima (Kazahaya *et al.*, 1994). We can estimate the total amount of the degassed magma if the degassing duration, degassing rate and gas content of the magma are known. These studies show that degassing of volatiles supplied from large magma chambers is necessary to explain the long-term degassing rates. Studies on volatile content of melt inclusions from Satsuma-Iwojima volcano further revealed the degassing evolution of the deep magma chamber (Saito *et al.*, 2001).

Magma convection in a conduit has been proposed as a mechanism responsible for intensive and continuous degassing of magmatic volatiles from magma chambers of basaltic to andesitic volcanoes (Kazahaya *et al.*, 1994). The driving force for convection is the density difference between a dense magma degassed at shallow level and less dense undegassed magma supplied from a deeper level. Shinohara *et al.* (1995) first modeled magma convection in conduits of silicic systems related to porphyry Mo deposits. Stevenson and Blake (1998) modeled the dynamics of convective magma degassing in a revision of the approach by

Kazahaya *et al.* (1994), in order to model silicic systems, and applied their model to the dacitic Mt. St. Helens magma system. Such modeling indicates that convective degassing is likely a common mechanism in basaltic to dacitic volcanoes (Stevenson and Blake, 1998).

Satsuma-Iwojima volcano is a rhyolitic example of intense and continuous degassing. This study summarizes the volatile study of Satsuma-Iwojima volcano, including SO$_2$ flux measurements and melt inclusion data, and applies the above-mentioned degassing mechanism to the more viscous rhyolitic magma systems of Satsuma-Iwojima volcano.

2. Outline of Geology

Mt. Iwodake, the main rhyolitic lava dome on Satsuma-Iwojima island, is located near the northwestern rim of the submarine Kikai caldera (ca. 18 km in diameter). This is the youngest caldera in Japan and formed 6300 yr b.p. (Fig. 1). Early in the post-caldera stage, Mt. Iwodake started to erupt, mainly as lava effusions, but sometimes explosively, producing pumice and pyroclastic flows. The latest explosive activity of Mt. Iwodake is dated at 500 yr b.p. (Kawanabe and Saito, 2002). Basaltic activities simultaneously occurred 2 km distant from Iwodake central crater at about 3000 yr b.p., creating the Inamuradake scoria cone and several basaltic lava flows (Ono *et al.*, 1982). The latest submarine activity occurred in 1934–35, 3 km east of Iwodake on 500-m-deep seafloor, with rhyolitic lava forming Showa-Iwojima Island.
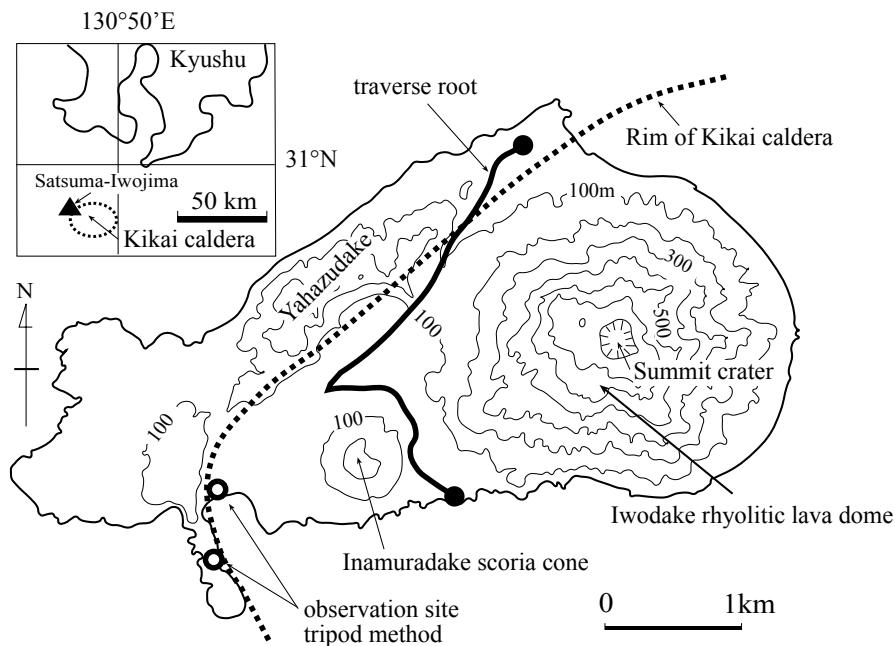
Fig. 1. Topographic map of Satsuma-Iwojima, Kyushu, Japan, showing the location of Iwodake rhyolitic dome and Inamuradake scoria cone. Locations of observation sites for COSPEC measurements by the tripod and the traverse method are also shown.

3. Magma System

Saito *et al.* (2001) measured the chemical and volatile composition of melt inclusions from rhyolites (pumice from caldera-forming eruption and lavas and ashes from the post-caldera stage) and from a basalt (scoria from the post-caldera stage). The post-caldera rhyolites were likely derived from a remnant of the caldera-forming magma, based on the similarity of major-element compositions (Ono *et al.*, 1982; Saito *et al.*, 2001).

Each inclusion has a distinctive volatile composition (Fig. 2; Saito *et al.*, 2001). The Takashima melt inclusions have the highest water concentrations. The saturation pressures based on water and CO_2 solubilities are calculated to be 80–180 MPa, indicating that a rhyolitic magma chamber existed at 3–7 km depth just before the caldera-forming eruption. The saturation pressure of rhyolitic magma that formed Iwodake, a post-caldera lava dome, was about 70 MPa, corresponding to a depth of about 3 km. Inamuradake basaltic activity simultaneously occurred with Iwodake rhyolitic activity, and the magma-chamber depth is estimated to be 3–5 km from the saturation pressure of water and CO_2 (70–130 MPa). This suggests that a layered magma chamber consisting of upper rhyolitic magma (3-km depth) and lower basaltic magma (3–5 km depth) existed during Iwodake and Inamuradake eruption.

Saito *et al.* (2002) estimated the temperatures of the magmas using pyroxene geothermometry. Adjacent orthopyroxene and clinopyroxene phenocrysts from Iwodake and Showa-Iwojima rhyolites have compositions that indicate magma temperatures of $960 \pm 28°C$ and $967 \pm 29°C$, respectively, whereas those from Inamuradake basalt showed a temperature of $1125 \pm 27°C$. The relatively high temperature of the rhyolites may have resulted from heating of the rhyolitic magma by the underlying basalt.

Water contents of the rhyolitic melt inclusions show a decreasing trend from older to younger lavas (Fig. 2). Because the major-element composition of the rhyolitic magma was almost constant during the post-caldera stage, the decrease in water content is likely due to degassing. The volatile-saturation pressure of the latest Showa-Iwojima magma, 20–50 MPa (0.5–2 km depth), is too low to represent the real pressure of the magma chamber. The present magma chamber is most likely located at 3-km depth, as estimated from the Iwodake melt-inclusion constraints. As the result of long-term and intense degassing, the Showa-Iwojima magma should be undersaturated with volatiles at the depth of the present rhyolitic magma chamber. However, the melt inclusions from Showa-Iwojima, the latest product of Satsuma-Iwojima volcano, have the highest CO_2 concentrations in rhyolites despite their water concentrations and saturation pressures being the lowest. The origin of the high CO_2 concentration in this rhyolite is discussed in Section 10.

4. Volcanic Gases

Many fumaroles exist in and around the summit. The chemical composition of volcanic gases from the summit crater of Iwodake has been relatively constant since the 1950s (Kamada, 1964) and there has been little change during the past 10 years (Shinohara *et al.*, 2002). Isotopic compositions of the summit volcanic gases indicate that the gases have a magmatic origin (Shinohara *et al.*, 1993; Hedenquist *et al.*, 1994). The highest fumarole temperature measured was 900°C in 1994 (Shinohara *et al.*, 2002).

The summit area of the main Iwodake lava dome is strongly silicified by volcanic gases (Hamasaki, 2002), indicating that degassing has continued for a long time. An old manuscript "Heike Monogatari," written about 800 years ago, indicates that intense volcanic gas emission and depo-
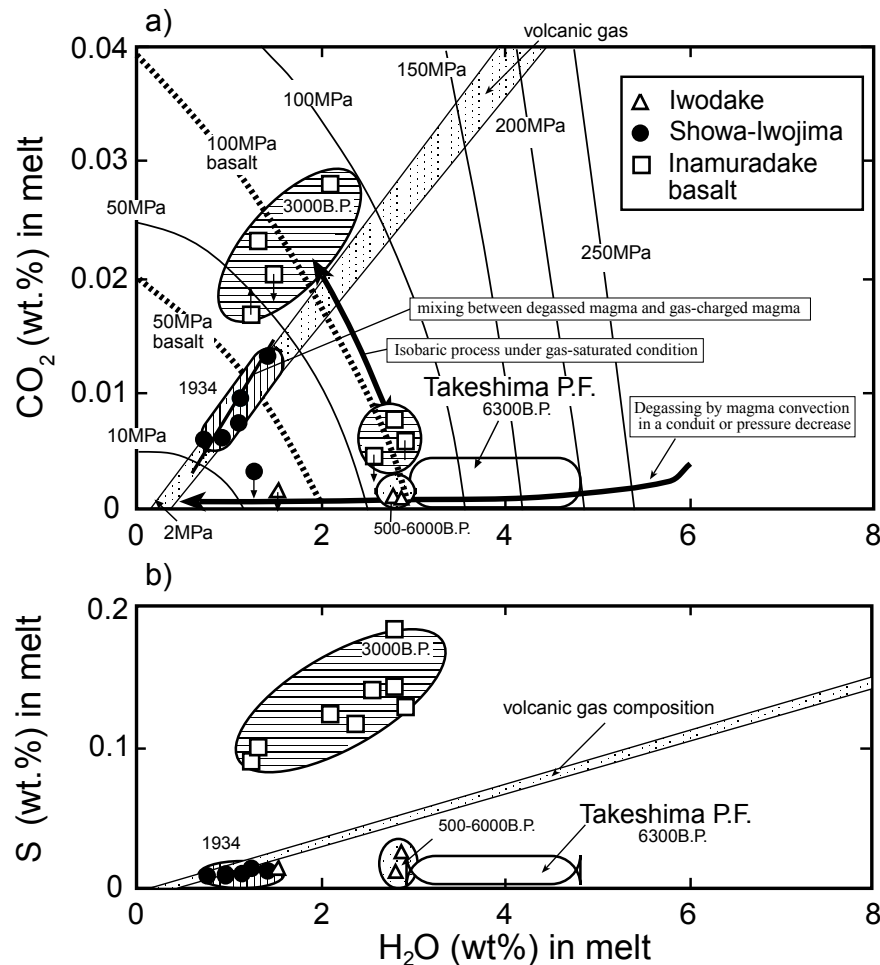
Fig. 2. Volatile composition of melt inclusions in pumices from Takeshima and Iwodake pyroclastic flows, scoria from Inamuradake and pumicious lava from Showa-Iwojima (revised from Saito *et al.*, 2001). a) H_2O and CO_2, b) H_2O and S. Isobaric solubility curves are drawn using solubilities of H_2O in rhyolite at 1000°C (Miyagi *et al.*, 1997), H_2O in basalt at 1100°C (Burnham, 1979), CO_2 in rhyolite at 1200°C (Fogel and Rutherford, 1990) and CO_2 in basalt at 1200°C (Stolper and Holloway, 1988). The dotted area indicates the range of CO_2/H_2O and S/H_2O ratios of high temperature volcanic gases at the summit crater (Shinohara *et al.*, 2002). This area is drawn assuming that magma does not degas all its H_2O even at low-pressure conditions, as usually found from the lava compositions.

sition of sulfur already existed at that time (Kamada, 1964). Therefore, volcanic gases have discharged for greater than 800 years from the summit crater of Iwodake.

5. Source of Volcanic Gases

Long-term intense discharge of volcanic gases from Iwodake implies that the underlying magma chamber is relatively degassed. Since the chemical composition of the melt inclusions in the rhyolites from Satsuma-Iwojima volcano is rhyolitic, these inclusions most likely represent the parental rhyolitic magma chamber at depth. The CO_2/H_2O ratio of the volcanic gas is found to be similar to that dissolved in the melt inclusions from the Showa-Iwojima and the Inamuradake melt inclusions (Fig. 2), and it is strongly suggested that volcanic gas comes from either residual portion of the Showa-Iwojima rhyolitic magma or Inamuradake basaltic magma.

Saito *et al.* (2001) measured the sulfur and chlorine contents of melt inclusions, and found that the Showa-Iwojima melt inclusions have S/H_2O ratios similar to the volcanic gases. By contrast, the Inamuradake melt inclusions contain

several times more sulfur than that expected on the basis of the volcanic gas composition (Fig. 2). As the composition of volcanic gas has been almost constant over the past 10 years (Shinohara *et al.*, 2002), a stable degassing system is likely to exist. This implies that the volcanic gases are emitted from magma with a constant volatile content and constant degassing pressure.

For the following reasons, we assume that the present volcanic gas is released from a rhyolitic magma with a volatile content similar to the Showa-Iwojima magma (erupted 67 years ago), rather than from a basaltic magma:

1) Basaltic to andesitic magma has never erupted from the Iwodake lava dome.

2) Less-dense rhyolitic magma may still be located in the upper part of a magma chamber above basaltic magma. Therefore, degassing of magmatic gases directly from an underlying basaltic magma is unlikely.

3) The high fumarolic temperature (900°C) is close to the temperature of the Showa-Iwojima rhyolite, estimated

from the two pyroxene geothermometer (967–990°C; Saito *et al.*, 2002). Thus, basaltic magma is not necessary to explain the high fumarole temperatures.

4) The Showa-Iwojima melt inclusions have volatile compositions that are more similar to the volcanic gases than those of the Inamuradake melt inclusions. The high fumarolic temperature also suggests a low pressure of degassing, and in this situation the volcanic gas composition should be close to the volatile composition of the magma. In particular, the Inamuradake melt inclusions have excessive sulfur concentrations to conclude that the sulfur in volcanic gases is directly derived from the Inamuradake magma.

Therefore, the present volcanic gas is most likely released from a rhyolitic magma similar in composition to that of Showa-Iwojima magma, rather than from the basaltic magma underlying the rhyolitic magma.

6. Sulfur Dioxide Flux Measurements

The first sulfur dioxide flux measurement by COSPEC III was performed in 1975 by the seaborne traverse method, measuring 570 t/d (Ohkita *et al.*, 1977). We measured SO_2 flux since 1990 using COSPEC V with the ground-based tripod method and the traverse method using a vehicle. During COSPEC measurement, volcanic plume movement was monitored by a video camera to determine the wind velocity. The results for the COSPEC measurements are summarized in Table 1.

For the tripod method, we used an automatic tilting mount and SO_2 flux was monitored every minute. As the volcanic plume was horizontal, during the monitoring, a vertical scan of the plume was performed during all the tripod measurements. The baseline changed during vertical

scanning, mainly due to the UV intensity variation in the scan range between low and high angles. Therefore, we always corrected for this effect by using background SO_2-free data, determined in a direction without any volcanic plume. As the observation points were restricted on the island, we sometimes found that part of the volcanic plume was hidden behind the flank of Iwodake. Such data underestimated the flux and were omitted from Table 1.

The flux values obtained by the traverse method are always higher than those obtained by the tripod method. On Satsuma-Iwojima, the traverse route is restricted to a road from southwest to northwest sites (Fig. 1). The route follows the valley between Inamuradake cone and Yahazudake caldera wall. Because of the topography, part of the plume is likely trapped and stagnant in the valley when the wind blows in the SW to NW directions. This causes an overestimation of the SO_2 flux during the traverse method, because COSPEC measures the SO_2 signal not only from the flowing plume but also from the trapped plume. Thus, we use only the SO_2 flux value obtained by the tripod method.

The SO_2 flux from the Iwodake summit crater varied between 320 and 750 t/d with the average flux of 550 t/d during the monitoring period from 1990 to 1998. Fluxes of other magmatic volatiles can be estimated using the chemical composition of the volcanic gases (Shinohara *et al.*, 2002) from the summit of Iwodake. These are 16000 t/d for water and 150 t/d for CO_2 (Table 2). The magmatic volatile flux condensed into groundwater and discharged from hot springs has been neglected. Therefore, these are minimum flux values from the Satsuma-Iwojima volcano.

7. Volatile Budget

We can calculate the mass rate of magma degassing using the magmatic volatile fluxes and volatile content of the Showa-Iwojima magma. A water content of 1 wt.% is used for the following calculation, because the highest water value of the Showa-Iwojima magma is 1.4 wt.% from melt inclusion analyses (Saito *et al.*, 2001), and some water is retained in the magma. The mass rate of magma degassing calculated on the basis of individual species, H_2O, CO_2 and S, varies in the range 17,000–30,000 kg/s or 7.5–13 m^3/s, assuming complete degassing for S and CO_2 (Table 2). The average value of 22,000 kg/s (1.9 Mt/d) or 10 m^3/s is used in the following discussion for the mass rate of magma degassing.

Since degassing is believed to have continued for more than 800 years (Yoshida and Ozawa, 1981), the estimate of the volume of degassed magma is 250 km^3, if all the gases were initially contained in the rhyolitic magma. This calculation assumes that the composition of volcanic gas and volatile content of magma has been constant over 800 years; however, there is no evidence to check this assumption. The volatile content of the Showa-Iwojima magma used in the above calculation is the highest value. Therefore, the 250 km^3 estimate for total volume of degassed magma is a minimum. The trend in volatile content of magmas over the past 6300 years (Fig. 2) also indicates that degassing of the magma chamber occurred during the post-caldera stage (Saito *et al.*, 2001). Consequently, long-term degassing of a rhyolitic magma chamber might be required.

Table 1. Sulfur dioxide flux from the Iwodake summit measured by COSPEC with the tripod and the traverse methods.

Date	SO_2 flux (t/d)		
	min.	max.	ave.
tripod method			
1990.10.27	430	540	470
1994.10.30	420	880	640
1996.10.16	210	900	460
1997.4.20	230	750	470
1997.4.21	470	1100	750
1998.11.8	120	600	320
traverse method			
1975.2.12*	510	620	570
1995.10.21**	(1370)	(2070)	(1760)
1997.4.20**	(920)	(1430)	(1210)
1997.4.21**	(1460)	(1600)	(1530)
average			550

*measured by Ohkita *et al.* (1977) using a boat.
**measured using a vehicle. values are not used (see text).

Table 2. High temperature volcanic gas composition, flux and melt inclusion concentration of H_2O, CO_2 and SO_2, and mass rate of the magma degassing calculated for each species.

	H_2O	CO_2	SO_2	
Mean chemical composition (mol%)*	97.4	0.037	0.093	
Flux (t/d)**	16000	150	550	
degassed from melt (wt%)***	1	0.010	0.021	
Mass rate of magma degassing				average
(m³/s)	8.2	7.5	13.1	10
(kg/s)	19000	17000	30000	22000

*average of high temperature volcanic gas calculated from the data given by Shinohara *et al.* (2002).
**calculated using SO_2 flux (550 t/d) and the mean chemical composition.
***reduced from the melt inclusion data given by Saito *et al.* (2001). See text.

8. Degassing Mechanism

Degassing of magma requires oversaturation of volatiles in a melt. Therefore, degassing occurs only at relatively low-pressure conditions. However, the magma chamber is concluded to be located at a relatively high pressure, greater than 3 km for Satsuma-Iwojima volcano (Saito *et al.*, 2001). Therefore, a huge amount of magmatic volatiles must be transported from such a deep magma chamber towards the surface. Because the volcanic gases from the fumaroles collected at the summit crater are water-rich (>97%) and of magmatic origin (Shinohara *et al.*, 1993; Hedenquist *et al.*, 1994), the degassing pressure must be low enough to degas water efficiently from the parental magma. As mentioned earlier, the highest fumarolic temperature of 900°C also supports the idea that volcanic gases were released from the magma at shallow depths. Therefore, it is necessary that the magma chamber system is connected to the surface by an open conduit and water-rich magmatic gases are separated at shallow depths. As effective water degassing from magma only occurs at shallow depths, water must be transported from a deep magma chamber either as bubbles or water-bearing magma. Because the Showa-Iwojima magma is likely to be undersaturated in volatiles at the depth of the magma chamber, water transport by bubbles not possible.

Water transport by volatile-bearing magma is possible as the result of magma convection in a conduit (Kazahaya *et al.*, 1994). When a magma conduit extends to a shallow level and is allowed to degas, the upper-most part of the magma may then degas efficiently. Density of the degassed magma increases by bubble separation and melt degassing, which makes the lower part of undegassed magma buoyant, and the degassed magma descend through the conduit.

9. Rhyolitic Magma Convection in a Conduit

In this section, we discuss whether convection of the Showa-Iwojima rhyolitic magma could occur in an open conduit system with a sufficient rate to account for the observed degassing rate. The degassing rate induced by magma convection in a conduit is controlled by two processes: 1) the rate of counter flow in a magma conduit, and 2) bubble separation rate at the top of the conduit. The first process can be evaluated by fluid dynamic model. Stevenson and Blake (1998) provided fluid dynamic equa-

tions for magma convection in conduits based on experiments and theory, revising the treatment by Kazahaya *et al.* (1994):

$$Q = \pi (R^*)^2 \mathrm{Ps}(g\Delta\rho R^4/\mu_d), \qquad (1)$$

where $R^* (= R_a/R_c)$ is the dimensionless radius of the rising flow and Ps is the Poiseuille number (Koyaguchi and Blake, 1989). Viscosity values for degassed magma with a water concentration of 0.4 wt.% (μ_d), and undegassed magma with a water concentration of 1.4 wt.% (μ_c), are calculated with the method of Persicov (1990). The viscosity of rhyolitic magma using the chemical composition of lava of Showa-Iwojima (Ono *et al.*, 1982) is $10^{6.1}$ Pa·s and $10^{4.9}$ Pa·s at 1000°C, respectively. The Ps is constant at a value of 0.064 when $\mu_d/\mu_c > 12$ (Stevenson and Blake, 1998), and Ps of 0.064 is used for calculation. An R^* value of 0.6 is used according to the experiments by Stevenson and Blake (1998). Degassing of 1 wt.% water results in a density difference of about 50 kg/m³, calculated from the method of Lange and Carmichael (1987). This density difference drives the magma convection in a conduit (Fig. 3). The diameter of the magma conduit obtained is 50 m using Eq. (1). This conduit diameter is realistic, based on estimations of conduit diameters at other volcanoes (80–120 m for Mt. St. Helens in 1980; Stevenson and Blake, 1998).

Another rate control factor for magma convection is the separation process of the bubbles from magma. This process might be very important for non-explosive eruption such as dome-forming eruptions. Formation of permeable foam in an ascending silicic magma would induce gas loss in a shallow conduit prior to eruption (Eichelberger *et al.*, 1986; Westrich and Eichelberger, 1994). Melnik and Sparks (1999) showed theoretically that gas exsolution of a silicic melt at shallow depth causes crystallization of magma during its ascent, and the effective gas release occurs through a permeable magma column. Although the above-mentioned process was modeled for dome-forming eruptions, it is applicable to degassing of a convecting magma, because the degassing process occurs in a shallow conduit prior to eruption and is controlled mainly by decompression rate and viscosity.

There are some volcanoes that have erupted effusively with an emission rate of volcanic gases similar to Satsuma-
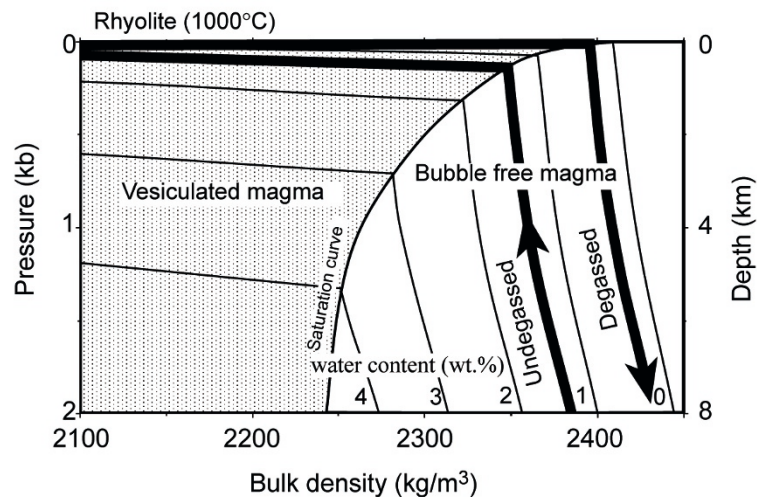
Fig. 3. Density changes of ascending undegassed magma and descending degassed magma as a function of pressure (depth) for the Showa-Iwojima rhyolitic composition at 1000°C. Arrow shows a path for the convective transport of magma. Numbers are water content in wt.%. The solubility curve is from Miyagi *et al.* (1997). Densities were calculated based on Lange and Carmichael (1987).
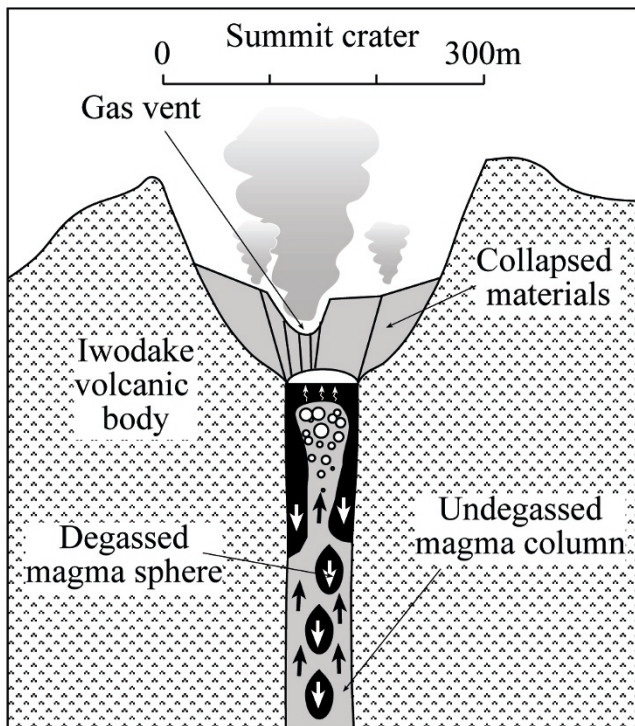

Fig. 4. Model of magma convection in a conduit at shallow depth. The flow style of degassed magma descending as spheres through the undegassed magma was originally suggested by Stevenson and Blake (1998) based on experiments with a parameter $12 < \mu_d/\mu_c < 300$.

Iwojima. For example, during the 1991 eruption of Unzen volcano, the highest emission rates of magma and SO_2 were 7 m³/s (Nakada and Motomura, 1999) and 240 t/d (Hirabayashi *et al.*, 1995), respectively. The effusion rate of dacite magma at Unzen volcano is very close to the mass rate of magma degassing for Satsuma-Iwojima of 10 m³/s. The estimated viscosity of Satsuma-Iwojima rhyolitic magma is not particularly high ($\sim 10^5$ Pa·s), and is comparable to that

of typical andesitic to dacitic magmas, including the Unzen magma. As the Unzen magma obviously degassed large amounts of volatiles without explosions, the Showa-Iwojima magma might also be able to degas at a similar mass rate, because of the similarities in magmatic and flow parameters. Finally, we conclude that degassing as the result of rhyolitic magma convection in a conduit may occur at Satsuma-Iwojima volcano. This is consistent with the occurrence of high-temperature fumaroles, high emission rate of magmatic gases and the long duration of degassing.

Stevenson and Blake (1998) performed experimental studies on the style of fluid convection when the viscosity ratio (μ_d/μ_c) is between 10 and 300 Pa·s. A possible style of degassing-induced magma convection in a conduit is illustrated in Fig. 4, based on the experiments by Stevenson and Blake (1998). The magma is hypothesized to lie very close to the bottom of the crater, near the location of the pressure source of low-frequency earthquakes as estimated by particle-motion analyses of broadband seismic data (Ohminato and Ereditato, 1997).

10. Volatile Transport from Basalt to Rhyolite

Showa-Iwojima magma has relatively higher CO_2 and lower H_2O contents than the other older magmas (Fig. 2). Long-term degassing during magma convection in a conduit could cause volatile undersaturation of the magma in the deep chamber. However, the high CO_2 content cannot be explained by degassing, because CO_2 is the less soluble species and the most readily degassed. Volatile supply from a mafic magma system to a silicic magma system has been suggested (e.g., Wallace *et al.*, 1995; Wallace, 2001) to explain the excess sulfur degassing during explosive eruptions.

In the case of Satsuma-Iwojima, however, CO_2 supply from basalt could be accompanied by H_2O but not by sulfur compounds, because of the low S content in the Showa-Iwojima rhyolite. Therefore, the volatile transport mechanism might be different from that suggested for other volcanoes. The transport mechanism of CO_2 from basalt to rhyo-
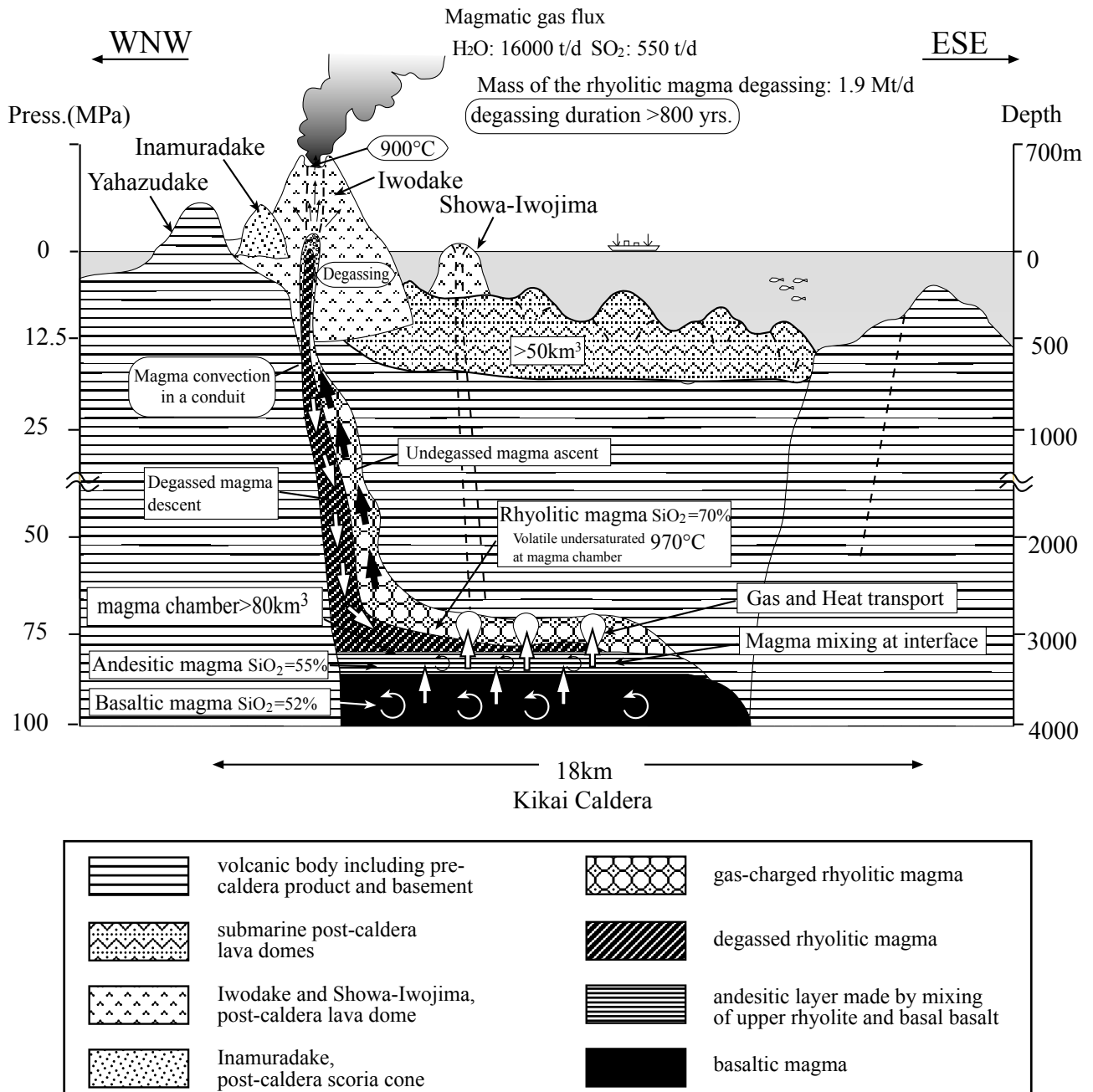
Fig. 5. Schematic illustration of magma system of Satsuma-Iwojima volcano (vertically exaggerated). The pressure of the basaltic magma and chemical compositions of the magma are from Saito *et al.* (2001). See text for details.

lite is not yet clear, but may result from bubble migration or diffusion in the deep chamber. Bubble migration can transport volatiles oversaturated at the chamber pressure. Therefore, the transported volatiles should be rich in CO_2 and poor in H_2O. As the solubility of sulfur compounds in a CO_2-rich gas phase is not yet known, the S content in the bubbles might be very low. This possibility is consistent with the present model but is not consistent with the commonly accepted hypothesis of sulfur supply mechanism (e.g., Wallace *et al.*, 1995; Wallace, 2001). In contrast, transport of CO_2 and H_2O may also be caused by diffusion, which is driven by the activity gradient of a component. As sulfide solu-

bility in silicate melt is much higher in a basaltic melt than in a rhyolitic melt (Carroll and Webster, 1994), the activity gradient of sulfur between a basalt and a rhyolite may be so small that little sulfur diffusion can take place.

Snyder and Tait (1998) theoretically modeled the chemical interaction caused by input of basalt to a more silicic magma chamber based on a flow-enhanced diffusive transport model, and concluded that diffusive exchange between silicic and basaltic magmas is easier to occur than that has been thought previously. If the diffusive exchange occurs between the degassed rhyolite and gas-bearing basalt, volatile transport from the basalt to the silicic magma would

occur. This process can explain the volatile supply to the magma chamber system of Satsuma-Iwojima. Long-term convective degassing results in the upper rhyolitic magma in the chamber becoming degassed, and the volatiles contained in the underlying basaltic magma could be transported into the upper degassed rhyolite.

The diffusion hypothesis can explain not only the CO_2 supply mechanism but also variation of volatile composition in the Showa-Iwojima magma that seems to lie along a straight line originating from 0.1–0.4 wt.% H_2O and zero CO_2 (Fig. 2). This volatile-poor composition could result from degassing at a low pressure of 0.5–3.0 MPa that might correspond to the degassing pressure at the top of convecting magma. As neither degassing nor crystallization can create such a variation along a straight line that does not pass through the origin, the variation is most likely created by mixing between volatile-poor rhyolite and volatile-rich rhyolite. The volatile-rich rhyolite might be created by volatile and heat supply from basalt.

The present rhyolitic magma is thought to have fully degassed its original volatiles, such as noted from the Iwodake magma or the Takeshima magma. It acts only as the carrier of volatile components from the underlying basaltic magma to the surface. The estimated mass of the degassed magma of 250 km^3 does not represent a real volume of the rhyolite in the chamber, but that circulated through the conduit. Inamuradake basalts contain H_2O 2–3 wt.%, obtained by melt inclusion study (Saito *et al.*, 2001). Assuming that all the magmatic water flux of 16000 t/d (Table 2) was supplied from a basalt with this H_2O content, we can estimate the total mass of degassed basaltic magma to be 80–120 km^3 over the past 800 years.

11. Summary

A schematic model is shown in Fig. 5, which summarizes the present magma system of Satsuma-Iwojima volcano deduced from the volatile studies (Shinohara *et al.*, 1993, 2002; Kazahaya and Shinohara, 1996; Saito *et al.*, 2001, 2002) and SO_2 flux studies. Combination of repeat SO_2 flux measurements using COSPEC and chemistry of volcanic gases (Shinohara *et al.*, 2002) indicate an average flux of volatiles of 550 t/d SO_2, 16,000 t/d water and 150 t/d CO_2. Based on studies of melt inclusions and mafic inclusions of the Satsuma-Iwojima magmas, a layered magma chamber is suggested to exist (Saito *et al.*, 2001, 2002). The depth of the basaltic and rhyolitic magmas in the chamber is estimated to be 3–5 km and 3 km, respectively (Saito *et al.*, 2001).

The Showa-Iwojima magma erupted in 1934–35, is likely representative of the present degassing magma at depth, because of the similarity between the volcanic gas composition and the volatile composition of its melt inclusions. Carbon dioxide concentration of the Showa-Iwojima melt inclusions is the highest in the rhyolitic melt inclusions, despite the water concentrations being the lowest. The CO_2 in the Showa-Iwojima magma is thought to be supplied from the basaltic magma located beneath the rhyolitic magma. The volatile transport from the underlying basaltic magma to the upper rhyolitic magma must occur at the rate of volatile emissions from the summit. Thus, the rhyolitic magma acts as the

volatile transporter through the process of magma convection in a conduit. This magma convection is driven by the density difference between degassed and undegassed magmas. The degassing has continued over at least the past 800 years. An estimate for the total amount of the degassed magma produced during this time is 80–120 km^3, assuming that the chamber degasses magma with a water of 2–3 wt.%, corresponding to the water content of the Inamuradake basaltic magma.

This process of magma convection in a conduit will work until the whole magma chamber is degassed, which includes both the rhyolitic and basaltic magmas. The convective degassing model presented here is plausible even for a rhyolitic magma system, and is consistent with the results by volatile studies, such as compositions of volcanic gases and melt inclusions, and the emission rate of magmatic gases. The specific mechanism of volatile supply from the basaltic magma to the upper rhyolitic magma is still unclear.

References

Allard, P., Endogenous magma degassing and storage at Mount Etna, *Geophys. Res. Lett.*, **24**, 2219–2222, 1997.

Allard, P., J. Carbobbelle, N. Metrich, H. Loyer, and P. Zettwoog, Sulfur output and magma degassing budget of Stromboli volcano, *Nature*, **368**, 326–330, 1994.

Burnham, C. W., Magmas and hydrothermal fluids, in *Geochemistry of Hydrothermal Ore Deposits*, edited by H. Barnes, 2nd ed., pp. 71–136, John Wiley & Sons, New York, 1979.

Carroll, M. R. and J. D. Webster, Solubilities of sulfur, noble-gases, nitrogen, chlorine, and fluorine in magmas, *Volatiles in Magmas, Rev. Mineral.*, 30, edited by M. R. Carroll and J. R. Holloway, pp. 231–279, Mineral. Soc. Am., Washington, 1994.

Eichelberger, J. C., C. R. Carrigan, H. R. Westrich, and R. H. Price, Non-explosive silicic volcanism, *Nature*, **323**, 598–602, 1986.

Fogel, R. A. and M. J. Rutherford, The solubility of carbon dioxide in rhyolitic melts: a quantitative FTIR study, *Am. Mineral.*, **75**, 1311–1326, 1990.

Hamasaki, S., Volcanic-related alteration and geochemistry of Iwodake volcano, Satsuma-Iwojima, Kyushu, SW Japan, *Earth Planets Space*, **54**, this issue, 217–229, 2002.

Hedenquist, J. W., M. Aoki, and H. Shinohara, Flux of volatiles and ore-forming metals from the magmatic-hydrothermal system of Satsuma Iwojima volcano, *Geology*, 585–588, 1994.

Hirabayashi, J., T. Ohba, K. Nogami, and M. Yoshida, Discharge rate of SO_2 from Unzen volcano, Kyushu, Japan, *Geophys. Res. Lett.*, **22**, 1709–1712, 1995.

Kamada, M., Volcano and geothermy of Iwo-jima, Kagoshima prefecture, *Jinetsu*, **3**, 1–23, 1964 (in Japanese).

Kawanabe, Y. and G. Saito, Volcanic activity of the Satsuma-Iwojima area during the past 6500 years, *Earth Planets Space*, **54**, this issue, 295–301, 2002.

Kazahaya, K. and H. Shinohara, Excess degassing of active volcanoes: processes and mechanisms, *Mem. Geol. Soc. Japan*, **46**, 91–104, 1996 (in Japanese with English abstract).

Kazahaya, K., H. Shinohara, and G. Saito, Excessive degassing of Izu-Oshima volcano: magma convection in a conduit, *Bull. Volcanol.*, **56**, 207–216, 1994.

Koyaguchi, T. and S. Blake, The dynamics of magma mixing in a rising magma batch, *Bull. Volcanol.*, **52**, 127–137, 1989.

Lange, R. and I. S. E. Carmichael, Densities of Na_2O-K_2O-CaO-MgO-FeO-Fe_2O_3-Al_2O_3-TiO_2-SiO_2 liquids: new measurements and derived partial molar properties, *Geochim. Cosmochim. Acta*, **51**, 2931–2946

1987.

Melnik, O. and R. S. J. Sparks, Nonlinear dynamics of lava dome extrusion, *Science*, **402**, 37–41, 1999.

Miyagi, I., H. Yurimoto, and E. Takahashi, Water solubility in albite-orthoclase join and JR-1 rhyolite melts at 1000°C and 500 to 2000 bars, determined by microanalysis with SIMS, *Geochem. J.*, **31**, 57–61, 1997.

Nakada, S. and Y. Motomura, Petrology of the 1991–1995 eruption at Unzen: effusion pulsation and groundmass crystallization, *J. Volcanol. Geotherm. Res.*, **89**, 173–196, 1999.

Ohkita, T., M. Kawamura, and S. Takagi, Amount of SO_2 emission from Satsuma-Iwojima volcano, *Kazan*, **22**, 107, 1977 (abstract in Japanese).

Ohminato, T. and D. Ereditato, Broadband seismic observation at Satsuma-Iwojima, Japan, *Geophys. Res. Lett.*, **24**, 2845–2848, 1997.

Ono, K., T. Soya, and T. Hosono, Geology of Satsuma-Io-jima district, Quadrangle series, Scale 1:50,000, 2, Geol. Surv. Japan, 80 p., 1982 (in Japanese with English abstract).

Persikov, E. S., The viscosity of magmatic liquids: experiment, generalized patterns, a model for calculation, applications, in *Physical Chemistry of Magmas*, edited by L. L. Perchuk and I. Kushiro, pp. 1–40, Springer-Verlag, 1990.

Saito, G., K. Kazahaya, H. Shinohara, J. Stimac, and Y. Kawanabe, Variation of volatile concentration in a magma system of Satsuma-Iwojima volcano deduced from melt inclusion analyses, *J. Volcanol. Geotherm. Res.*, **108**, 11–31, 2001.

Saito, G., J. A. Stimac, Y. Kawanabe, and F. Goff, Mafic-felsic magma interaction at Satsuma-Iwojima volcano, Japan: Evidence from mafic inclusions in rhyolites, *Earth Planets Space*, **54**, this issue, 303–325, 2002.

Shinohara, H., W. F. Giggenbach, K. Kazahaya, and J. W. Hedenquist, Geochemistry of volcanic gases and hot springs of Satsuma-Iwojima, Japan: Following Matsuo, *Geochem. J.*, **27**, 271–285, 1993.

Shinohara, H., K. Kazahaya, and J. B. Lowenstern, Volatile transport in a convecting magma column: Implications for porphyry Mo mineralization, *Geology*, **23**, 1091–1094, 1995.

Shinohara, H., K. Kazahaya, G. Saito, N. Matsushima, and Y. Kawanabe, Degassing activity from Iwodake rhyolitic cone, Satsuma-Iwojima volcano, Japan: Formation of a new degassing vent, 1990–1999, *Earth Planets Space*, **54**, this issue, 175–185, 2002.

Snyder, D. and S. Tait, The imprint of basalt on the geochemistry of silicic magmas, *Earth Planet. Sci. Lett.*, **160**, 433–445, 1998.

Stevenson, D. S. and S. Blake, Modelling the dynamics and thermodynamics of volcanic degassing, *Bull. Volcanol.*, **60**, 307–317, 1998.

Stolper, E. and J. R. Holloway, Experimental determination of the solubility of carbon dioxide in molten basalt at low pressure, *Earth Planet. Sci. Lett.*, **92**, 107–123, 1988.

Wallace, P. J., Volcanic SO_2 emissions and the abundance and distribution of exsolved gas in magma bodies, *J. Volcanol. Geotherm. Res.*, **108**, 85–106, 2001.

Wallace, P. J., A. T. Anderson, and A. M. Davis, Quantification of pre-eruptive exsolved gas contents in silicic magmas, *Nature*, **377**, 612–616, 1995.

Westrich, H. R. and J. C. Eichelberger, Gas-transport and bubble collapse in rhyolitic magma—an experimental approach, *Bull. Volcanol.*, **56**, 447–458, 1994.

Yoshida, M. and T. Ozawa, Abundance of some chemical elements produced by Satsuma-Iwo-Jima Volcano in relation to their provenance, *Bull. Volcanol. Soc. Japan*, **26**, 25–34, 1981.

K. Kazahaya (e-mail: kazahaya-k@aist.go.jp), H. Shinohara, and G. Saito