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Degassing activity from Iwodake rhyolitic cone, Satsuma-Iwojima volcano, Japan: Formation of a new degassing vent, 1990–1999

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Large changes in the surface manifestation of degassing activity were observed from 1990 to 1999 at the summit crater of Iwodake cone of Satsuma-Iwojima volcano. During this period, a new high-temperature fumarolic area formed in the center of the crater floor and became a degassing vent with a diameter of 40 m. Altered volcanic rocks were ejected during the course of vent formation. Although glass fragments were observed in the ejected ash, the glass comes from altered Iwodake rhyolite that covers the crater floor. The highest fumarolic temperature and equilibrium temperatures of volcanic gases had a maximum of about 900°C at the beginning of the vent formation. The flux of SO_2, measured by COSPEC, varied from 300 to 700 ton/day and correlated directly with maximum fumarole temperature. During this period, open fractures formed along the southern rim of the crater almost contemporaneously with the vent formation and changes in the nature of fumarolic discharges. The continuous and intense degassing at Satsuma-Iwojima is likely caused by volatile transport from a deep magma chamber through a convecting magma column. An increase in the magma convection rate might have caused these large changes in surface manifestations, including increase in the SO_2 flux and fumarolic temperatures, ground deformation, and the vent formation.

1. Introduction

The rate of volcanic gas emission is now regarded as an important factor for evaluating not only volatile transport processes beneath a volcano but also movements of magma itself. A large flux of volcanic gases has been observed commonly at weakly to non-erupting volcanoes (e.g., Andres *et al.*, 1991; Allard *et al.*, 1994). Convection in a volcanic conduit was proposed as a mechanism to move volatile-bearing magmas from a deep magma chamber to the near-surface, allowing such intensive degassing from non-erupting volcanoes (Kazahaya *et al.*, 1994). This model revealed that magma is actively moving near the surface beneath such degassing volcanoes despite little magmatic eruption. Satsuma-Iwojima volcano is a good example of such an actively degassing but non-erupting volcano.

High-temperature fumarolic gases at a temperature greater than 800°C have long discharged at Satsuma-Iwojima. Emission of such high temperature gases, accompanied by a large SO_2 flux of $\sim$500 ton/day, require that magma convection is also operating beneath this volcano (Kazahaya *et al.*, 2002). However, the only major surface manifestation of convection in the summit area has been the fumarolic activity (e.g., Kamada, 1964; Yokoyama *et al.*, 1966), and therefore a direct relation to magmatic processes was not readily apparent. There have been several recent changes in the surface manifestations of volcanic activity at this volcano, including changes in the distribution of fumaroles, fumarolic temperature, gas flux and ground deformation. Ejection of volcanic materials have also occurred from a newly formed, high-temperature fumarolic area, resulting in a degassing vent of 40-m diameter. This report describes these recent changes from 1990 to 1999 and discusses their volcanological implication, particularly in relation to the process of magma convection.

2. Geological Background

Satsuma-Iwojima is a volcanic island on the northwestern rim of Kikai caldera, located 40 km south of Kyushu island, Japan (Fig. 1). The caldera formed during at least three major eruptions with pyroclastic flows. The most recent major caldera-forming eruption occurred about 6,300 years ago, forming the Takeshima pyroclastic flow (Ono *et al.*, 1982). Eruptions of two volcanic cones, the basaltic cone of Inamuradake and the rhyolitic cone of Iwodake, occurred after the caldera-forming eruptions and ceased about 3,000 years ago at Inamuradake and about 500 years ago at Iwodake (Kawanabe and Saito, 2002).

Old Japanese literature “Heike-monogatari” describes fumarolic activity and sulfur mining at the summit of Iwodake about 800 years ago, suggesting intense fumarolic activity for at least the past 800 years. Although there is no description of historical eruptions in the literature, Kamada (1964) reported a tale of old residents that small eruptions have been frequent in the summit crater area. However, the age and the detail of the activity were not reported. The most recent eruption within the Kikai caldera occurred in 1934, when a submarine eruption formed a small island, Showa-Iwojima, 2 km east of Satsuma-Iwojima.

Petrological study of this volcano indicates that magmas

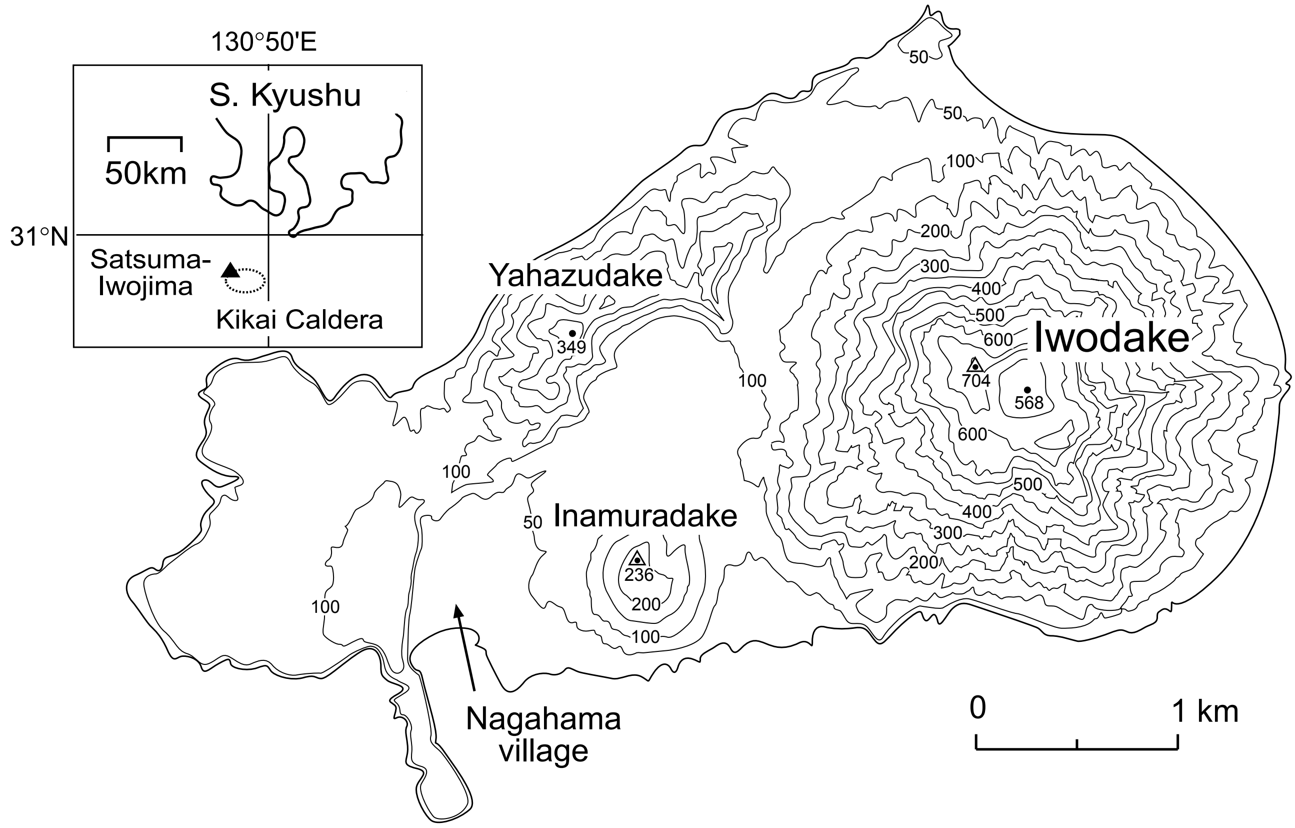

Fig. 1. Topographic map of Satsuma-Iwojima, with inset showing location.

associated with the Takeshima pyroclastic flow, Iwodake eruptions and Showa-Iwojima eruptions are essentially identical in bulk composition but have different phenocryst contents (Saito *et al.*, 2001). Therefore, these eruptions were likely derived from a single large magma body that is crystallizing over time. As the volatile composition of melt inclusions in the Showa-Iwojima rhyolite is similar to that of the volcanic gases presently emitted from the Iwodake summit crater, the volcanic gases are also likely supplied from the same magma chamber (Saito *et al.*, 2001). Degassing activity of Satsuma-Iwojima is characterized by continuous, long-term emission of a large amount of high-temperature volcanic gases (Shinohara *et al.*, 1993). These features require that the volcanic gases are supplied from a large magma body and are transported by convection of volatile-bearing magmas in a conduit (Kazahaya *et al.*, 2002).

3. Recent Changes in the Summit Crater Area

3.1 1960s to October 1990 (Fig. 2(a))

Most of the high-temperature fumaroles were located along the inner rim of the summit crater in October 1990, and the center floor of the crater was cool at the surface. The high-temperature fumarolic areas were highly altered by high-temperature gas to gray ash that can be distinguished from a distance. Distribution of the highly altered areas associated with high-temperature fumaroles at this time was similar to that of the 1960s (Kamada, 1964), although the most active fumarolic area shifted from Kamanokuchi in the early 1960s (Kamada, 1964) to Arayama in the 1970s (Matsubaya *et al.*, 1975). In 1990, gas emissions from both Kamanokuchi and Arayama were quite weak, whereas a new fumarolic area with temperature up to 877°C was found on the south-southwest margin of the crater floor. There were no high-temperature fumaroles present here in the 1960s (Shinohara *et al.*, 1993).

In 1961, the temperature at 25 cm depth was more than 90°C only along the crater rim, and the temperature was less than 50°C at the center of the crater floor (Yokoyama *et al.*, 1966). The temperatures measured at 100 cm depth in 1975 were all more than 98°C inside the crater (Geological Survey of Japan, 1976). In 1990, the surface of the crater floor was cool, however, the temperature at about 30 cm depth was 98°C, boiling point at this elevation. These measurements may indicate that the subsurface temperature increased from 1961 to 1990.

3.2 November 1994 (Fig. 2(b))

A crater with a diameter of 15 m and a depth of several meters was found at the southern end of the crater floor in November 1991, and a second crater of similar size was seen further to the northwest in October 1993. In November 1994, the second crater had enlarged and was actively emitting gas from the bottom, with altered sand being blown around at the crater bottom. In spite of the formation of the large craters, there had been relatively little material ejected. Many fumaroles were present in the middle of the crater floor in 1994. Creation of such new fumaroles may have caused evaporation of native sulfur deposits that had accumulated underground, resulting in collapse that led to crater

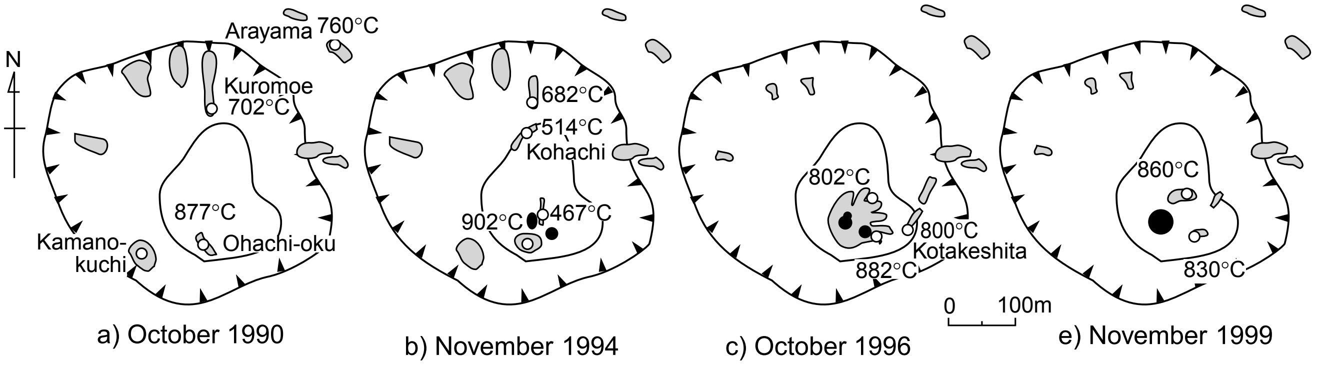

Fig. 2. Change in distribution of high-temperature fumarolic areas and temperature of some representative fumaroles of Iwodake summit area. a) October 1990, b) November 1994, c) October 1996 and d) November 1999. The hatched area shows a high-temperature fumarolic zone, and circles indicate points of temperature measurements. The outer boundary with teeth indicates the rim of the summit crater and the inner boundary shows the area of the crater floor. Black dots indicate degassing vents.

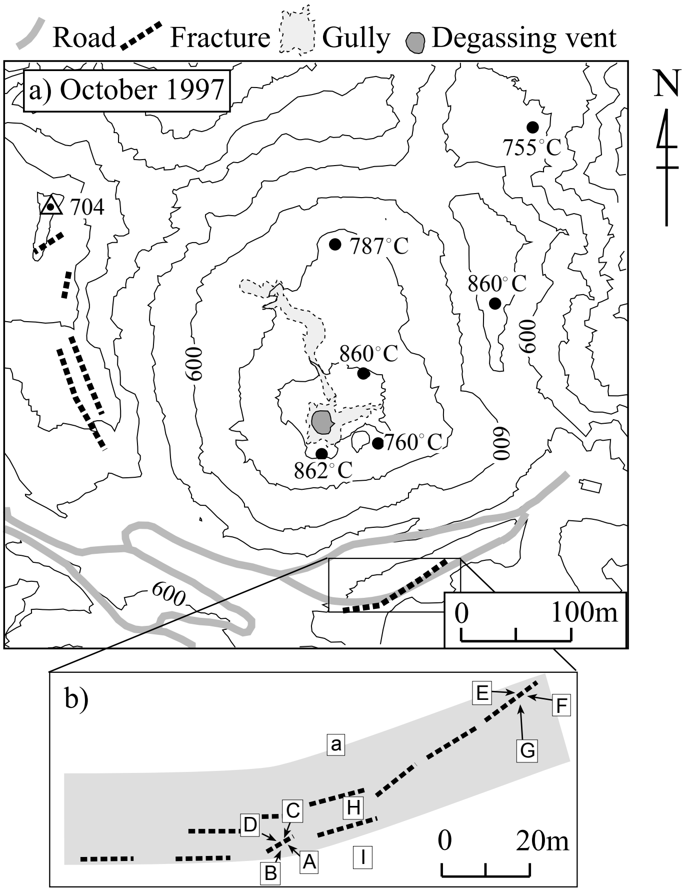

Fig. 3. a) Topographic map of Iwodake summit area, after Saito (1997), showing distribution of high-temperature fumaroles, the degassing vent and fractures in October 1997. Black dots show location of fumaroles whose temperatures were measured. The dashed lines denote fractures. b) Simplified distribution map of fractures and posts for measurements of deformation. The square with a letter shows the post, and the shaded area shows the mining road. Post "a" was installed by the Meteorological Agency of Japan.

formation. Alteration by high-temperature gases causes a volume decrease of silicates and this might also have partially contributed to the collapse.

3.3 October 1996 (Fig. 2(c))

A large area in the middle of the summit crater floor was highly altered and gray at this time. In contrast, the highly altered area along the inner rim of the crater were largely reduced in its area. Temperature in the newly altered area was >500°C at 5 cm depth, and many small high-temperature fumaroles were distributed across this altered area. Fumaroles with temperature greater than 800°C were found not only at the south end of the crater floor but also at several places around the highly altered area. A new small but steep vent several meters in diameter had opened at the northern end of the first crater, and gases were emitted from the vent with jet-like sounds. A red glow reflected on the volcanic plume could be seen over this new vent during the night, indicating emission of high-temperature volcanic gases. The gas emission rate from both of the old craters appeared to be less than that in 1994.

3.4 1997–1999 (Fig. 2(d))

In January 1997, the south side of the northern crater, which was covered by highly altered ground in October 1996, was relatively cool (~100°C at 20 cm depth). A steep vent, 20-m wide and 10-m deep, was found where the cone-shaped crater and attached small vent were located during the previous October. High-temperature gases were emitted with roaring sounds from the vent. A red glowing area was observed during daylight at the bottom of the vent in February. Several lithic blocks up to 1-m size, observed around the vent in October 1996, had been buried with sand and small blocks of altered volcanic rocks prior to January 1997.

By November 1997, the degassing vent had enlarged by a factor of about two, and the vent wall had a steep slope (Fig. 3). Glow could not be observed, but the roaring sound of escaping gas and a large plume suggest intensive gas emission from the bottom area of the vent. A deposit of altered sand and small blocks 30–40 cm thick covered the southern area of the degassing vent after April 1997. Deposits of altered material, 5-mm thick, were also observed in April 1997 on the northern side of posts which had been installed in February along the southern rim of the crater (Fig. 3(b)). The degassing vent gradually enlarged and finally reached a diameter of 40 m with a depth of 20 m by November 1999.

4. Volcanic Ash

The degassing vent formed and enlarged by ejecting altered material, although the early stage of vent formation may also have been caused by subsidence due to sulfur evaporation and acid leaching beneath the surface. About 1 m of ejected material was deposited just around the vent between October 1996 and January 1997, and 30–40 cm more accumulated between April and November 1997. Mining of silica rocks (altered volcanic rocks) continued until July 1997 along the southwestern margin of the summit area, and mining vehicles drove on the road along the southern rim of the crater every day. In spite of the daily traffic only 100 m south of the vent, there was no report by the workers of any eruptive phenomena, indicating that there was no explosive activity during this period. In September 1997, ash fall occurred at the village of Nagahama, 2.5 km southwest of the summit crater. The ash was very fine and the amount was so small as to be recognized only on smooth surfaces such as tree leaves. Similar ash falls at the village were observed several times in 1998 and in July 1998 reached the next island, Takeshima, 10 km east of the summit.

We observed discharge of fine ash from the vent in November 1998. During seven days of observation in the summit crater, ash discharge was observed on only two days. On one day, ash discharge occurred several times during a 5-hour period of work in the summit crater. Each ash discharge continued only five to ten minutes, and very fine ash was discharged in a white plume without any extraordinary sound except for the constant roaring sound of gas emission. Height of the ash-containing plume was about 100 m above the crater floor, similar as of the plume without ash. Between the ash discharge periods, volcanic gases were emitted continuously with the typical roaring sound. The white color of the plume during the ash discharge was due to steam condensation, implying a water-rich and/or cooler plume than that emitted between the ash discharge periods.

Several samples of ash were observed under a microscope and analyzed by X-ray diffraction. The analyzed samples include ash collected at the summit area in November 1997, July 1998, November 1998 and January 2000. Some of these samples were supplied by the Sakurajima Volcano Research Center of Kyoto University and the Meteorological Agency of Japan. All of the samples are fine powder of gray to pink ash and consist of similar components. Most of the constituents are white or transparent mineral fragments; some fragments of colored minerals and glasses are also present (Fig. 4). The glass fragments are transparent or brown, and although they contain a few crystallites and bubbles, the fragments are angular and do not indicate intense effervescence (Fig. 4). The X-ray diffraction patterns of the powdered samples show peaks indicating quartz, cristobalite and tridymite (Fig. 5). Peaks indicating pyroxene, plagioclase,

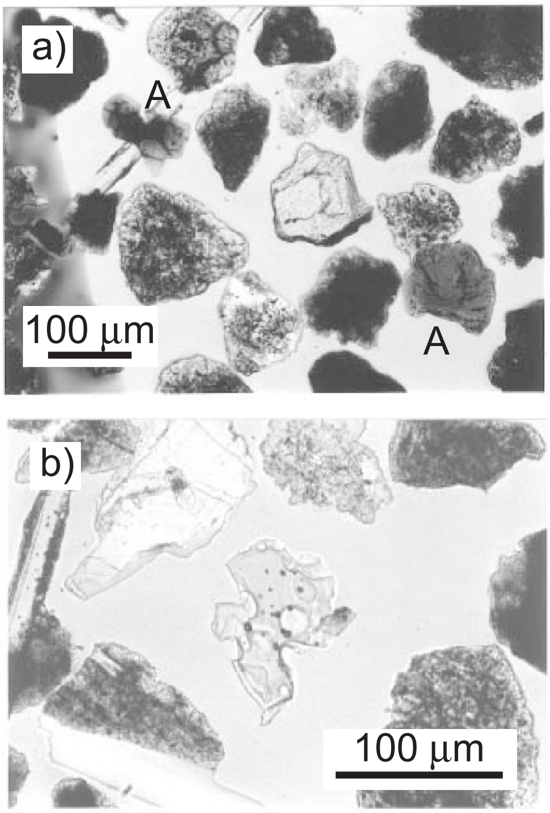

Fig. 4. Photomicrograph of ash collected at the summit area on 30 July 1998. a) Major constituents of the ash. The brown glass (A) is a hydrated glass of Iwodake rhyolite. Others are fragments of minerals and matrix of rhyolite. b) Fragment of vesiculated glass (center) in the ash, with chemical composition similar to that of the Iwodake rhyolite erupted 1,300 years ago.

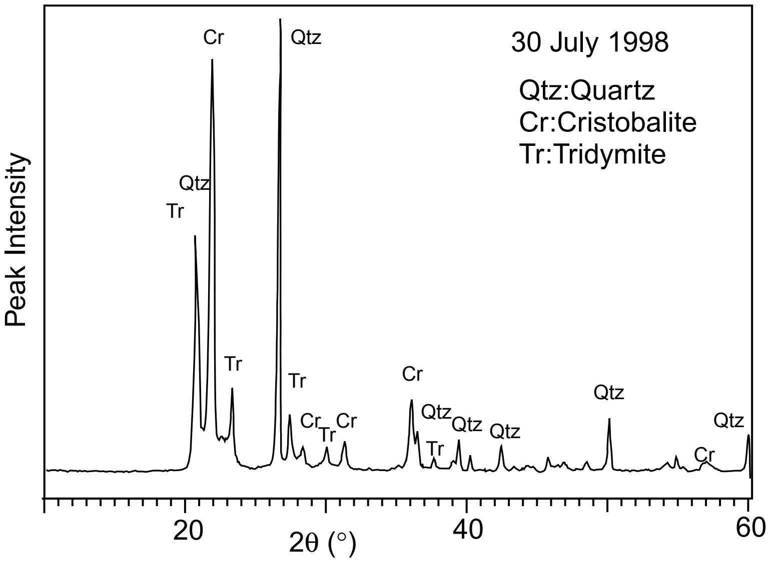

Fig. 5. X-ray diffraction pattern of ash collected at the summit area on 30 July 1998.

Table 1. Chemical composition of glass fragments in the ash and matrix glass of Satsuma-Iwojima volcanic rocks (wt.%).

No.	1	2	3	4	5	6	7
SiO_2	72.41	69.68	72.63	73.94	77.45	73.72	76.51
TiO_2	0.50	0.43	0.53	0.59	0.46	0.58	0.37
Al_2O_3	11.81	11.37	11.89	10.20	11.07	11.76	11.63
FeO	1.24	1.34	1.39	1.15	0.7	1.98	1.40
MnO	0.01	0.04	0.00	0.08	0.14	0.10	0.06
MgO	0.42	0.41	0.35	0.37	0.02	0.27	0.17
CaO	1.31	1.41	1.30	1.02	0.56	1.30	1.02
Na_2O	4.17	1.34	4.56	0.94	0.25	4.29	3.92
K_2O	2.96	2.57	2.86	2.41	3.34	3.14	3.19
Total	94.83	88.59	95.51	90.70	93.99	97.14	98.27
Normalized to 100 wt.%							
SiO_2	76.36	78.65	76.04	81.52	82.40	75.89	77.86
TiO_2	0.53	0.49	0.55	0.65	0.49	0.60	0.38
Al_2O_3	12.45	12.83	12.45	11.25	11.78	12.11	11.83
FeO	1.31	1.51	1.46	1.27	0.74	2.04	1.42
MnO	0.01	0.05	0.00	0.09	0.15	0.10	0.06
MgO	0.44	0.46	0.37	0.41	0.02	0.28	0.17
CaO	1.38	1.59	1.36	1.12	0.60	1.34	1.04
Na_2O	4.40	1.51	4.77	1.04	0.27	4.42	3.99
K_2O	3.12	2.90	2.99	2.66	3.55	3.23	3.25

1: Center part of brown glass with bubbles and microlites, 230 × 100 μm.
2: Near fracture of sample No. 1.
3: Center part of brown glass with bubbles and microlites, 200 μm.
4: Near fracture of sample No. 3.
5: Clear glass, 80 × 50 μm.
6: Matrix glass of Iwodake pumice.
7: Matrix glass adhering to a plagioclase phenocryst in Showa-Iwojima lava.
The analyses were made with a JEOL JXA-8800 Superprobe.

The analytical conditions were 15 keV accelerating voltage, 12 nA beam current, 6 sec counting time and defocused beam of 20 μm diameter to minimize Na loss during the analysis.

Table 2. Distance between the posts installed to measure ground deformation along fractures at southern rim of the Iwodake crater (Fig. 3).

		AC	BD	CD	aH	HI	EF	EG	FG
Initial measurement (mm)		2,630	2,726	2,075	10,652	8,000	2,898	2,884	2,442
Date	Difference in level (cm)	Change in the distance between posts after installation (mm)							
97.2.20	20*	=	=	=	−	−	−	−	−
97.4.17	26	0	0	0	=	=	=	=	=
97.11.1	30	15	18	−1	46	38	40	58	5
98.3.19	35	18	25	3	48	58	51	57	4
98.11.7	40	24	28	0	46	56	49	35	−1
99.11.21	40	18	21	1	14	25	35	0	−1

−: not measured, =: beginning of the measurement, * measured on 7 January 1997.

or sulfide minerals were not noted. Trace of a kaolinite peak was found for the ash collected in November 1997, but not in other samples. These constituents indicate that the ash consists of fragments of altered and leached volcanic rocks that may have been derived from fill of the summit crater floor of Iwodake.

The transparent glass fragments in the ash collected on 30 July 1998 were handpicked, mounted in resin, and polished. The samples were then analyzed for major element composition with an electron microprobe. The total for the nine major oxides range from 88 to 99 wt.%, indicating a variable water concentration (Table 1). Smaller totals were measured at the rim of the glass fragments. Backscatter images of the glass fragments also show stronger hydration on the surface and along fractures. The hydration depth is about 20 μm. The strongly hydrated part is poor in alkali and rich in Si, likely due to leaching by acid condensates. The chemical compositions of less hydrated parts of the glass are more similar to that of fresh Iwodake matrix glass than to that of more recent Showa-Iwojima matrix glass (Table 1). Therefore, the glasses are also derived from fill of the summit crater floor of Iwodake.

5. Fractures

Open fractures trending E to N60°E, with total length of 100 m, were discovered on the mining road along the southern rim of the summit crater in October 1996 (Fig. 3). The width of the widest fracture was about 30 cm. The northern side of the fractures was lower than the southern side, with a maximum difference of 20 cm on 7 January 1997, indicating relative depression of the central part of the summit area. These fractures were not recognized during the survey in March 1996, suggesting rapid opening. A felt earthquake of M2.9 occurred on 8 June 1996 at the summit of Iwodake and a major slip of the fault likely occurred with this earthquake (Iguchi *et al.*, 2002). Although quantitative measurements were not performed in October 1996, the fractures seem to have widened by January 1997. Fumarolic gases with temperature ~100°C discharged from some of the fractures.

Plastic posts were installed in February and April 1997 along the fractures to measure relative movements (Fig. 3(b)). The distances between the posts were measured with a tape, and the measuring error is likely to be several millimeters as seen in the variation in distance between the posts C and D, and F and G (Table 2). Although the posts were installed after the major fracture-opening period, movement of the ground across the fractures was clearly recorded (Table 2, Fig. 6). The fracture opening continued at least until October 1997 but then changed to closing after October 1998.

6. Volcanic Gases

6.1 Highest temperature of fumaroles and SO_2 flux

After 1990, the highest temperature of fumaroles was almost constant, between 850° and 900°C (Table 3, Fig. 7), in spite of the significant change in distribution of the high-temperature fumarolic areas. Similar temperatures were also measured in the mid-1970s, whereas lower temperatures were measured in the 1960s (Fig. 7). Although the temperature may have increased from the 1960s to mid-1970s, the increase could also be apparent, due to an incomplete survey of the area in the 1960s, because most of the highly altered area was located on the upper part of the crater wall and would have been difficult to approach. Looking closer, we can also recognize a trend of decreasing fumarolic temperature with time after the maximum value in 1994.

The temperature of the rhyolitic magma of Showa-Iwojima, erupted most recently, was estimated to be 950–1000°C, using the two-pyroxene geothermometer (Saito *et al.*, 1997). Saito *et al.* (2001) concluded that the present volcanic gases are likely to be supplied from a magma with composition similar to that of Showa-Iwojima. Agreement of the magmatic temperature and highest fumarolic temperature might indicate magma degassing near the surface, possibly also explaining the constant maximum temperature.

Flux of SO_2 was measured repeatedly by COSPEC (Fig. 7). The measurements were done with the tripod method by Kazahaya *et al.* (2002). Rather large variation was observed during each measurement period of a day or two. In spite of the large variation, the average fluxes were similar between 1994 and 1997. The variation in the average SO_2 flux roughly parallels the variation of the highest fumarolic temperature, which decreased slightly from 1975 to 1990, increased to 1994, then decreased afterward (Fig. 7).

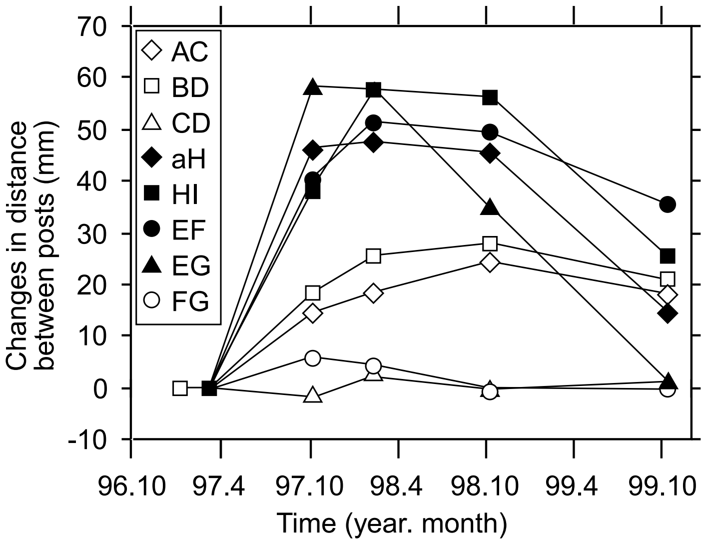

Fig. 6. Variation of distance between the posts used for measuring relative movement of the ground across the fractures. Locations of the posts are shown in Fig. 3.

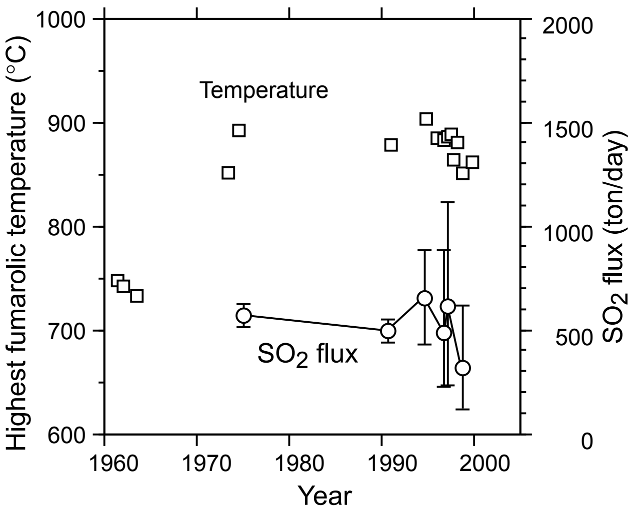

Fig. 7. Variation of the highest fumarolic temperature and SO_2 flux. Temperatures values are shown by squares, and SO_2 fluxes by circles, with bars showing their maximum and minimum values during the monitoring period. Temperature data for 1961, 1962 and 1963 are from Kamada (1964), and those for 1973 and 1974 are from Kanzaki *et al.* (1979). Flux data of SO_2 for 1975 are from Ohkita *et al.* (1977).

6.2 Composition of high-temperature fumarolic gases

A number of fumaroles with temperatures from 100° to 900°C are located in the summit crater area. The chemical compositions of these fumarolic gases also range widely, but most of these gases are likely derived from a single parent gas, whose composition is similar to that of the fumarolic gas with highest temperature (Shinohara *et al.*, 1993). Repeat samples of high-temperature fumarolic gases were collected and analyzed to evaluate changes in the parent gas, whose composition might indicate changes in the condition of magma degassing. Sampling and analytical methods of fumarolic gases are essentially the same as those reported in Giggenbach and Goguel (1989). Correction for CO decrease with time during sample storage was also made according to Giggenbach and Matsuo (1991), except for the results reported by Shinohara *et al.* (1993). Because of the lack of correction for the CO decrease, CO values reported by Shinohara *et al.* (1993) are less than half of those analyzed later (Table 3, No. 22 and 23).

In some cases, sampling was not performed at the highest temperature fumarole because of its inaccessibility (Fig. 8). Chemical and isotopic compositions of the high-temperature fumarolic gases appear to be constant during this nine-year period (Table 3). Although there is a range in N_2 and Ar content, the variation is most likely due to variable air contamination. Isotopic compositions of hydrogen and oxygen of water and carbon of CO_2 are also almost constant at 28 ± 3‰, 6.5 ± 0.5‰ and -4.4 ± 0.6‰, respectively. As elemental and isotopic compositions are almost constant, there was probably little change in the condition of gas exsolution from the magma.

The composition of the volcanic gases is controlled not only by magma degassing but also by the conditions that the gases experienced during ascent to the surface. Assuming that a chemical reaction was in equilibrium at a certain temperature and was later quenched, we can calculate the temperature of that condition from the chemical composition of the gases and equilibrium constants. This calculated temperature is called an apparent equilibrium temperature (AET; Matsuo, 1962; Ohba *et al.*, 1994). Apparent equilibrium temperatures of the following reactions are calculated with equations given by Ohba *et al.* (1994; Table 3, Fig. 8);

$$\mathrm{AET_S} : SO_2 + 3H_2 = H_2S + 2H_2O, \qquad (1)$$

and

$$\mathrm{AET_C} : CO + H_2O = CO_2 + H_2. \qquad (2)$$

The calculated $\mathrm{AET_S}$ and $\mathrm{AET_C}$ result in values similar to the temperature of fumaroles in most samples, except for

Table 3. Composition of highest temperature fumarolic gases at Ohachi-oku, Iwodake cone, Satsuma-Iwojima volcano.

No.	Date	Temp. (°C)	H_2O μmol/mol	CO_2	$SO_2^{\#}$	$H_2S^{\#}$	HCl	H_2	N_2	Ar	$CO^{\$}$	δD (‰)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	$AET_S^{\&}$ (°C)	$AET_C^{\&}$ (°C)
1	99.11.21	853	974 981	3 818	8 048	718	6 853	4 468	65	0.8	18	−29	6.3		840	824
2	99.11.21	853	976 207	3 679	8 504	585	5 963	4 133	64	1.0	17				841	844
3	98.11.7	840	973 024	3 808	8 756	971	6 783	5 593	92	1.0	23	−28	6.1		863	843
4	98.11.7	840	974 493	3 972	8 634	1 139	5 025	5 853	96	1.2	26				861	849
5	98.3.18	860	974 149	3 992	9 661	520	6 289	4 638	83	0.9	21	−31	6.0	−4.9	870	850
6	98.3.18	860	974 432	3 995	9 587	576	6 047	4 636	76	1.1	20			−4.7	865	842
7	97.11.2	848	975 649	3 698	8 950	482	6 593	4 549	56	0.6	21	−28	6.4	−4.1	867	892
8	97.11.2	848	976 815	3 660	8 839	572	5 544	4 493	55	0.5	22			−4.2	857	905
9	97.11.2	848	974 634	3 706	8 884	489	7 008	4 529	61	0.7	20			−4.0	866	865
10	97.11.2	848	975 657	3 961	8 933	493	5 733	5 131	67	0.5	24			−3.7	883	861
11	97.11.2	848	975 085	3 747	8 697	519	7 156	4 681	93	1.2	20			−3.9	866	860
12	97.4.18	886	972 176	3 803	10 672	479	7 429	5 310	104	1.0	26	−26	6.4	−4.5	899	900
13	97.2.20	884	974 842	3 837	9 994	337	6 150	4 729	90	1.3	19				896	834
14	97.2.20	884	974 686	3 870	9 671	467	6 240	4 924	107	1.5	27				884	923
15	97.1.6	880	976 714	3 356	8 392	442	6 729	4 233	109	1.3	24	−29	6.4	−4.4	858	992
16	97.1.6	868	975 972	3 714	9 023	564	6 279	4 313	111	1.3	24			−4.5	853	951
17	96.10.15	882	975 652	3 977	10 088	536	4 600	5 026	96	1.0	23	−28	6.2	−4.3	882	857
18	96.10.15	882	974 796	4 018	10 124	421	5 552	4 993	72	0.7	22			−4.7	894	850
19	96.3.10	882	972 574	3 439	11 741	281	6 585	5 224	121	2.2	34	−28	6.1		929	1047
20	94.10.29	881	974 400	3 879	9 993	272	5 839	5 488	98	1.1	27	−28	8.4	−4.3	930	896
21	94.10.29	881	974 129	3 804	9 853	341	6 410	5 327	107	1.1	27			−4.6	913	905
22[+]	90.10.27	877	974 798	3 758	9 181	656	6 767	4 740	82	0.7	11	−23	6.6	−5.0	860	(696)
23[+]	90.10.27	877	975 130	4 117	9 318	1035	5 185	5 101	90	0.9	12	−26	7.1	−5.0	849	(679)

[#] Calculated from total sulfur content and average oxidation states of sulfur species (Giggenbach and Goguel, 1989).

[$] Corrected for CO decrease during sample storage according to Giggenbach and Matsuo (1991), except for samples 22 and 23.

[&] Apparent equilibrium temperatures calculated with equations given by Ohba *et al.* (1994).

[+] From Shinohara *et al.* (1993). Since a mistake in calibration for the CO_2 analyses was found by the author after publication, the results were recalculated considering the new calibration, which causes a 20% increase in CO_2 contents.

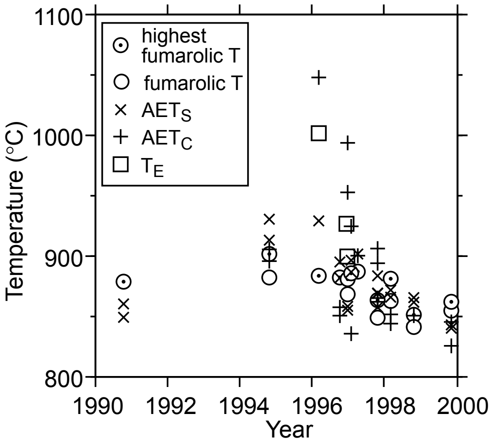

Fig. 8. Variation of fumarolic temperature and the apparent equilibrium temperatures. The circles indicate temperature of the sampled fumaroles and the circles with a dot indicate the highest fumarolic temperature that was measured in the same period. The + and × show the apparent equilibrium temperature for reactions (1) and (2), respectively (see text). Squares indicate the calculated equilibrium temperature (T_E) with an assumption of partial advance of reaction (1), as discussed in the text.

sample No. 15, 16 and 19. The agreement of the two AET values and fumarolic temperature at Satsuma-Iwojima is better than at many other volcanoes (Ohba, 1997), indicating that the high-temperature gases of Satsuma-Iwojima were in equilibrium for these reactions close to the conditions of the fumarole outlets.

In samples No. 15, 16 and 19, AET_C is more than 100°C higher than AET_S. Similar disagreements in the two AET values were observed by Ohba *et al.* (1994) in the volcanic gases of Unzen volcano, Japan. They examined the following two mechanisms as the cause of the disagreement: a) advance in reaction (1) with temperature decrease without advance in reaction (2), and b) addition of external water to volcanic gases. As the fumarolic temperature of samples No. 15, 16 and 19 are as high as that of other samples, addition of external water to these samples is not likely to have occurred. These three samples have isotopic compositions of water similar to the other samples, further indicating that the addition of such external water is unlikely. Assuming that the disequilibrium was caused by advance in reaction (1) without advance in reaction (2), the last temperature at which both reactions were in equilibrium can be determined by back calculating reaction (1), as formulated by Ohba *et al.* (1994). The calculated temperature (T_E) is 928°, 898° and 999°C for sample No. 15, 16 and 19, respectively (Fig. 8).

The fumarolic temperatures appear to have peaked between 1994 and 1997. The calculated temperatures (AET_S, AET_C and T_E) vary in an almost parallel fashion with the fumarolic temperature, but with larger variation. The rather high values of AET_C and T_E for sample No. 19 is the result of a high CO concentration that may partly be due to analytical error. The high AET_S (929°C) of the same sample, however, is not affected by the high CO concentration, and is also consistent with variation of other temperature data with time.

7. Discussion

7.1 Discharge of volcanic ash

A large amount of high-temperature volcanic gas discharged continuously from the vent even during the vent formation and ash discharge. Direct observation of the small-scale ash discharges in November 1998 revealed that the gas emission was continuous even just before the ash discharge, implying plugging of the vent and accumulation of gas pressure did not occur before the ash discharge. The ejection of the altered ash was probably caused by partial collapse at depth of the degassing vent and ejection of material with a strong flow of high-temperature volcanic gases. The water-rich and/or cool plume associated with the ash discharge is likely due to mixing with wet and/or cool deposits from the vent wall. Although mining at the summit area was underway during these eruptions until July 1997, there was no report of eruptive phenomena by the mining workers. This suggests that small-scale ash discharges repeatedly occurred during the vent formation period in early 1997, rather than a single large burst formed the vent.

A similar ash discharge and vent formation was observed at Kudriavy volcano, Kurile islands in October 1999 (Korzhinsky *et al.*, 2002). This phenomenon is quite similar to that at Satsuma-Iwojima: fresh magma was not found in the ash and a new vent was formed near a high-temperature fumarolic area with intense degassing activity. In contrast, a vent of 40 m diameter and 20 m depth formed by a single event within several hours at Kudriavy volcano, whereas a similar size vent formed during a few years at Satsuma-Iwojima. Because of the rapid ash discharge and possible involvement of meteoric water at Kudriavy volcano, Korzhinsky *et al.* (2002) classified this phenomenon as a phreatic eruption. Similar phreatic eruptions could also have occurred at Satsuma-Iwojima. However, frequent and small-scale ash discharges at Satsuma-Iwojima were observed along continuous emission of high-temperature gases and are not considered to be a typical phreatic eruption.

7.2 Model for activity during 1990–1999

The new degassing vent formed contemporaneously with the fracture formation, increase in SO_2 emission rate and the temperature increase of fumaroles. These changes most likely were caused by a single process in the system supplying the magmatic gas. Convection in a magma column was proposed as the mechanism responsible for rapid and continuous volcanic gas supply from a deep magma chamber (Kazahaya *et al.*, 1994). A similar mechanism is required to result in the intense and continuous gas emission observed from Iwodake cone (Kazahaya *et al.*, 2002). Based on melt inclusion analyses, Saito *et al.* (2001) suggested that the presently discharging volcanic gases are derived from magma with composition similar to that of Showa-Iwojima rhyolite. The similar H_2O/CO_2 ratio of the volcanic gas to that of melt inclusions in the Showa-Iwojima rhyolite require separation of the gases from the magma at low pressure. All the phenomena observed in the 1990s likely took place during continuous degassing of the convecting magma column.

Before 1990, high-temperature fumaroles were located mainly on the inner slope of the summit crater, not at the bottom of the crater. The near-surface temperature was also

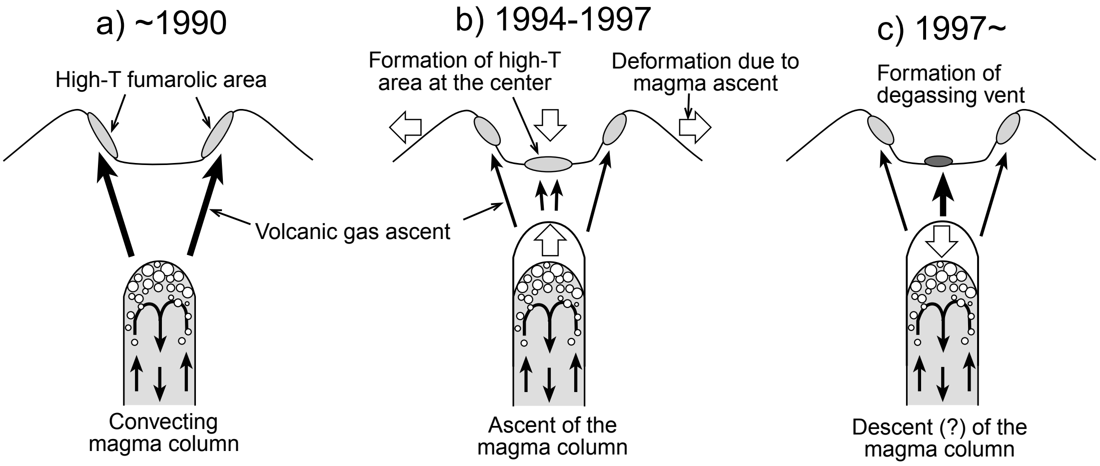

Fig. 9. Activity model of Iwodake during 1990 to 1999. a) Volcanic gases are supplied from a convecting magma column through concentric fractures, forming major high-temperature fumarolic areas on the inner slopes of the summit crater. b) Increase in magma convection rate caused an increase in volcanic gas flux and ascent of the magma column, resulting in deformation of the summit area. The increase in gas flux from the top of the magma column created new gas passages, forming a high-temperature fumarolic area in the center of the crater. c) Ash discharges occurred during formation of the gas passages. Establishment of a focussed gas passage at the degassing vent reduced the area of surrounding high-temperature fumaroles. The magma column may have descended after vent formation, as indicated by the decrease in fumarolic temperature and gas flux, and the closing of summit fractures.

low at the center of the crater floor in 1961 (Yokoyama *et al.*, 1966). At this stage, volcanic gases were probably supplied from the convecting magma to the crater rim through concentric fractures (Fig. 9(a)).

The elemental composition of volcanic gases changed little with time, so the composition of the magma likely was constant during these periods. The gas flux increased in the mid-1990s, likely caused by an increase in magma convection rate. The increased gas flux heated the crater floor creating the new high-temperature fumarolic area at the crater bottom. The intense gas emission from the crater floor subsequently caused ejection of crater-filled material, forming degassing vents. This accelerated centralization of the gas emission to the vent, further enlarging the degassing vent (Fig. 9(b)).

Open fractures with depression on the crater side formed on the southern rim of the summit crater during 1996–1997. The M2.9 earthquake that occurred on 8 June 1996 at the summit was a normal fault-type, leading Iguchi *et al.* (2002) to suggest that a pressure decrease beneath the crater caused the earthquake and ground deformation (fractures). Such depression beneath the crater, however, will not result in open fractures but normal faults. In contrast, pressure increase beneath the crater can cause the ground deformation, with extension in the overlying area and relative depression at the center (Fig. 9(b)). The normal-fault type slip can occur as the result of depression at the center. The convecting magma column likely ascends as the result of an increase in the convection rate, and this ascent of the magma column can act as the pressure source beneath the crater.

The fumarolic and equilibrium temperatures started to decrease in 1997, and SO_2 flux decreased in 1998. Centralization of gas flow to the degassing vent decreased the gas and heat flux to the surrounding fumarolic area, resulting in the decrease in temperature at fumaroles prior to the decrease in the gas flux (Fig. 9(c)). The fractures started to close in 1998 (Fig. 6). Decrease in the gas flux implies decrease in the magma convection rate, possibly leading to descent of the magma, resulting in a closure of the fractures that is coincident with the gas flux decrease.

Although variation of the magma column depth is considered above, the depth to the top of the magma column has not been determined quantitatively. Ohminato and Ereditato (1997) estimated a shallow source of low-frequency earthquakes only 40 m below the degassing vent and suggested that they occurred in relation to the degassing process, such as sudden discharge of volcanic gas or rapid bubble growth in the magma. A source of B-type earthquakes is also estimated to be very shallow, likely above sea level beneath the summit crater (Iguchi *et al.*, 2002). The B-type earthquakes are initiated by volume expansion of the source, likely caused by bubble expansion in magma within the conduit (Iguchi *et al.*, 1999). Further investigations of earthquakes, ground deformation and other geophysical observations may provide further quantitative estimates of the magmatic processes beneath the degassing volcano.

7.3 Long-term activity

The degassing activity of Iwodake has likely continued more than 1,000 years. Silica rock fragments are present in deposits from eruptions that occurred between 1,000 and 500 years ago (Kawanabe and Saito, 2002), indicating that the acid leaching started to form long ago as the result of intense degassing activity. Deposits of silicic-altered lithic ash occur on the slope of the summit cone overlying pyroclastic flows of the last magmatic eruption 500 years ago (Kawanabe and Saito, 2002). The amount of recent ash discharge is so small that such deposits will not remain for a long time. Thus, the old ash layer suggests that the ash discharges were once more frequent or voluminous than those of the 1990s. More frequent past eruptions are also suggested by the tales of old residents, who mentioned common small-scale eruptions in the summit crater (Kamada, 1964).

Therefore, the present activity with the ash discharges may be common for Satsuma-Iwojima volcano.

Quantitative volcanological observation started in the 1960s (Kamada, 1964; Yokoyama *et al.*, 1966), and intensive emission of high-temperature gases was observed. The highest temperature of summit fumaroles, and SO_2 flux, has remained relatively constant since the mid-1970s (Fig. 7). Except for the vent formation and ash discharges in the mid-1990s, the fumarolic activity at the summit area has been the major volcanic activity of this volcano, and the activity apparently has been relatively constant for at least 40 years. As magma convection in a volcanic conduit is necessary for the passive degassing of a large amount of high-temperature volcanic gases (Kazahaya *et al.*, 1994), magma convection may have been continuous for long periods at this volcano. Thus, a fluctuation in the convection rate may have caused the changes at the summit area in the 1990s and the frequent small eruptions recorded by the tales of old residents.

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