Earth Planets Space, **54**, 337–347, 2002

Decade-long study of degassing at Kudriavy volcano, Iturup, Kurile Islands (1990–1999): Gas temperature and composition variations, and occurrence of 1999 phreatic eruption

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(Received May 29, 2000; Revised September 11, 2001; Accepted September 20, 2001)

A high-temperature (up to 940°C) fumarolic activity at Kudriavy volcano had been studied during 1990–1999. The maximum gas temperatures of the fumaroles were measured in 1992 as 940°C, then gradually decreased with time and reached to 907°C in 1999. Gas composition of the high-temperature fumarole became enriched in H_2O and depleted in other gas components, in particular in CO_2. Hydrogen isotopic compositions of the high-temperature fumarolic gases were gradually depleted in deuterium. The gradual and continuous decrease in temperature and changes in gas composition observed during the last 10-year suggest that a magmatic melt have been degassing in a relatively steady-state manner from a single magma chamber. The detail investigations in 1998 and 1999 revealed short-term changes in gas composition characterized by sporadic increases in H_2, CO_2, and S_{total} after intense precipitations. Small-scale eruptions occurred on October 7, 1999 at the summit. The ratios of major gas components (C/S, C/Cl, S/Cl, C/F, S/F, and Cl/F) significantly increased just prior to the eruption. The eruption at the Kudriavy volcano in 1999 was likely a phreatic eruption as a result of the intense precipitations after unusually long dry period. Meteoric water penetrated into the hot zone of volcano edifice and rapidly boiled causing the eruption.

1. Introduction

A few volcanoes demonstrate vigorous high-temperature fumarolic activity during a long-term periods of non-eruptive reposes. Satsuma-Iwojima (Japan) and Kudriavy (Russia) volcanoes located along the Pacific volcano ring are the most pronounced examples of such degassing volcanoes. The last magmatic eruption with basaltic andesite lava flows occurred at the Kudriavy volcano in 1883 (Gorshkov, 1970). Nevertheless, even 116 years after the eruption, the temperatures of fumarolic gases exceed 900°C. High-temperature gas emissions (up to 900°C) continued at the Satsuma-Iwojima despite the fact that the most recent eruption occurred about 500–600 years ago (Shinohara *et al.*, 2002). High-temperature fumarolic activity at both volcanoes are likely to be quite stable since eruptions ceased. Some changes in the degassing activity during the last decade are reported for the Satsuma-Iwojima volcano, including changes in gas flux, temperature, fumarolic gas composition, distribution of fumaroles and ground deformations (Shinohara *et al.*, 2002). Fumarolic activity at Kudriavy volcano was relatively stable during the last decade although some changes in gas composition and temperature were recently observed. Formation of new craters (30–40 m in diameter) accompanied by ejection of friable crater deposits lacking fresh magmatic materials occurred recently at both volcanoes. Despite the fact that these volcanoes differ in size, magma composition, emission rate, and composition of the fumarolic gases, their activities have several common features. Comparison of the similar volcanic processes at Kudriavy and Satsuma-Iwojima may be useful for understanding the causes of the long-term degassing activity.

2. General Setting

Kudriavy is a basaltic andesite volcano located in the Medvezhya caldera in the north part of Iturup Island. The volcano is a part of a post-caldera eruptive complex oriented along an E-W trending line and consisting of Medvezhy, Sredny, Kudriavy, and Men'shoi Brat volcanoes (Fig. 1). Maximum altitude of the Kudriavy is 991 m above sea level. The summit is about 500–600 m in length with the width of 200–250 m. Rhyolite and dacite are found at the base of the volcanoes and at the caldera floor. Flanks of the volcanoes are composed of numerous basalt and andesite lava flows (Ermakov and Steinberg, 1999). Top of the Kudriavy volcano consists of two cones; the eastern one immediately adjacent to the Sredny volcano and the western one steeply sloped to the Men'shoi Brat volcano (Fig. 2). Eastern part of the volcano is a flat crater with an altered andesitic dome of 20 m height in the center (Ermakov and Steinberg, 1999). The central crater of 80 m in diameter is adjacent to the eastern dome slope and filled with friable deposits. The friable crater materials consist of an altered basaltic andesite rocks formed by interaction with the fumarolic gases and acid rains. The last magmatic eruption with basaltic an-

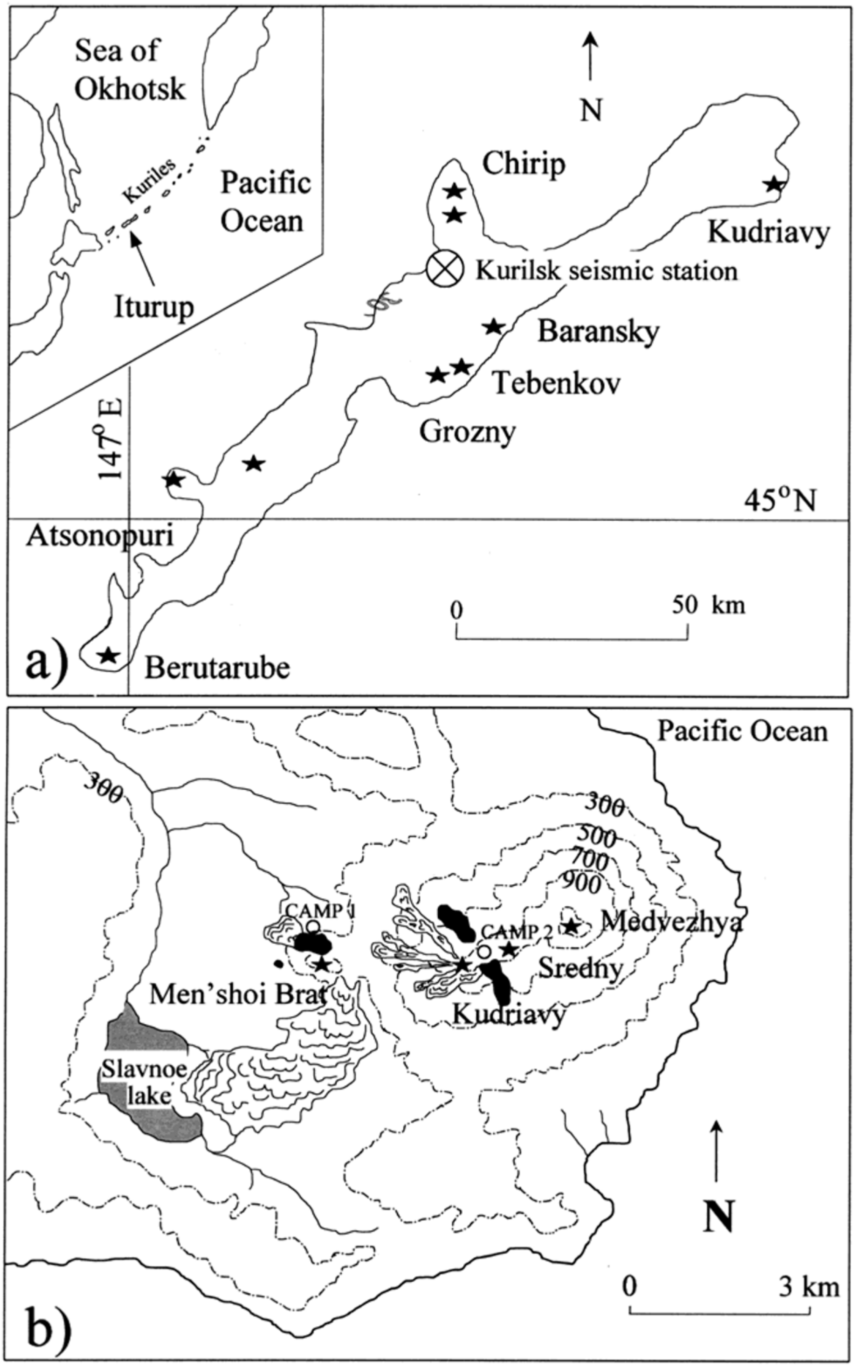

Fig. 1. Location map of Kudriavy volcano (a) and topographic map of Medvezhya caldera (b). Stars in (a) indicate the active volcanoes on the Iturup Island. The crossed circle shows the location of Kurilsk seismic station 80 km southwest from the Kudriavy volcano. Stars in (b) indicate the volcanoes of Medvezhya caldera. Open circles are camp sites. Solid black areas denote the rhyolite and dacite domes near the Kudriavy and Men'shoi Brat volcanoes. The area hatched with short curved lines are the last andesitic and basaltic lava flows from Kudriavy and Men'shoi Brat. Hatched area is Slavnoe lake. Dash-dot lines are contours with 200 m intervals.

desite lava flows at the Kudriavy volcano occurred in 1883 (Gorshkov, 1970). The additional eruptive activity in 1946 was reported by Simkin and Siebert (1994), but it could be either erroneous or weak phreatic eruptions because the ruins of Japanese mining in the crater are not affected by the eruption. A small pit with the depth about 3–5 m was observed in the southeastern part of the central crater floor near the dome in 1987 (A. Korablev, personal communication). The temperature of gases escaping from the pit was about 800°C whereas its depth diminished to 1–1.5 m in 1992–1993. This small pit was completely filled by the friable crater deposits and fumarole temperatures decreased down to slightly above 100°C in 1994. Phreatic eruptions occurred at the same place on October 7, 1999 as will be described below in detail.

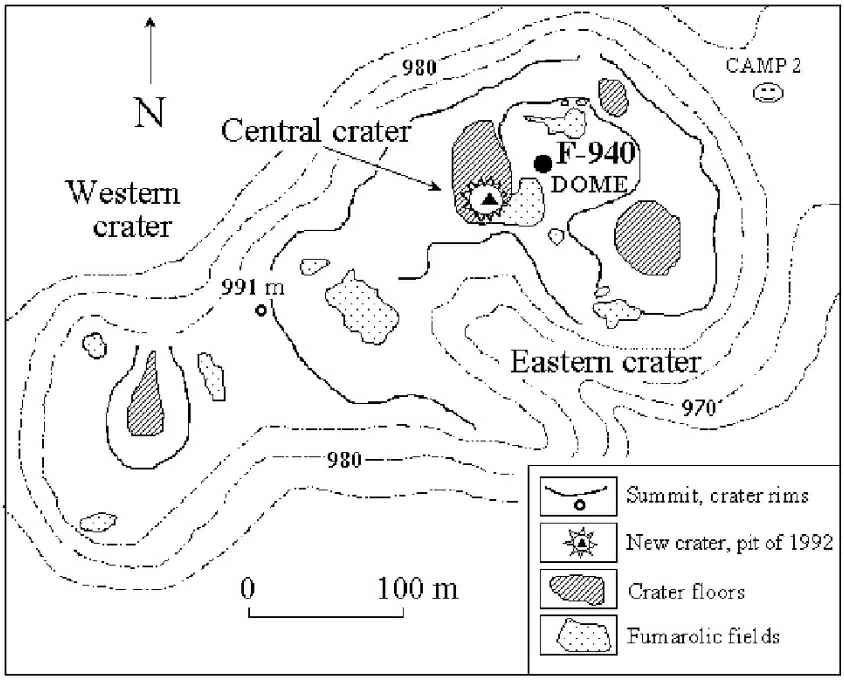

Fig. 2. Topographic map of the Kudriavy summit with elevation contours in meters. Black circle is the F-940 fumarole located on the top of the dome. Triangle is a small pit observed in 1992–1993 (see legend).

3. Measurement Technique and Equipment

Chromel-alumel thermocouples, sheathed by stainless-steel capillary of 6 mm outer and 3 mm inner diameters, were used to measure temperature of the volcanic gases. Precision of the temperature measurements was ±5°C before 1994 and ±1°C after 1995. One sample of the high-temperature fumarolic gas was collected during each field trip from 1990 to 1992 while 3 and 5 samples were collected from the highest-temperature fumarole (F-940) during one month in 1998 and 1999, respectively. The samples were collected using quartz tube and Giggenbach flasks filled with 4N KOH solution. The gases collected in 1990–1991 were analyzed according to the method described by Giggenbach (1975). After 1992, the samples were analyzed using method of Giggenbach and Goguel (1989). All samples were analyzed in the Institute of Volcanic Geology and Geochemistry RAS (Petropavlovsk-Kamchatsky). Gas condensates were collected and analyzed for hydrogen isotope composition as described by Taran *et al.* (1995) and Goff and McMurtry (2000).

Seismicity was measured at the summit of the Kudriavy volcano in 1999 by a seismic detector which was placed at one of the lava flows close to Camp 2 (Fig. 2). It recorded only the amplitude of vertical component of seismic oscillations. At appearance of ten signals above the noise, the data logger automatically started registration of the signals with the frequency of 0.2 s. Meteoric precipitations were measured in September–October 1998 and 1999 at the summit crater of Kudriavy volcano by meteorological vessel each 12 hours.

4. Overall Characteristics of Fumarolic Activity

Although the Japanese sulfur mining had existed in the summit crater of the Kudriavy volcano before 1945, we could not find any records of fumarolic activity in that period in literatures. The first detail geological and petrological studies as well as mapping of active fumarolic fields in the crater were conducted in 1948 (Vlasov and Petrachenko, 1971). The authors depicted low- and high-temperature fumarole areas at the Kudriavy summit, although quantitative data on the temperatures were not reported. V. Ostapenko (personal communication) also observed discharge of high-temperature (>500°C) fumarolic gases in 1961. The annual investigations of Kudriavy volcano were initiated in 1989. At present, there are eight fumarolic fields in the Kudriavy craters with the total surface area about 2,600 m^2. Most of them are located on the inner slopes of the eastern crater (Fig. 2). Fumarole temperatures increase from the southwest (~100°C) to the northeast (~900°C) along the summit. The highest-temperature fumarole (F-940) is located near the top of the dome. Sulfur deposits with the thickness of up to 1.5 m were observed at the fumarole fields. The distribution of fumarolic fields was almost identical during 1990–1999, but some changes in the gas temperature and discharge rate were observed for several fumaroles. Only small changes in their location can be recognized by comparison with the fumaroles mapped in 1948 (Vlasov and Petrachenko, 1971).

Temperatures of the high-temperature fumarole (F-940) varied only ±10–20°C during 1990–1999. Meteoric precipitations affected mostly the temperature of low-temperature fumaroles. Fumaroles with high temperature and discharge rate showed little dependence from the meteoric precipitations. For example, the temperature of the F-940 fumarole, with gas flow rate of 80 m/s (Botcharnikov *et al.*, 1998a), did not changed even after intense rains with precipitations of 70 mm in 1999. In contrast, gas temperature of a fumarole

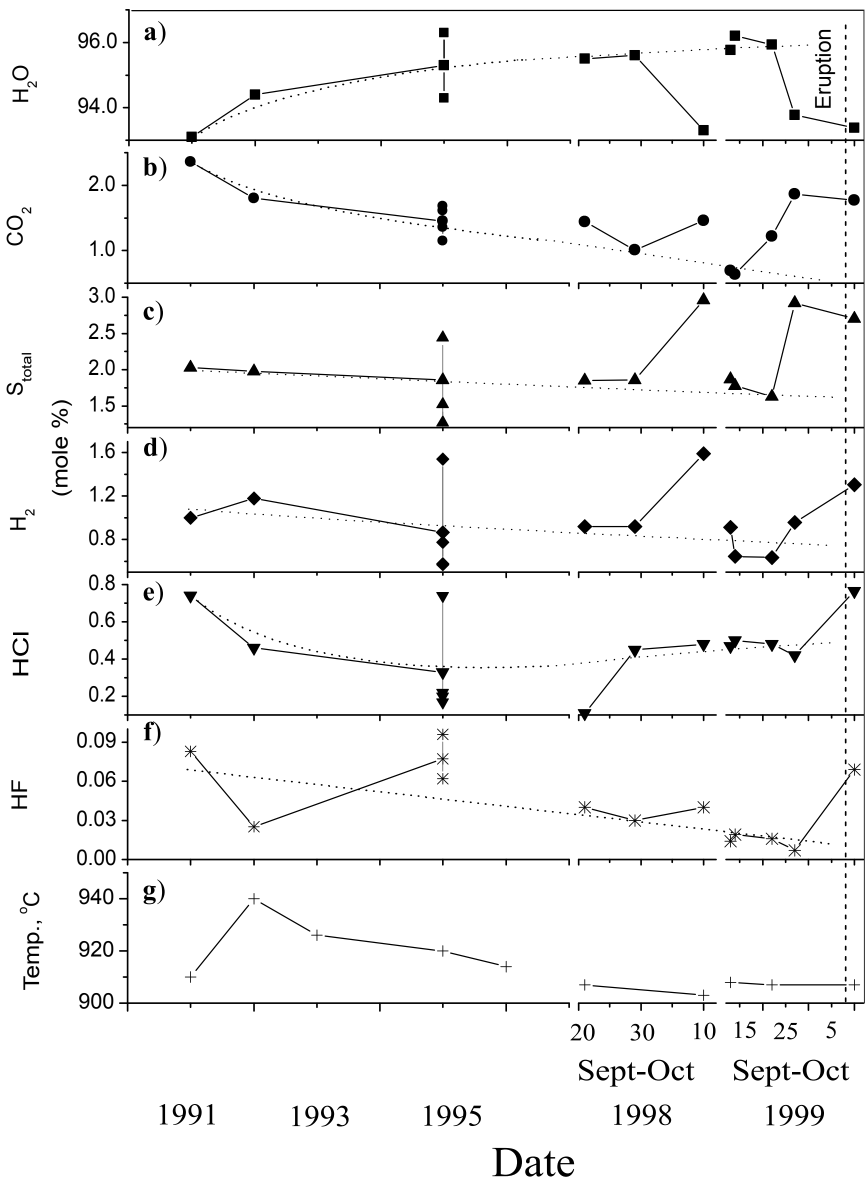

Fig. 3. Long-term changes in gas composition in mole % (a)–(f) and temperature in °C (g) of high-temperature F-940 fumarole during 1991–1999. Vertical dashed line corresponds to the date of the eruption and the dotted lines indicate the long-term trend.

with gas flow rate about 1 m/s decreased from 760° to 725°C after precipitations of 50 mm and asymptotically recovered to the former value in 2.5 days in 1998. Temperature of the fumarole with the gas flow rate of 5–10 m/s decreased from 153° to 86°C after an intense rain of 65 mm and remained at the same level for 7 days in 1996.

Chemical composition of major components of high-temperature fumarolic gases are typical of an arc volcanism (Giggenbach, 1992b) and varies in the following range (mol %): H_2O: 94–96; SO_2: 1–2.3; H_2S: 0.4–0.7; CO_2: 1.8–2.7; H_2: 0.5–1.3; HCl: 0.4–0.7; HF: 0.03–0.1 (Taran *et al.*, 1995; Wahrenberger, 1997; Fischer *et al.*, 1998). The Kudriavy parent gas composition is characterized by higher concentrations of CO_2 and S_{total}, and lower content of H_2O and HCl than that of the parent gas of Satsuma-Iwojima (Shinohara *et al.*, 1993; Fischer *et al.*, 1998). The SO_2 flux of 73±15 t/d from the Kudriavy was measured by COSPEC using the ground-based stationary technique in 1995 (Fischer *et al.*, 1998). The average value of SO_2 flux from the Satsuma-Iwojima is around 500 t/d (Shinohara *et al.*, 2002) that is 7 times larger than the Kudriavy SO_2 flux. Hydrogen isotopic composition of fumarolic gases correlates with their temperatures (Taran *et al.*, 1995; Goff and McMurtry, 2000). This implies that the involvement of meteoric water in the fumarolic system of Kudriavy volcano is the main process of magmatic gas cooling.

5. Temperature and Gas Composition of F-940 Fumarole

Fumaroles with high gas discharge rate and temperature are least affected by meteoric water. Therefore, monitoring of such fumaroles should give the information on changes in a magma degassing conditions. One of the most high-temperature fumaroles (F-940), easily accessible for direct observations and sampling, is located on the western slope of the andesite dome in the central crater (Fig. 2). It is char-

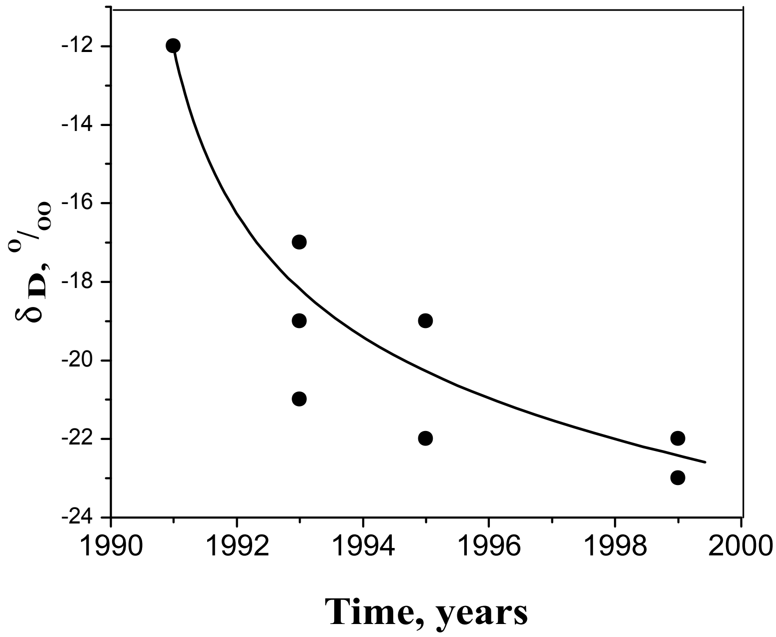

Fig. 4. Variation of hydrogen isotope composition (δD) of gas condensates from F-940 fumarole. The data are cited from Taran *et al.* (1995) and Goff and McMurtry (2000), except the middle point in 1993 and two points in 1999.

acterized by temperatures in excess of 900°C and gas velocity of up to 80 m/s. The hydrogen and oxygen isotopic compositions of F-940 fumarolic gases (Taran *et al.*, 1995; Goff and McMurtry, 2000) are typical of a magmatic water (Giggenbach, 1992a). The F-940 fumarole is likely to be the most representative for evaluation of magmatic activity of the Kudriavy volcano. Temperature and chemical composition of the F-940 fumarolic gas during 1991–1999 are listed in Table 1. The data obtained in 1995 on F-940 fumarolic gas composition by Wahrenberger (1997) and Fischer *et al.* (1998) are also presented in Table 1.

5.1 Long-term variation

The temperature of the F-940 fumarole varied from 903° to 940°C (Fig. 3(g)). The maximum temperature of 940°C was measured in 1992. Since 1992, the temperature slowly decreased with time, but remained almost constant for the last two years of observations. The F-940 temperature remained constant before and after the phreatic eruption on October 7, 1999. The δD value of the fumarolic gas decreased from −12‰ in 1991 to −22.5‰ in 1999 (Fig. 4). A continuous increase in H_2O concentration from 93 to 95 mol % and decrease in CO_2 concentration from 2.4 to 0.7 mol % was observed during the decade of observations, except for the last sample in 1998 and last two samples in 1999 (Figs. 3(a) and (b)). Those three samples were collected after intense rains and therefore their gas composition was likely affected by the precipitations (see below). With the exception of these samples, the concentrations of S_{total} and hydrogen in the gases were almost constant (Figs. 3(c) and (d)). Hydrogen chloride and hydrogen fluoride concentrations show large variations with time (Figs. 3(e) and (f)). Although the relatively low HCl concentration of 0.11 mol % measured in the middle of September, 1998 is out of the general trend, it is likely due to either the effect of a sampling procedure such as a partial gas condensation in a sampling tube (Shinohara, 1999) or analytical error. In the first case, the same behavior of HF should be expected during sampling procedure but low HF concentration was not found in that sample. Thus, the analytical errors are more appropriate to explain such a low HCl concentration. For this reason, the concentration of HCl in that sample will not be discussed below.

Ratios of the major components are plotted in Fig. 5. Carbon to sulfur ratio gradually decreased during ten years (Fig. 5(a)) as a result of the larger decrease in CO_2 than S_{total} (Fig. 3). Neglecting the three samples collected after the intense precipitations in 1998 and 1999, we can recognize the maximum in C/Cl and S/Cl ratios and the minimum in Cl/F ratio in 1995 (Figs. 5(b) and (d)). Carbon to fluorine and sulfur to fluorine ratios were relatively constant except for three samples after the precipitations (Fig. 5(c)).

5.2 Short-term variation in 1998 and 1999

Detailed investigations of the F-940 fumarole were carried out in September–October, 1998 and 1999 to elucidate the effect of meteoric precipitations on fumarolic gas composition. Gas temperature, meteoric precipitations and seismicity were measured periodically and gas samples were collected repeatedly during those periods. The data are plotted on Fig. 6.

5.2.1 Precipitations Variations of the precipitations during September–October, 1998 and 1999 are presented in Fig. 6(g). The most intense rains in 1998 (100 mm) were observed during the night on October 3. The weather condition from the end of July to the beginning of September in 1999 was unusually dry at Kurile Islands. Several heavy rains were observed from September 25 to October 3 in 1999. The heaviest rains in 1999 (130 mm) occurred on October 3 and a small short-lived lake with a depth of 5–15 cm formed in the central crater. Although similar lakes were also observed during 1990–1998, the surface area of the lake in 1999 was

Table 1. Chemical composition of gases from the F-940 fumarole.

No.	Date	T/°C	H_2O	CO_2	CO	HCl	HF	H_2	S_{total}	N_2	O_2	Ar	CH_4
1[a]	1991	910	93.1	2.36	0.036	0.74	0.083	1.00	2.03	0.547	0.15	0.005	<0.0002
2[a]	1992	940	94.4	1.80	0.00065	0.46	0.025	1.18	1.98	0.133	0.02	0.001	<0.0001
3[b]	95.08.27	920	95.3	1.15	0.00084	0.74	0.096	0.775	2.44	0.025	0.0176	0.00009	<0.000005
4[b]	95.08.28	920	96.3	1.61	0.0011	0.2	—	0.576	1.27	0.022	<0.0005	0.00005	0.000003
5[c]	95.08.27	920	95.29	1.36	0.000006	0.22	0.062	1.54	1.52	0.001	—	—	—
6[c]	95.08.28	920	94.29	1.68	0.056	0.17	0.074	0.57	2.03	1.11	—	—	—
8	98.09.21	905	95.51	1.44	0.011	0.11	0.04	0.92	1.85	0.11	0.0098	0.00058	0.000024
9	98.09.29	908	95.59	1.01	0.016	0.44	0.03	0.92	1.86	0.12	0.0024	0.00023	0.000009
10	98.10.10	903	93.3	1.46	0.025	0.48	0.04	1.59	2.96	0.13	0.0047	0.00058	0.000008
11	99.09.13	908	95.76	0.69	0.0082	0.47	0.014	0.91	1.87	0.27	0.0057	0.0027	0.000005
12	99.09.14	—	96.19	0.63	0.0059	0.50	0.019	0.65	1.78	0.23	0.0035	0.0029	0.000003
13	99.09.22	907	95.91	1.22	0.0094	0.48	0.016	0.63	1.65	0.082	0.003	0.0025	0.000002
14	99.09.27	—	93.77	1.86	0.011	0.42	0.007	0.96	2.92	0.042	0.0046	0.0024	0.000002
15	99.10.10	907	93.32	1.77	0.011	0.76	0.069	1.30	2.70	0.055	0.0082	0.00025	0.000005

Composition is given by mole %.
—not analyzed.
[a]From Taran *et al.* (1995).
[b]From Fischer *et al.* (1998).
[c]From Wahrenberger (1997).
*the average gas composition of four samples collected by Fischer *et al.* (1998) and Wahrenberger (1997) in 1995.

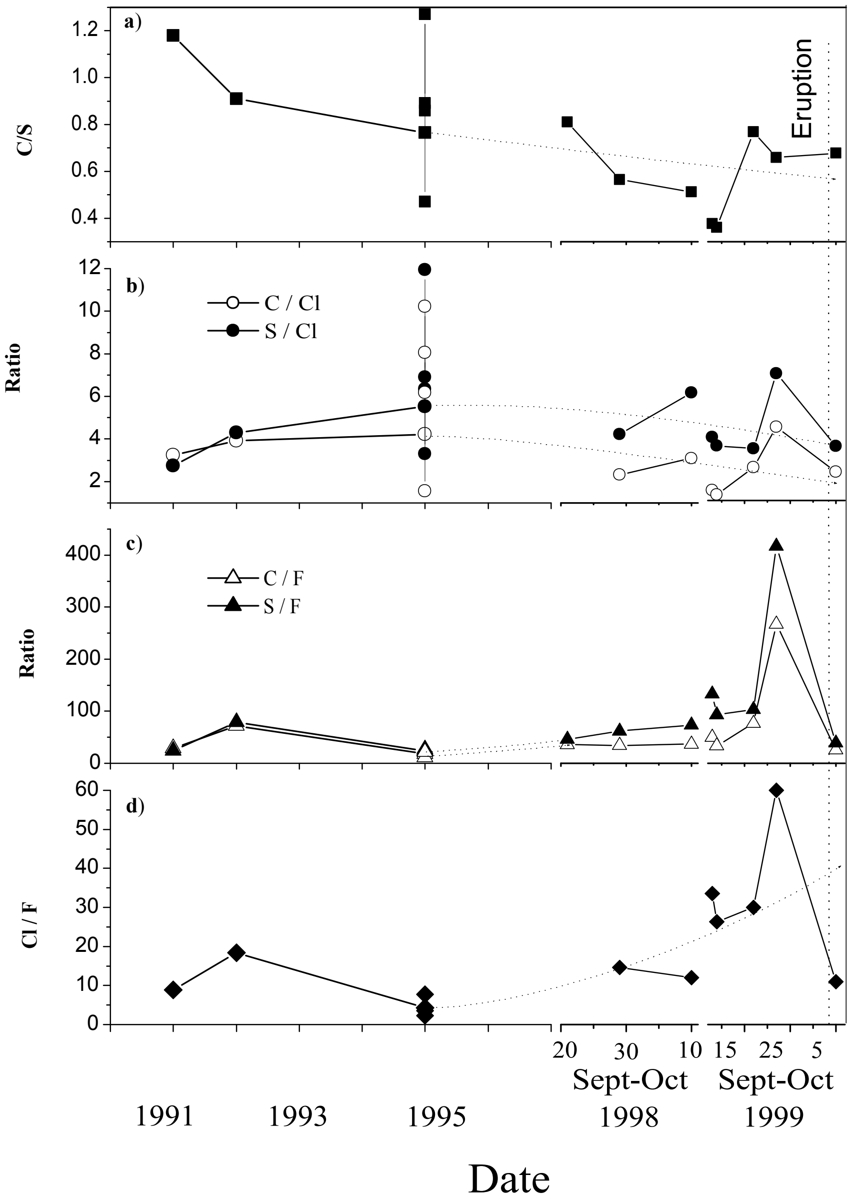

Fig. 5. Variation in molar ratios of the major components in the F-940 fumarolic gas during 1991–1999. Vertical dashed line corresponds to the date of the eruption and the dotted lines indicate the long-term trend.

much larger. The lake remained until the eruption on October 7.

5.2.2 Seismicity Results of the seismicity measurements at Kudriavy volcano from September 13 to October 7, 1999 are presented in Fig. 7(a). Seismic events related only to intrinsic activity of the Kudriavy (Figs. 6(h) and 7(b)) were obtained after subtracting the events registered at Kurilsk seismic station (located 80 km southwest, see Fig. 1) from the events recorded at the Kudriavy summit. The regional earthquakes of about 3–3.5 magnitude in Richter scale occurred on September 22 and 27. Their magnitudes were recorded as 3000 relative units by the summit seismic detector (Fig. 7(a)). The intrinsic volcano seismic events occurred 15 hours before the eruption (Figs. 6(h) and 7(b)) were recorded as the magnitude 1300 relative units. The intrinsic seismicity at the Kudriavy volcano was observed 2–4 day after the intense meteoric precipitations (Fig. 6).

5.2.3 Temperature and gas composition F-940 gas temperature was constant during September–October of 1998 and 1999 indicating that it was not affected by the meteoric precipitations. The D/H ratio of the gas was also constant at −23‰ on September 23 and −22‰ on September 29, 1999 (Fig. 4). In contrast, chemical composition of the F-940 fumarolic gas shows significant changes (Figs. 3 and 6). The variations in gas composition correlate with changes in the meteoric precipitations and the seismicity (Fig. 6). The H_2O content decreased from 95.6 to less than 94 mol % in five days after the first heavy rain on October 3, 1998. Simultaneously, contents of sulfur and hydrogen increased by 1.5 times, while concentrations of CO_2, HCl and HF showed only negligible changes. Ratios of C/S, C/Cl, C/F, S/F, and Cl/F were almost on the long-term trend, while S/Cl ratio increased after the intense rain by 1.5 times

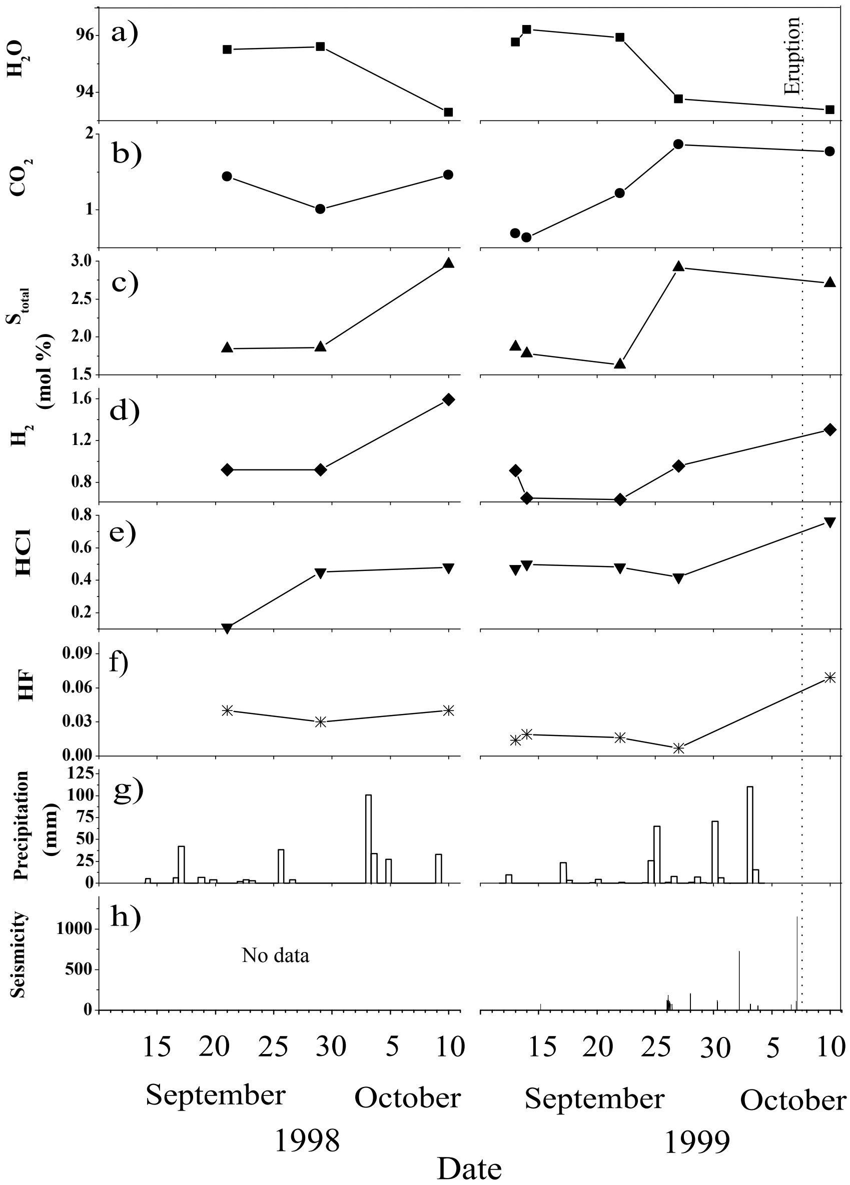

Fig. 6. Short-term variation in gas composition (in mol %) of F-940 fumarole (a)–(f); meteoric precipitations in mm (g) during September 13 to October 10, 1998–1999; (h) intrinsic seismicity of Kudriavy volcano during September 13 to October 7, 1999.

(Fig. 5). In two days after the intense rains on September 25, 1999, water content decreased, CO_2 and total sulfur increased, while H_2, HCl and HF only slightly changed. These changes are very similar to the variations in gas composition observed on October 10, 1998, however significant changes in C/Cl, S/Cl, C/F, S/F and Cl/F ratios are observed only in 1999. In addition, C/S ratio increased by twice 3 days before the intensive rains and the change was mainly due to the increase in CO_2 content. However, the dramatic changes in gas component ratios in the sample # 13 (Table 1) can be due to errors during sampling or analytical procedures.

Two days prior to the changes in gas composition, a weak seismic swarm (less then 150 relative units in magnitude) with total duration of several hours was observed at the Kudriavy. Unfortunately, next gas sample was collected only on October 10, three days after the eruption and the gas composition variations are unknown for the period from September 27 to October 10. After the eruption, H_2O, CO_2 and S_{total} contents were similar as that in September 27 while H_2, HCl and HF concentrations in fumarolic gas increased. The C/S ratio was constant regardless of the eruption, and C/Cl, S/Cl, C/F, S/F and Cl/F ratios significantly decreased back to the level of the 10-year trend. It must be noted that the contents of water, sulfur and hydrogen in the gas samples collected after the rains in 1998 and 1999 are quite similar. The limited number of gas samples is not enough to evaluate the duration of these gas composition changes. However, the continuous monitoring of hydrogen fugacity in the fumarole revealed that the elevated hydrogen concentration continued for 5 days in 1998 (Korzhinsky *et al.*, 2000).

6. Eruption in 1999

The eruption occurred on October 7, 1999 at the south-eastern part of the central crater of Kudriavy Volcano (Fig. 2). As a result of intense rains 5 days prior to the eruption, a small lake was formed in the central crater.

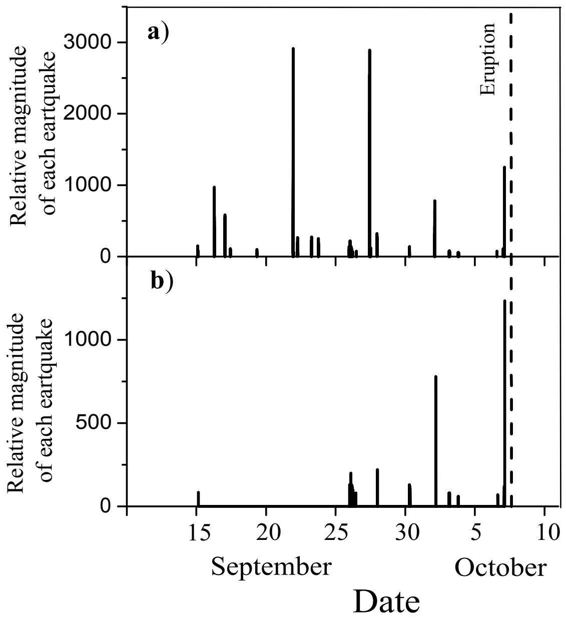

Fig. 7. Seismic activity from September 13 to October 7, 1999 measured at the summit of Kudriavy volcano: (a) total seismicity; (b) intrinsic seismicity of the Kudriavy volcano. The diagrams show the magnitude of each earthquake in arbitrary units (see text for details).

There were several fumaroles with the temperatures of about 100°C in the south-eastern part of this crater just near the dome wall where 800°C fumaroles were located. Some of these low-temperature fumaroles were covered by the water and boiling springs were observed. The eruption was first observed at 5:20 p.m. local time although possibly could have started earlier. Bad weather conditions after 2:00 p.m. prevented observations.

The active phase of the eruption consisted of periodic ejection of ash to the height of up to 300–400 m with 3–5 min intervals. The active phase of the eruption continued for 1.5 hours. Although some people stayed at the summit Camp 2 (Fig. 2) at the distance of 250 m from the eruption center at the beginning of the eruption, they did not hear any explosion sounds. Direct observation from the crater rim at 7:05 p.m. showed decrease in eruption activity. Ejection of 10–30 cm-size blocks had already ceased, but the ejection of ash from the crater still continued.

A new crater of 35 m depth and 30–40 m diameter was formed as a result of the eruption. A cavern with the dimensions of 3 × 6 m opened at 20 m depth on the southern vertical wall of the crater. Rims and inner walls of the cavern were red-yellow glowing and its temperature seems to be higher than 900°C. The vigorous gas stream discharged from the cavern. A power of roaring sound, that caused by gases escaped from the cavern, was comparable with a jet engine. The ejected materials were deposited just around the new crater. Thickness of these deposits was about 1.5 m at the crater rim and continuously decreases to zero approximately at 20–25 m away from the crater. Maximum size of the ejected rock fragments was 30 cm. The rate of gas discharge from the cavern did not weaken until the end of the field observation on October 15, 1999.

Optical investigations of the volcanic ash under the microscope revealed that the ash consists of the altered material of crater deposits. Its constituents are mainly quartz, tridymite, cristobalite, pyroxene, plagioclase, olivine, and anhydrite. Fragments of magmatic glass were not identified in the volcanic ash.

7. Discussion

7.1 Long-term variation in temperature and gas composition of the F-940 fumarole

The gradual changes in temperature and gas composition observed during the ten years at the Kudriavy Volcano is typical for fumaroles after a major eruptive period or increase in volcanic activity (e.g., Symonds *et al.*, 1996; Shevenell and Goff, 2000). The increase in gas temperature to 940°C during 1991–1992 most likely was caused by ascent of fresh magma batch into shallow reservoir of the Kudriavy Volcano. Gradual and continuous decrease in temperature and changes in gas composition observed during the last 10 years (Figs. 3 and 4) suggest degassing of the isolated magma volume in a relatively steady-state manner (e.g., Giggenbach, 1996; Symonds *et al.*, 1996).

7.2 Short-term variation in gas composition of the F-940 fumarole

The long-term gradual change in the composition of the F-940 fumarolic gas was repeatedly disturbed by short-term variation in 1998 and 1999. It is remarkable that both these disturbances in chemical composition occurred several days after the intense precipitations. Similar correlation between precipitations and changes in gas composition was also observed at Galeras volcano (T. Fischer, personal communication). In contrast, Zimmer *et al.* (2000) reported the inverse correlation between precipitations and water content in fumarolic gases at Merapi volcano.

The changes in gas composition were accompanied also by an increase in intrinsic volcano seismic activity in 1999 (Fig. 6). The observed short-term changes in gas composition may be explained by the following processes: 1) Increase of the magma degassing pressure caused by decrease of the volcanic edifice permeability. 2) Ascent of fresh non-degassed batch of the magma, and 3) Non-equilibrium gas phase exsolution from the melt caused by a change in magma convection rate.

The intense rains and penetration of meteoric waters into volcano edifice could: (a) cool down the fumarolic channels and reduce the crossection of fumarolic vents due to sublimate precipitation on the walls; (b) decrease soil gas discharge rate as a result of soil permeability decrease caused by rain water penetration. If gas discharge rate from the magmatic melt is constant, both processes will result in increase of magma degassing pressure. According to the solubility model of Dixon and Stolper (1995), and the data compiled by Holloway and Blank (1994), pressure increase in the melt-fluid (H_2O-CO_2) system will result in water content decrease in the gas phase relative to CO_2. Unfortunately, volatile concentrations in the Kudriavy magma are not studied yet. The initial water content in the Kudriavy magmatic melt is assumed to be the same as average water concentration in andesitic melts of arc-type volcanoes (17,000 ppm; Giggenbach, 1996). Pressure above the shallow magmatic melt for the volcanoes with high-temperature fumarolic degassing is expected to be a few bars as suggested by Stevenson (1993). According to the data on temperature dependence of mixing between magmatic gases and meteoric waters at the Kudriavy volcano (Botcharnikov *et al.*, 1998b), the temperature of magmatic gas and shallow magma can be estimated as around 1050°C. Based on the model of Dixon and Stolper (1995), in order to increase the initial carbon dioxide concentrations in the gas phase by 1.5 and 2 times as observed in 1998 and 1999, the pressure above the melt should be increased from a few bars to 25 and 75 bars, respectively. It is unlikely that such a large pressure increase could be caused by precipitations. The relatively constant chemical composition of fumarolic gases before and after the eruption also contradicts to this model because the process, accompanied by the release of a large amount of gases during the eruption, should significantly decrease the magma degassing pressure.

The changes in chemical composition could be the result of ascent of new magma batches with different volatile compositions. However, the constant hydrogen isotopic composition of the gases does not suggest the new magma supply. For instance, the increase in D/H ratio was observed prior to the magmatic eruption of Colima volcano in 1998 by the input of new magma in a shallow magma chamber (Taran *et al.*, 2001). The constant temperature of fumarolic gases during this period also contradicts the idea of new magma injection at the Kudriavy.

Following to the degassing model of Kazahaya *et al.* (1994) for Izu-Oshima volcano, one can suppose that the convection of magmatic melt occurs in the shallow magmatic conduit of the Kudriavy. Increase in magma convection rate will result in the increase in decompression rate of the ascending magmatic melt. In this case, the gas phase may be released from the melt in a chemically disequilibrium manner (Mangan and Sisson, 2000). Therefore, the gas composition may correspond to an equilibrium gas phase at higher pressures than the degassing pressure. It is expected that the fluid phase, enriched in less soluble gas components (e.g., H_2, CO_2, SO_2) and depleted in H_2O, will release from the melt if the magma convection rate increases.

The gas composition changes after heavy rains in 1998 and 1999 suggest that meteoric waters, penetrating the volcano edifice, can affect the rate of magma convection in magmatic chamber and/or conduit. Penetration of meteoric waters into volcano edifice after heavy rains will cause cooling of magmatic plumbing system, accelerating magma crystallization and increase in magma viscosity in the column, especially at its peripheral parts. As a result, a viscous plug can be formed in the conduit reducing magma convection rate and increasing pressure in the magmatic system below the viscous plug. When pressure reaches some critical value, the viscous plug might be destroyed and magma convective rate sharply increases. This process can cause disequilibrium release of volatiles from the melt.

7.3 Eruption mechanism

The eruption at the Kudriavy volcano were preceded by: (1) unusually dry 1.5 month-long period , (2) two regional earthquakes with magnitude of 3–3.5 at the Richter scale that occurred on September 22 and September 27, 1999, (3) heavy rain prior to the eruption (most intense on October 3, 1999), (4) increase in intrinsic seismic activity of the Kudriavy volcano, and (5) changes in gas composition. According to classification of Barberi *et al.* (1992), phreatic eruption "indicates an eruption caused by violent explosion of steam and gas with no direct involvement of magma (all ejecta are fragments of pre-existing rocks), independent of the source of the steam (phreatic or hydrothermal system) and of the involvement or not of juvenile fluids." The lack of fresh magmatic fragments in the eruptive materials indicates phreatic character of the eruption.

The phreatic explosions at the Kudriavy can be a result of pressure increase by rapid boiling of meteoric waters. After the unusual long dry period in 1999 (1.5-month), the country rocks of fumarolic system can be progressively heated to more shallow level. As a result of two regional earthquakes on September 22 and 27, new fractures may be opened. After the heavy rainfalls, waters penetrated the hot zone of the volcanic structure and boiled. The excess pressure caused by boiling of meteoric waters provokes the destruction of overlying rocks. Observed correlation between amount of precipitations and magnitude of seismic events suggests that the boiling of the meteoric waters in the volcano edifice could be the cause of increase in intrinsic seismic activity (Fig. 6). Similar correlation between the number of microearthquakes and intensity of rainfalls was observed at volcanic island of Tenerife (Jimenez and Garcia-Fernandez, 2000).

The comparison of the modern degassing and crater formation processes at the Kudriavy and Satsuma-Iwojima (Japan) Volcanoes (Shinohara *et al.*, 2002) shows general similarity of their extremely high-temperature fumarolic activity. Both volcanoes are characterized by the presence of recently-formed craters with high-temperature gas discharge from the bottom. However the process of crater formation at the Satsuma-Iwojima was much longer (1991–today) than the single-stage phreatic eruption at the Kudriavy Volcano. Crater formation at the Satsuma-Iwojima, according to Shinohara *et al.* (2002), was caused by periodical intense ejection of crater-filled materials, as a result of gas flux increase.

8. Conclusion

During the last decade, the fumarolic activity of the Kudriavy volcano was relatively constant. Temperature changes of the highest temperature fumarole F-940 at the Kudriavy gradually decreased from the maximum value of 940°C in 1992 to 908°C in 1999. Gas composition of F-940 fumarole showed continuous increase in water content and decrease in concentrations of typical magmatic components (CO_2, S_{total}, H_2) while hydrogen isotopic ratio gradually decreased with time. These trends of changes in temperature and gas composition are typical for fumarolic gases in two major cases: (1) immediately after volcanic eruption (posteruptive stage), and (2) after the periods of noneruptive activization of volcanic system. The steady-state high-temperature degassing at the Kudriavy was repeatedly disturbed by increase in H_2, CO_2 and S_{total} concentrations whereas the gas temperature was almost constant. The changes in gas composition occurred after intense meteoric precipitations and also correlated with the increase in intrinsic volcano seismicity in 1999. We suggest that the changes in gas composition resulted from disequilibrium degassing of magma due to increase in magma convection rate in a shallow magmatic system induced by meteoric water penetrating volcanic edifice after heavy rainfalls.

The eruption at the Kudriavy volcano on October 7, 1999 was phreatic in character and occurred after two regional seismic events and heavy rains following the unusually long dry period. The dry period caused heating of the volcanic edifice. The regional seismic events caused fracturing of the rocks. The rain water rapidly penetrated the hot zone of the volcano edifice and boiled, producing excess pressure enough for destruction of the overlying rocks. The unusually long dry period at the Kudriavy volcano was likely to be a key condition for initiation of the phreatic eruptions at Kudriavy. Similar heavy rain conditions, accompanied by changes in gas compositions were also observed in 1998 but they did not result in the phreatic volcanic activity.

Acknowledgments. We are very grateful to Hiroshi Shinohara for opportunity to prepare this contribution for the special issue on Satsuma-Iwojima volcano and critical review of the manuscript. We also thank Kirill Shmulovich and Eduard Persikov (IEM RAS) for suggestions and helpful discussions. We address special thanks to Felix Shaderman (IMGRE RAS) for the data on precipitations in 1999, Mikhail Zelensky and Viktor Okrugin (IVGG RAS) for gas sample analyses in 1998 and 1999. Igor Usyshkin (Kurilsk seismic station) is gratefully acknowledged for providing us the sensor detector and help for processing the data on seismicity measurements. Later review by Yu. Taran (UNAM, Mexico) and an anonymous reviewer greatly improved the final version of the manuscript.

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