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Monitoring Quiescent Volcanoes by Diffuse CO_2 Degassing: Case Study of Mt. Fuji, Japan

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Absrtract—Since the 8th century, more than seventeen eruptions have been recorded for the Mt. Fuji volcano, with the most recent eruption occurring in 1707 (Hoei eruption). For the past 300 years the volcano has been in a quiescent stage and, since the early 1960s, has exhibited neither fumarolic nor thermal activity. However, the number of low-frequency earthquakes with a hypocentral depth of 10–20 km increased significantly beneath the northeastern flank of Mt. Fuji in 2000–2001, suggesting a possible resumption of magmatic activity. In this study, diffuse CO_2 efflux and thermal surveys were carried out in four areas of the volcano in 2001–2002 in order to detect possible signs of the upward movement of deep magma. At all survey points, the CO_2 efflux was below the detection limit with the exception of a few points with biological CO_2 emission, and ground temperatures at a depth of 20–30 cm were below ambient, indicating no surface manifestations of gas or heat emission. Should magma rise into the subsurface, the diffuse CO_2 efflux would be expected to increase, particularly along the tectonically weakened lineation on the Mt. Fuji volcano, allowing for the early detection of pre-eruptive degassing.

Key words: Quiescent volcanoes, CO_2 degassing, Mt. Fuji.

1. *Introduction*

Recent developments in the monitoring of active volcanoes have revealed that CO_2 and He degassing can signal the upward movement of magma. At the time of the 1986 eruption of the Izu-Oshima volcano in Japan, the $^3He/^4He$ ratio of steam emitted from a well 3 km away from a vent extruding new magma increased from 1.7 to 5.5 Ra (Ra: unit of atmospheric $^3He/^4He = 1.40 \times 10^{-6}$) over six months, reflecting the upward magma movement, and then decreased gradually corresponding to drain-back of the magma (SANO *et al.*, 1995). Similar changes were also observed at Unzen volcano, Japan (NOTSU *et al.*, 2001) and at Mammoth Mountain,

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USA (SOREY *et al.*, 1998). In the case of Mammoth Mountain, soil CO_2 efflux was also found to be a good indicator of magma behavior (GERLACH *et al.*, 2001). Prior to the 2000 eruption of Usu volcano in Japan, integrated soil CO_2 efflux for the entire area of the summit caldera increased significantly, and then decreased following the eruption (HERNÁNDEZ *et al.*, 2001a). Anomalous levels of soil CO_2 degassing have also been found to correlate with faults and eruptive fissures at Mt. Etna, Italy (GIAMMANCO *et al.*, 1998).

These examples show that the degassing of He and CO_2 can be useful for monitoring subsurface magma movement. In the cases of Izu-Ozhima and Unzen volcanoes, magma is extruded to the surface as lava flows or lava domes, whereas at Mammoth Mountain, a dike is thought to have been emplaced at a depth of about 2 km (SOREY *et al.*, 1998). From the viewpoint of eruption prediction, the development of a method for monitoring magma behavior at depths greater than 10 km could be useful, because such deep events are difficult to be detected by geodetic, gravitational, electromagnetic or thermal observations. At present, the observation of volcanic earthquakes and tremors is the most reliable method for detecting deep magma behavior.

Recent volcanic activity at Mt. Fuji volcano in Japan provides a good example of seismic-based monitoring. The number of low-frequency earthquakes taking place at a depth of 10–20 km beneath the northeastern flank of this volcano increased in 2000–2001, suggesting renewed deep magma activity (UKAWA, 2003). However, no other manifestations suggestive of magma movement, such as thermal anomalies, geodetic change or magnetic anomalies, have been observed. Considering that large amounts of magmatic CO_2 can be released from deep magma reservoirs via the volcanic edifice without thermal manifestations, as observed at Hakkoda volcano, Japan (HERNÁNDEZ *et al.*, 2003) and Mammoth Mountain (GERLACH *et al.*, 1998), CO_2 efflux surveys can be expected to provide information on the current conditions of deep magma below Mt. Fuji volcano. Thus far, studies of this type on the features of diffuse degassing from quiescent volcanoes have been conducted only infrequently. In the present study, the potential utility of CO_2 efflux surveys to evaluate the volcanic activity at quiescent volcanoes is discussed.

2. Fuji Volcano and its Eruption History

Mt. Fuji is the highest mountain (3776 m asl) in Japan and is located in the northernmost reaches of the Izu-Ogasawara arc, which is formed by subduction of the Pacific Plate. More than seventeen eruptions are recorded in historical documents since the 8th century AD (METEOROLOGICAL AGENCY, 1995). Among them, large, disastrous eruptions took place in 800, 864–865 and 1707 AD. In the 864–865 eruptions, more than 1 km^3 of lava flowed from the northwestern flank of the volcano, bisecting a large lake. In the latest 1707 eruption, approximately 0.7 km^3 of scoria and ash was emitted from new vents (Hoei craters) on the southeastern flank 3 km from the summit (MIYAJI, 1988).

According to historical documents, it is known that intense fuming from the summit crater was a continuous feature during that period (TSUJI, 1992). However, significant summit fuming has not been seen for 300 yrs, although small-scale steaming within the summit crater was observed from the crater rim up until the early 19th century. After the 1854 Ansei Tokai Earthquake (M 8.4) off the southern coast of the Tokai area, fumarolic and geothermal activity migrated to the eastern edge of the summit crater (around "Aramaki", see Fig. 2), where the temperature decreased from 82°C in 1897, to 80°C in 1928, 54°C in 1954, and only slightly warm in 1963. Geothermal manifestations have also been observed around Hoei craters and on the eastern flank until about 1950 (SUWA, 1982). However, neither geothermal nor fumarolic manifestations have been reported for any region of Mt. Fuji for the last 30 years, indicating that the volcano is currently in a quiescent stage.

From October 2000 to May 2001, the number of low-frequency earthquakes at a depth of 10–20 km below the northeastern flank increased significantly, suggesting a possible resumption of magmatic activity (UKAWA, 2003). During the period 1980–1999, the total number of these events was 274, while the numbers in 2000 and 2001were 180 and 172, respectively. AIZAWA (2004) suggested the existence of an active hydrothermal system deep beneath the summit crater based on the positive self-potential (SP) measured in 2001 and 2002.

3. Observation

Diffuse CO_2 efflux and thermal surveys were conducted in four areas (summit area, around Hoei craters on the southeastern flank, along paths on the northeastern flank, and along a path on the eastern flank), including previous geothermal or fumarolic sites, in order to detect possible signs of magmatic activity (Fig. 1). Diffuse CO_2 efflux was measured by an accumulation chamber method (CHIODINI *et al.*, 1998). The system consists of a cylindrical chamber opened at the bottom with a fan to improve gas mixing and an NDIR (non-disperse infrared) spectrophotometer with an accuracy of approximately 5%. The reproducibility for the range of 100 to 10,000 $gCO_2/m^2/day$ is 10%.

The summit area of Mt. Fuji is characterized by a summit crater 600 m in diameter and 200 m in depth. Diffuse CO_2 efflux and soil temperature measurements were carried out at 18 sites along the circular path around the rim of the summit crater on July 10, 2001. Figure 2 shows the location of sampling sites. Several measurements were conducted in a small area near Aramaki on the eastern edge of the summit crater, where fumarolic and geothermal activity was observed until the 1960s. Soil gas samples were also collected at depths of 25–30 cm using a commercial soil gas sampling probe, and the CO_2, N_2 and O_2 concentrations were determined by standard

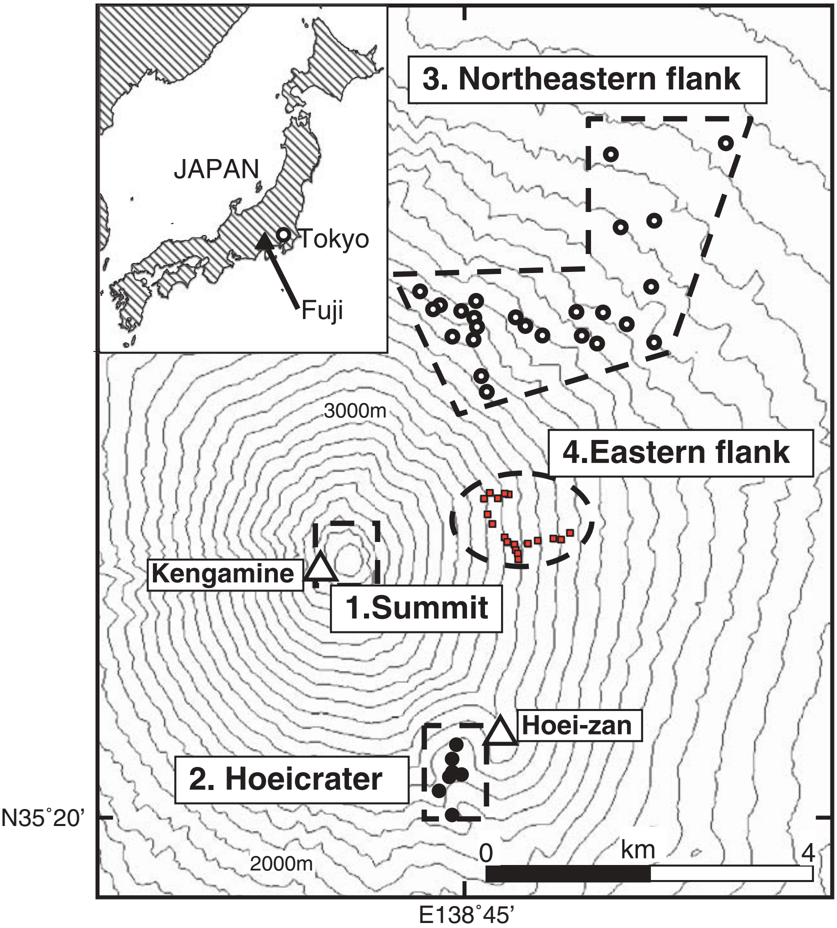

Figure 1
A map of Fuji volcano showing 4 surveyed areas. Observation sites are shown as solid circles (around Hoei craters), open circles (along the Takizawa and Yoshidaguchi paths on the northeastern flank) and solid squares (along the Subashiriguchi path on the eastern flank). For the summit area, observation sites are shown in Figure 2.

gas chromatography. A column filled with Porapak-Q and He as a carrier gas were used for CO_2 determination, whereas a molecular sieve column and Ar carrier gas were used for other species.

Soil CO_2 efflux and temperature measurements were carried out at 7 sites around the Hoei I crater, which was formed by a large phreatic eruption in 1707, on the southeastern flank on September 23, 2001. Along the Takizawa and Yoshidaguchi paths on the northeastern flank, soil CO_2 efflux measurements were carried out at 25 sites on July 23, 2002. This area corresponds to the epicentral region of a low-frequency

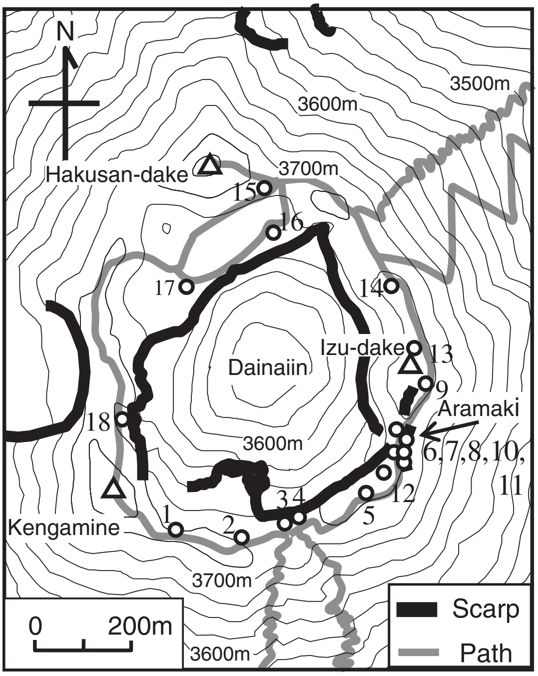

Figure 2
Observation sites in the summit area of Mt. Fuji. Numbers correspond to those in Table 1.

earthquake swarm that occurred at a depth of 10–20 km in 2000–2001. Soil CO_2 efflux measurements were carried out at 16 sites along the Subashiriguchi path on the eastern flank on September 19, 2002. This region was later reported to exhibit a negative SP anomaly (Aizawa, 2004).

4. Results

Tables 1, 2 show the data obtained in the summit area and around Hoei craters on the southeastern flank. For all of these survey points, CO_2 effluxes were below the detection limit of 5 $gCO_2/m^2/day$, and the ground temperature at 20–30 cm was below the ambient temperature, indicating no gas or heat emission. As the summit area and Hoei crater region are free of vegetation, it is reasonable to assume negligible CO_2 efflux due to biological activity occurs. Thus, chemical composition of the soil gas is assumed to be atmospheric, with 500–1000 ppm CO_2, implying that any CO_2 efflux due to magma degassing, if it occurs, should be detected immediately.

Although steam flow at the Aramaki site ceased around 1963 and the present ground temperature at 25–30 cm is 5–10°C indicating no surface thermal

Table 1

CO_2 efflux, soil temperature (25–30 cm deep) and chemical composition of soil gases in the summit region of Mt. Fuji

Location	CO_2 efflux (g m^{-2} d^{-1})	Soil temperature (°C)	Chemical composition of soil gas			
			CO_2(ppm)	N_2 (%)	O_2(%)	N_2/O_2
fuji01	n.d.	9.0	680	77.9	21.1	3.69
fuji02	n.d.	9.1	–	77.1	20.9	3.68
fuji03	n.d.	3.4	–	–	–	–
fuji04	n.d.	6.3	–	77.3	21.0	3.68
fuji05	n.d.	10.2	540	77.9	21.1	3.69
fuji06	n.d.	8.8	880	77.8	21.2	3.68
fuji06-1	n.d.	8.0	–	–	–	–
fuji06-2	n.d.	7.5	–	–	–	–
fuji07	n.d.	9.0	–	–	–	–
fuji08	n.d.	8.0	–	–	–	–
fuji09	n.d.	11.7	1000	77.8	21.2	3.68
fuji10	n.d.	12.0	650	77.8	21.2	3.68
fuji11	n.d.	–	–	–	–	–
fuji12	n.d.	7.6	690	77.8	21.2	3.68
fuji13	n.d.	1.1	710	77.8	21.2	3.68
fuji14	n.d.	9.0	680	77.9	21.1	3.68
fuji15	n.d.	12.5	950	77.8	21.1	3.68
fuji16	n.d.	7.5	740	77.9	21.1	3.68
fuji17	n.d.	8.7	590	77.9	21.1	3.68
fuji18	n.d.	12.0	740	77.8	21.1	3.68

Location numbers correspond to those in Figure 2. n.d.: not detected (below 5 g $m^{-2}d^{-1}$) –: not determined

Table 2

CO_2 efflux and soil temperature around Hoei craters

Location	CO_2 efflux (g m^{-2} d^{-1})	Soil temperature (depth) (°C (cm))
hoei01	n.d.	18.2 (20)
hoei02	n.d.	12.9 (50)
hoei03	n.d.	–
hoei04	n.d.	10.3 (50)
hoei05	n.d.	11.5 (–)
hoei06	n.d.	13.9 (25)
hoei07	n.d.	12.8 (25)

n.d.: not detected (below 5 g $m^{-2}d^{-1}$) –: not determined

manifestations related to magmatic activity, AIZAWA (2004) suggested the existence of a deep hydrothermal system based on a positive SP anomaly in the summit region. Above 3000 m, Mt. Fuji hosts a permafrost layer (KAIZUKA, 1986), and the steaming that persisted up until the 1960s is considered to have escaped via a defrost path through this permafrost layer. However, the path is now closed, presumably due to a decrease in the steam pressure and/or temperature, and no further thermal manifestations or diffuse CO_2 efflux occur at the surface in this region. The deep SP anomaly source associated with the suggested hydrothermal system might be sealed by the overlying permafrost layer, effectively preventing any effect on surface conditions. In contrast, the large amount of porous scoria around Hoei craters readily allows mixing with ambient air, resulting in a dilution of the gas and decreasing the CO_2 efflux.

Along the paths on the northeastern flank corresponding to the epicenter region of the 2000–2001 low-frequency earthquake swarm (UKAWA, 2003), all CO_2 effluxes were below the detection limit of 5 $gCO_2/m^2/day$ except a few points located in woodlands where CO_2 emissions reached 87 $gCO_2/m^2/day$ due to biological contribution. Judging from the depth of the swarm, magma might have moved to a depth of 10–20 km, too deep to trigger significant diffuse soil degassing without deep fissures and allow direct transport of gas to the surface. Along the path on the eastern flank, a negative SP anomaly has been reported and interpreted as a manifestation of the downward percolation of groundwater in weak and permeable ground (AIZAWA, 2004). All 16 measurement points on this path exhibited CO_2 effluxes below the detection limit of 5 $gCO_2/m^2/day$. Although characteristic CO_2 efflux related to the negative SP anomaly was expected since the negative SP region coincides with the locations of fumaroles of 40 years ago (AIZAWA, 2004), no efflux was observed in this region.

5. *Discussion*

In the present survey, relatively low CO_2 effluxes were measured, suggesting the absence of magmatic gas in the diffuse emanations along the surface environment of Mt. Fuji. However, based on the hypocentral depth of the 2000–2001 low-frequency earthquake swarm, magma appears to be pooling at a depth of 10–20 km below the volcano. Furthermore, the $^3He/^4He$ ratios of bubbling gases released in the hot spring discharges on the northeastern and southeastern slopes of Mt. Fuji indicate a significant contribution of magmatic helium. The maximum $^3He/^4He$ ratio recorded in these areas is 6.43 Ra, obtained at the Suyama hot spring about 15 km southeast of the summit (OHNO *et al.*, personal communication). The positive SP anomaly suggests the existence of a deep hydrothermal system below Mt. Fuji (AIZAWA, 2004), implying that magmatic fluids and gases are currently being supplied at deep levels, although the exact depth remains unclear. These gases are stored in a deep chamber and only helium in them might seep up to the surface.

Previous studies on diffuse CO_2 efflux have revealed that high efflux is typically observed on volcanoes when active plume degassing is low, corresponding to a low-activity stage, as exemplified by the Hakkoda volcano (HERNÁNDEZ *et al.*, 2003) and

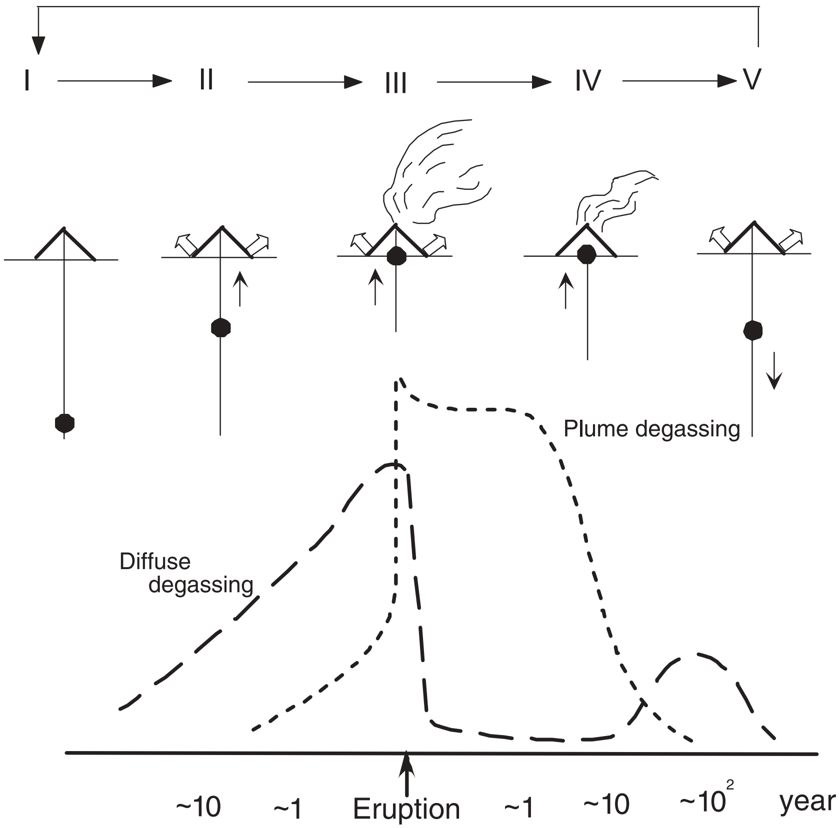

Figure 3
Schematic illustration showing an evolutionary model of gas release from volcanoes. Solid circle is magma rising and descending along the vent. Emission patterns of both diffuse and plume degassing are roughly illustrated as two broken lines. Time scale of horizontal axis is tentatively indicated in case the recurrence time of eruptions is $10^2 \sim 10^3$ years. The time scale generally differs considerable volcano by volcano, because the recurrence time of eruptions varies from several years to more than 10^3 years and the duration of each stage in a cycle varies case by case.

Mammoth Mountain (GERLACH *et al.*, 2001). On the other hand, it is not unusual to observe a very week efflux on volcanoes exhibiting intense plume activity from a central crater. In the case of White Island, New Zealand, plume CO_2 efflux was measured to be 2570–2650 ton/day, whereas diffuse CO_2 efflux was only 8.7 ton/day (WARDELL *et al.*, 2001). Similar contrasts have also been reported for the Nisyros volcano, Greece (BROMBACH *et al.*, 2001). The Popocatepetl volcano in Mexico provides an extreme example of negligible diffuse CO_2 emissions of magmatic origin throughout the extensive volcanic edifice (VARLEY and ARMIENTA, 2001) despite huge emissions of up to 390,000 ton/day of CO_2 from the summit crater (GOFF *et al.*, 2001).

Considering these observations on the two types of volcanic gas release, it is possible to propose a five-stage evolutionary model for the release of volcanic gas, as follows. Figure 3 shows the sketch of this model, demonstrating the evolutionary change in the correspondence between magma behavior and degassing pattern.

Stage I: When magma pools at a significant depth (e.g., > 10 km), neither plume degassing nor diffuse degassing of volcanic gas is typically observed.

Stage II: As magma rises into the subsurface, diffuse degassing through the permeable ground begins, and the efflux at the surface increases as the magma migrates upward. Such increases in efflux have been observed at Mt. Usu, Japan, prior to the 2000 eruption (HERNÁNDEZ *et al.*, 2001a). Another example of Stage II is observed at Mammoth Mountain, where very significant diffuse soil CO_2 degassing appeared after shallow intrusion of magma in 1989 (SOREY *et al.*, 1998; GERLACH *et al.*, 2001), although the magma intrusion has not lead to eruption in the following fifteen years or more. If magma comes into contact with the subsurface groundwater layer, new fumaroles will appear.

Stage III: When magma reaches the surface, volcanic eruptions occur associated with lava extrusion or violent explosions accompanied by an instantaneous release of a large amount of volcanic gas and ash as a plume. This causes a sudden drop in gas pressure within the volcanic body and results in a rapid decrease in diffuse degassing throughout the volcanic edifice. This was observed just after the 2000 Usu eruption (HERNÁNDEZ *et al.*, 2001a).

Stage IV: While new magma is being supplied to the surface, intense pluming continues and diffuse degassing remains negligible. Examples of this stage have been observed at Mt. Popocatepetl (VARLEY and ARMIENTA, 2001) and at White Island (WARDELL *et al.*, 2001).

Stage V: As magma begins to drain away from the surface, the efflux of plume degassing decreases. After degassing from the volcanic vent stops, if gases are still released from the descending magma at greater depth, diffuse degassing increases considerably due to an increase in the gas pressure of the volcanic body. Diffuse degassing from quiescent volcanoes such as that at Mt. Hakkoda (HERNÁNDEZ *et al.*, 2003) may represent post-eruptive degassing. This diffuse degassing will gradually recede as the volcanic system returns to Stage I.

According to this evolutionary model, Mt. Fuji can be considered to be in Stage I at the present time. Parasitic cones of Mt. Fuji are distributed in NW-SE direction following the direction of tectonic stress originating from the movement of the Philippine Sea plate (NAKAMURA *et al.*, 1984). The major eruptions in 864–865 and 1707 took place on this parasitic cone belt, and the highest $^3He/^4He$ ratios have been observed at the SE extent of this belt (OHNO *et al.*, personal communication). Based on CO_2 efflux measurements at Mt. Etna, GIAMMANCO *et al.* (1998) suggested that only zones of strain are capable of channeling deep gases to the surface. Prior to the 2000 Miyakejima eruption, soil CO_2 efflux was observed only in the summit area (HERNÁNDEZ *et al.*, 2001b), the site of a major collapse during the eruption (GESHI *et al.*, 2002). Since gas components seem to migrate, finding an easy passageway to the surface via faults, fractures, or other zones of weakness, soil CO_2 efflux can be expected to appear in the summit area or in the NW-SE lineation of Mt. Fuji when magma does begin to rise into the subsurface. However, it is a difficult proposition to predict exactly where the gas will reach the surface. At present, no indications of anomalous soil CO_2 efflux have been observed in either the summit region or the southwest region. However, continuous measurement of soil CO_2 efflux is considered a necessary aspect of any monitoring program to detect pre-eruptive activity at the Mt. Fuji volcano.

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