Open and almost shut case for explosive eruptions: Vent processes determined by SO_2 emission rates at Karymsky volcano, Kamchatka

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ABSTRACT

Vent processes were examined at Karymsky volcano, Kamchatka, by measuring SO_2 emissions using a correlation spectrometer (COSPEC). Continuous high-sensitivity COSPEC measurements and physical observations were collected on 11 and 12 September 1999, when Karymsky was producing small ashy eruptions every 5–20 min. Each eruptive event began with an explosion and audible rumbling (lasting ~30 s) followed in some cases by audible chugging (lasting to 2 min). Gas plumes accompanied each event, and almost without exception the plumes dissipated and became invisible despite significant SO_2 emissions. Variations in SO_2 output show distinctive patterns that correlate with eruption activity. Maximum SO_2 output occurred following each explosion and then declined rapidly to low, but detectable levels. In contrast, a second type of event, often associated with audible chugging, was characterized by high SO_2 output long after the initial ash blast. Variations in degassing at Karymsky can be explained by secondary boiling, gas-pressure accumulation, and vent resealing. We developed a new application of the COSPEC technique to study the dynamic vent processes of erupting volcanoes. This application provides insights into the processes that occur at the otherwise inaccessible vents of erupting volcanoes particularly when a volcano changes from passive degassing and small explosions to degassing patterns that may precede a larger and more dangerous eruption.

Keywords: SO_2 flux, volcanology, second boiling, vent sealing, eruptions.

INTRODUCTION

Volcanic plumes are indicators of subsurface magma conditions. During their ascent to Earth's surface, magmas exsolve volatiles because gas solubilities decrease with decreasing pressure (Holloway and Blank, 1994). This solubility relationship forms the basis of one method of volcano monitoring: remote SO_2 measurements by correlation spectrometer (COSPEC) are used to detect changes in volcanic plume compositions. Most previous studies of volcanic emissions have focused on long-term changes (days to years) to identify new magma input (Williams et al., 1986), degassing of a crystallizing magma body (Zapata et al., 1997), convection rates in a lava lake (Kyle et al., 1994), and to detect pressurization of a volcanic edifice (Fischer et al., 1994). Hourly and daily changes in emissions have been recognized to relate to Earth tides (Connor et al., 1988) and frequent explosive eruptions (Williams-Jones et al., 2001). The ''puffing'' of volcanic plumes has been studied at Pu'u 'O'o vent, Kilauea, with frequent SO_2 flux measurements (Chartier et al., 1988). Here we develop a new application of the COSPEC technique and show how volcanic plume measurements may be used to study dynamic vent processes during intermittent ash eruptions. The observed changes in SO_2 emissions occur on a scale of seconds to minutes. Our results suggest that short-term variations in volatile emissions are common at active volcanoes, especially during intermittent ash eruptions.

Since early 1996, Karymsky volcano has had small eruptions characterized by loud explosions, rumbling, intermittent ash plumes and, in some instances, audible chugging (Gordeev et al., 1997; Johnson et al., 1998). We demonstrate the use of closely spaced SO_2 flux measurements to investigate the dynamics of an active volcano and its degassing behavior. Continuous gas measurements that span the period before, during, and after eruptions reveal systematic degassing patterns that correlate with physical eruption characteristics.

NEW CYCLE OF ACTIVITY AT KARYMSKY

Karymsky volcano is the most active volcano of Kamchatka's eastern volcanic zone. It is a ~800 m stratovolcano constructed within a 5-km-wide caldera that formed during the Holocene. The formation of the Karymsky cone began ca. 5.5 ka, and the latest eruptive cycle began 500 yr ago following 2300 yr of quiescence. Most of Karymsky's cone is mantled by lava flows that are <200 yr old (Khrenov et al., 1982). In the 1970s, Karymsky's activity consisted of ash explosions with column heights of 1.5–6 km. Nuées ardentes occurred in 1970, and dacitic lava flows issued from the cone in 1970 and 1979 (Smithsonian Institution, 1970, 1975, 1976, 1979). A lava dome grew inside the crater in 1982 and was destroyed explosively in the same year (Ivanov et al., 1984). The most recent activity began on 2 January 1996, when mafic ash erupted from a new vent at the northern end of Karymsky Lake that occupies the Akademia-Nauk caldera, ~5 km south of Karymsky. Almost simultaneously, Karymsky erupted, and a new vent was formed. By 5 January, ash was ejected up to 5.5 km, and explosions occurred every 1–3 min. Over the first three days of the eruption, $\sim 2–3.5 \times 10^5$ m^3 of ash, lapilli, cinder, and bombs were ejected. During the next 2–3.5 months, $\sim 1.3–1.7 \times 10^3$ m^3 of andesite-dacite tephra ($SiO_2 = 61\%$) and some bombs were emitted (Smithsonian Institution, 1996a). By July 1996, Karymsky's activity was characterized by low-level eruptions. Gas and ash explosions occurred ~5–20 min apart with plumes reaching heights of 0.5–3.0 km. This eruptive activity continued through 1999 and was described as Strombolian (Smithsonian Institution, 1996b, 1999).

In September 1999, small discrete ashy eruptions were occurring from the new crater. The discrete explosions were separated by periods of quiescence ranging from ~5 to 20 min. After each explosion the volcano seemed inactive with no visible plume until the next event. Incandescent material (visible at night) was ejected with each blast, indicating that the eruptions involved juvenile magma. Although small recurring eruptions are associated with Strombolian activity (e.g., Stromboli; Fisher and Schmincke, 1984), the eruptions that we observed at Karymsky in September 1999 would more accurately be classified as small ash eruptions. In contrast to Strombolian eruptions, which typically involve fluid magma and produce material such as ovoid, fusiform bombs and scoria (i.e., cinders), the 1999 eruptions produced nonvesiculated material. The Karymsky ash particles are dense, blocky grains with rare small vesicles; the bombs are dense and

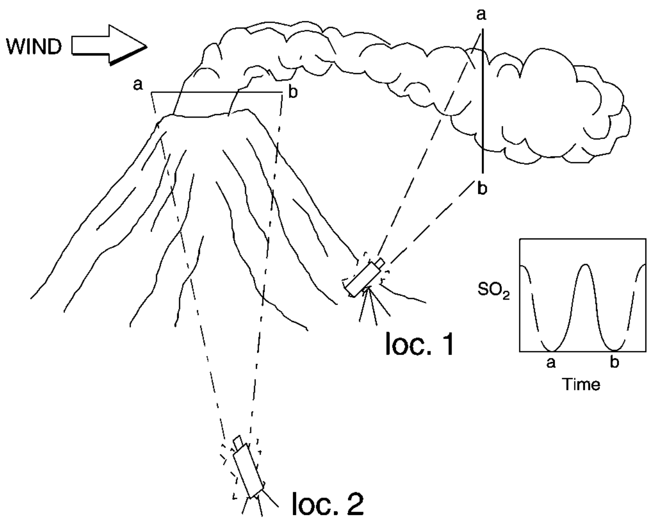

Figure 1. Schematic diagram of correlation spectrometer (COSPEC) technique. Two COSPECs were deployed at 0.6 (location [loc.] 1) and 3.8 km (location 2) from vent. At location 1, measurements were taken by vertically scanning through horizontally moving plume. Each scan (~5 s) produces one voltage peak on chart recorder. Values are zero at either side of plume (sky). Measurements were taken quasi-continuously over period of ~2–4.5 h, producing >1000 individual SO_2 flux values. At location 2, measurements were taken by horizontally scanning through vertically moving plume above crater rim.

angular. This implies that the magma is mostly crystallized and that gas is predominantly released by brittle fracturing.

All eruptions were initiated with an audible ash blast. Frequently the initial blast was followed, within 30 s, by an audible jet or roar resulting in a visible white gas plume. Occasionally, the jet would last as long as 20 s. Small puffs of gas, without ash, occurred minutes after the blasts. The visible ash and gas plume accompanying each blast rose ~200–300 m vertically above the crater.

MEASUREMENT OF SO_2 IN KARYMSKY'S PLUME

The SO_2 emissions were monitored with two stationary COSPECs installed on the southern side of the volcano ~0.6 km (location 1) and 3.8 km (location 2) from the vent. The COSPEC at location 1 vertically scanned through the plume at 5 s intervals, and the voltage output was recorded on a strip chart (Figs. 1 and 2). Frequent calibrations of the instrument were performed by using internal calibration cells. The SO_2 burden in the plume was determined from the average peak height (Stoiber et al., 1983), which is 0.43 × (maximum peak height) for our measurements. The regularity of the peak shapes (Fig. 2) and checks against manually measured average peak heights indicate that the method had an error in precision of ±10%.

The COSPEC, at 3.8 km, made horizontal scans through the plume directly above the crater rim at ~10 s intervals (Fig. 1). A mechanical scanner was used, and data were recorded and reduced on a laptop computer (Kyle et al., 1994). Conditions permitted data collection on 8, 11, and 12 September, and measurements were made continuously in sessions lasting to 4 h.

A key variable in determining volcanic flux is the accurate characterization of plume motion or wind speed. The difficulty of measuring wind speeds near the vent of a volcano can introduce errors of 10%–30% (Stoiber et al., 1983). We used video recordings taken at 3.8 km distance to determine wind speed (location 1) and plume rise rate (location 2). Additional wind-speed measurements were made at ground level by anemometer. Overlapping data records from the two COSPECs are most complete for 12 September, when wind speed was 5.4 m/s and relatively constant throughout the measurement period (11.63–13.73 decimal hours, local time). The vertical-rise rate of the plume was more variable (3.3–13.4 m/s) and averaged ~5 m/s. Video recordings were also used to accurately time the occurrence of eruptions (Fig. 3) and to characterize the changing summit activity.

SO_2 VARIATIONS IN KARYMSKY'S PLUME

Measurements taken on 12 September 1999 show the most complete record of the degassing behavior of Karymsky (Fig. 3). Less continuous COSPEC observations were made on other days and showed similar results. Correspondence of the data from the two COSPECs is remarkable and indicates that both were recording the same degassing events despite the different scanning modes and distances from the vent. The SO_2 flux measured by the COSPEC in location 2 (267 measurements from 11.83–12.79 h) ranged from near detection limits to 141 Mg/day (d). The measurements of location 1 show that the SO_2 flux never declines to zero emission but remains at or above 50 g/s (>~4 Mg/d) at all times. Each initial peak in SO_2 follows an audible ash blast, and for comparison, we define an event as the degassing period between two blasts (Fig. 3).

Two distinct types of degassing events are observed: short events with a gas pulse that rapidly decays to background (type I events) and long events characterized by waxing and waning, yet overall high (above background) SO_2 levels (type II events) (Figs. 2 and 3). All

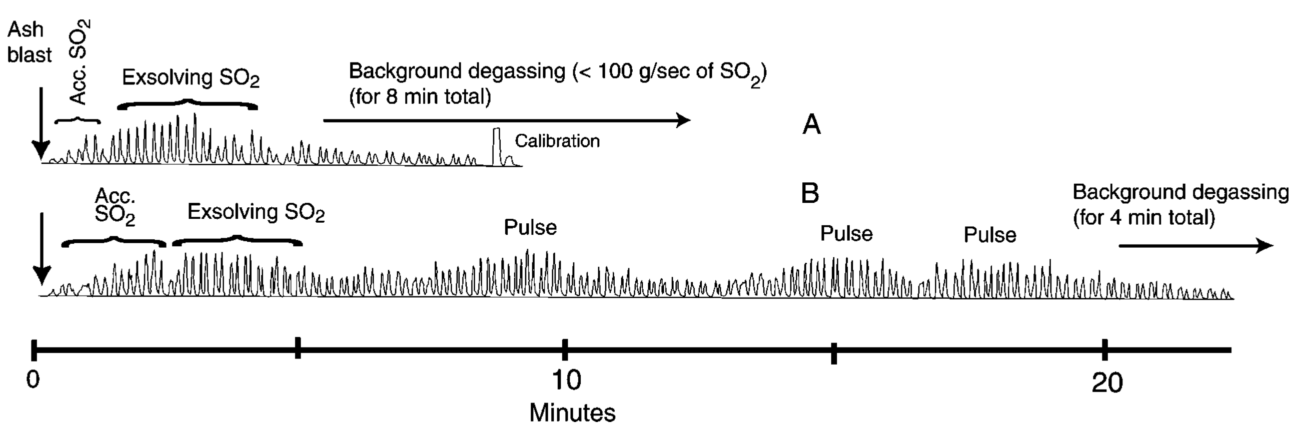

Figure 2. Comparison of type I and type II events. These are actual chart records showing correlation spectrometer SO_2 flux measurements. Each peak is voltage signal and represents one vertical scan through plume. A: Record of type I event—short duration and sharp decline to background (passive degassing). B: Record of type II event—longer duration and waxing and waning of gas emissions (pulse). For both events, initial surge in SO_2 (accumulated [acc.] SO_2) is followed by short decline before reaching maximum flux.

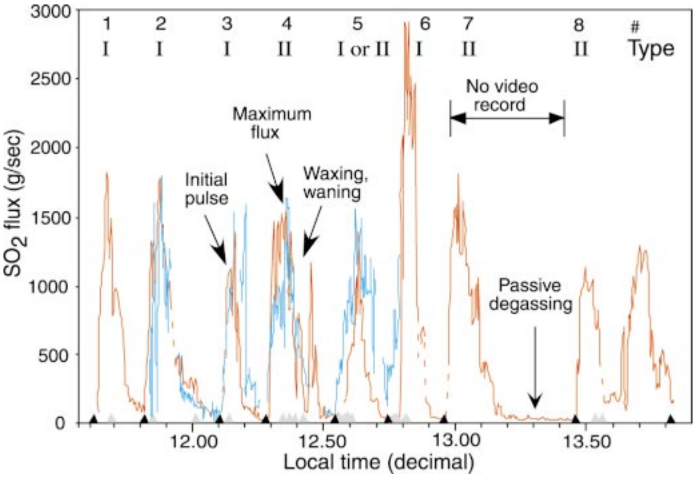

Figure 3. SO_2 fluxes measured during 12 September 1999 campaign. Type I and type II events are shown. Black triangles represent ash blasts. Red trace is record of correlation spectrometer (COSPEC) at 0.6 km distance (see Fig. 1). Blue trace is from COSPEC at 3.8 km. Gray triangles represent occurrences of white gas plumes. All times were determined by using global positioning system clock.

TABLE 1. COMPARISON OF ERUPTIONS AT KARYMSKY

	Type I	Type II
Physical Characteristics		
Frequency of occurrence	5–20 min	~1 h
Duration	5–20 min	10–20 min
Audible chugging*	Never	Common
Number of cycles†	N.A.	3 average; range 2–4
Length of each cycle (min)	N.A.	3 average; range 2–6
SO_2 Output		
Maximum flux rate§	250 t/d	250t/d
Average time to reach max (sec)	145 (range: 110–180)	180 (range: 150–240)
Average total SO_2 per event (kg)	1050	1525
Average passive SO_2 (% of total)#	7%	3%

Note: Based on 41 measured events on 8, 11, and 12 September 1999.

*The term ''chugging'' was used for Karymsky by Johnson et al. (1998), following the terminology of Benoit and McNutt (1997).

†One cycle includes an increase and decrease in SO_2 concentration (i.e., wax and wane; see Fig. 2).

§Maximum flux rates varied over the span of 4 d but on any given day were similar for both event types.

#Calculated by subtracting amount of SO_2 degassing passively after an eruption from total amount of SO_2 released during event (see also Fig. 3).

events (type I and II) start with a first peak in SO_2, followed by a sharp decline before reaching the maximum flux of the event (Figs. 2 and 3). The type I events comprise ~65% of the eruptions that occurred during our measurements, and no pattern in the sequence of type I and type II events has been recognized.

All events (type I and II) begin with a peak in SO_2, but only the type II events were accompanied by audible chugging as defined by Benoit and McNutt (1997). Typically the chugging would begin shortly after the initial blast and then abruptly stop seconds later (~10–30 s). In addition to chugging, there were other significant differences between type I and type II events (Table 1). Most notable was the waxing and waning gas flux of type II events (see Fig. 2B). In contrast to type I events, the type II events would continue to outgas at high levels long after the initial blast. At times the flux rates during these waxing and waning cycles would equal the highest observed flux rates. The waxing and waning of SO_2 flux was accompanied by visible gas puffs that contained no ash.

DISCUSSION

Short-term (seconds to minutes) fluctuations of SO_2 from Karymsky's plume provide information on conditions in the conduit and at the summit vent. We interpret the patterns of gas emission as being primarily controlled by second boiling (Burnham, 1979, 1985), vent sealing, and gas overpressure buildup. Second boiling accompanying magma crystallization releases gas initially by exsolution of volatiles from the melt into vapor bubbles (Burnham, 1985). Subsequently the remaining volatiles are exsolved during magma decompression. Both processes are efficient in providing explosive energy that may be released in a matter of seconds (Burnham, 1983). The short-term fluctuations in SO_2 flux observed at Karymsky illustrate the processes of degassing occurring during second boiling and decompression with some important differences that are the result of the highly viscous nature of the magma.

The initial surge in SO_2 immediately following each blast is interpreted to represent the release of gas that has exsolved from the melt due to continuous crystallization and has accumulated below a sealing viscous plug in the conduit. Accumulated gas pressure, once the strength of the viscous magma plug and overlying rock has been exceeded, opens the conduit by brittle fracture. The resulting blast ejects fine-grained dense ash and is associated with a peak in SO_2 flux that is followed within 2–3 min by a short and sharp decline (seconds) that possibly represents a transition in the process of gas release. The subsequent maximum SO_2 flux results from the delayed (seconds) exsolution of (1) the remaining volatiles from the top of the melt column and (2) additional volatiles from deeper levels in the conduit that provide proportionally more gas than had previously accumulated below the plug (accumulated and exsolving SO_2 in Fig. 2). The maximum SO_2 flux is sustained for several minutes without ash emission, but produces a white pulse of gas. This indicates that the conduit is open, and volatiles released from deeper levels efficiently stream though the open vent. The SO_2 flux always decreases to background levels prior to the next event. This discovery indicates that vent sealing and gas accumulation are required for the next blast to occur.

Prior to the next blast, exsolving volatiles accumulate below the sealing plug that now consists of previously degassed magma and blocks that have fallen back into the vent after the blast. Continuous, low-level gas emissions before each blast indicate that the plug is always leaky and that the magma below continuously degasses. Once the gas pressure exceeds the strength of the plug, another event occurs, destroying the plug.

During type I events, the SO_2 emission quickly declines after the maximum flux, suggesting that the top of the magma column becomes rapidly depleted in volatiles and the plug efficiently reestablishes itself. Type II events show a different degassing behavior in which SO_2 fluxes wax and wane but remain at high levels. The lack of ash emission during these pulses suggests that gas is efficiently exsolving from the magma and streaming through the vent. The degassing magma becomes increasingly viscous and inhibits gas release as the event continues. Waning of gas emissions represents short-term reduction of gas release from the increasingly viscous and degassed magma accompanied by a partial sealing of the conduit. The gas flux does not decline to the level of passive degassing, which suggests that volatile exsolution from somewhat deeper levels is efficient enough to counter the decrease in permeability of the degassed magma. The viscous plug is repeatedly forced open, resulting in a surge of accumulated gas as represented by a pulse during type II events (Fig. 2). Volatile exsolution continues until the magma column is depleted in volatiles, and the viscous magma plug is reestablished. The total amount of gas released during type II events exceeds that released during type I events, suggesting that a significant amount of gas is released from deeper levels in the conduit.

Johnson et al. (1998) and Johnson and Lees (2000) used seismic and acoustic signals to study frequent ash eruptions at Karymsky. They were able to distinguish three types of events: a ''single impulse'' event and two high-frequency, harmonic events. The harmonic events are associated with chugging. Our measurements and observations show that the events can be recognized on the basis of gas-emission patterns. The maximum gas-release rate is similar for all events, suggesting that they initially tap the same source in the magma. The total amount of released gas and the duration of the gas release are different and are functions of vent resealing after the explosion. During type II events, the vent remains open owing to continuous gas release from deeper in the conduit. Partial sealing of the vent is countered by gas release from depth and is associated with the audible chugging and visible gas pulses.

Pressure accumulation in volcanic conduits has been explained at other volcanoes by decrease in magma permeability due to foam collapse (Westrich and Eichelberger, 1994), precipitation of hydrothermal minerals in pores and fractures, closure of fractures due to subsidence of the crater floor (Mathews et al., 1997), and microlite growth (Sparks, 1997). Our observations indicate that the time scale of pressure accumulation, breaking of a sealing viscous magma plug, and reestablishment of the plug can be very short (minutes) during this kind of explosive activity.

CONCLUSIONS

Measurement of SO_2 emissions by COSPEC is very useful for investigating vent processes at active volcanoes. Continuous SO_2 measurements at Karymsky volcano reveal that (1) most degassing occurs in the absence of a visible ash plume and (2) there is significant short-term variability in the SO_2 flux. The SO_2 output is nonrandom and forms two distinct degassing patterns. Type I events show a rapid decline in SO_2 flux, whereas type II events wax and wane at relatively high SO_2 levels. During both events, a surge in SO_2 is observed with the initial eruption. The patterns of degassing at Karymsky can be explained by gas release from the magma due to second boiling, pressure accumulation in the magma below a viscous plug in the conduit, and the subsequent efficient streaming of volatiles exsolving from the melt. Continuous measurement of short-term gas fluctuations offers a means of studying the otherwise inaccessible and dynamic vent area of active volcanoes. This approach could be applied to the numerous volcanoes that commonly exhibit low-level degassing or continuous small-scale explosive activity (e.g., Yasur, Vanuatu; Semeru, Indonesia; and Arenal, Costa Rica). An improved understanding of low-level degassing activity might eventually help identify the processes that occur when volcanoes change from low-level activity to dangerous eruptions.

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