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Plugs and chugs—seismic and acoustic observations of degassing explosions at Karymsky, Russia and Sangay, Ecuador

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Abstract

Frequent degassing explosions, occurring at intervals of minutes to tens of minutes, are common at many active basaltic and andesitic volcanoes worldwide. In August 1997, April 1998, and September 1998 we recorded seismic and acoustic signals generated at two andesitic volcanoes with ‘Strombolian-type’ activity. Despite variations in explosion frequency (5–15 h^{-1} at Karymsky as opposed to 1–3 h^{-1} at Sangay), the signatures of the explosions are remarkably similar at these two, diverse field sites. In all explosions, gas emission begins rapidly and is correlated with an impulsive acoustic pressure pulse. Seismic waveforms are emergent and begin 1–2 s before the explosion. We classify explosion events at the two volcanoes as either short-duration (less than 1 min) simple impulses or long-duration (up to 5 min) tremor events. Many tremor events have harmonic frequency spectra and correspond to regular 1 s acoustic pulses, often audible, that sound like chugging from a locomotive. Chugging events are intermittent, suggesting that the geometry or geochemistry of the process is variable over short time scales. We attribute the 1 Hz periodic chugs to a resonant phenomenon in the upper section of the conduit. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: degassing explosions; Strombolian-type activity; seismo-acoustic signals

1. Introduction

The broad spectrum of volcanic behaviors worldwide can be attributed to variable magma chemistries, which govern the volatile contents and viscosities of magmas. Because time scales and explosivities range over many orders of magnitudes at different volcanoes, it is likely that mechanisms for volcanic degassing are highly variable. We focus on activity at andesitic volcanic centers with Strombolian-type activity because this type of activity is interesting, common, and poorly understood (Simkin, 1994; Sparks, 1997). Because degassing events are frequent and relatively small (VEI 2), this type of volcano offers ideal opportunities for seismic field analysis. In this paper we present data and observations from three field experiments at two volcanoes, Karymsky and Sangay, and introduce physical models to explain the phenomena. Karymsky and Sangay both possess middle-of-the-spectrum volcanic characteristics including: eruptive time scale (many discrete explosions each day), magma viscosity (10^3–10^5 Pa s), volatile content (3–5 weight percent at depth), and mass flux through vent (less than 10^3 kg/s) (Simkin, 1994; Sparks, 1997).

In 1997 and 1998, we conducted similar seismo-acoustic experiments at two different andesitic

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volcanoes with Strombolian-type activity: Karymksy Volcano in Kamchatka, Russia and Sangay Volcano in the Northern Andes, Ecuador. Prior to our field efforts, neither of these volcanoes had been the focus of detailed seismo-acoustic studies. At both volcanoes, activity was characterized by summit vent explosions, which occurred several times each hour, releasing gas and ejecting small amounts of ash and ballistics. Such explosions are typical of activity at the two volcanoes during historic times (Hall, 1977; Ivanov et al., 1991).

Degassing at Karymsky and Sangay is similar in many ways to degassing at other volcanoes, such as Arenal in Costa Rica (Benoit and McNutt, 1997), Langila in Papua New Guinea (Mori et al., 1989), and Semeru in Indonesia (Schlindwein et al., 1995). At these sites, discrete explosive events, audible ‘chugs’, intermittent lava flows, and an andesitic or basaltic–andesitic magma composition have been documented. We consider the regular explosions at volcanoes such as Stromboli, Kilauea, Villarica, and Erebus to be less analogous because they possess generally lower magma viscosities. Though regular, frequent explosions also characterize activity at these centers, the observations of large gas bubbles rising and bursting at the surface of lava lakes indicates unobstructed degassing without a significant magmatic flux (Sparks et al., 1997; Global Volcanism Program, 1999).

2. Background

Karymsky Volcano, located in the central portion of Kamchatka’s main active arc, began erupting in January 1996 after 14 years of quiescence (Gordeev et al., 1997). Though vigorous Vulcanian activity marked the eruption onset, activity quickly declined to discrete explosive events. In the summer of 1996, about 12 explosions occurred each hour, while only 5 per hour occurred in the summer of 1997. A block lava flow, which was energetic in 1996, was barely moving in 1997. In 1998, the lava flow remobilized and explosions were again more frequent. Though the ratio of ejected magma to gas is variable, each explosion appears to contain a ballistic or ash component, indicating that degassing may not be possible without a magmatic flux. Karymksy is a young (4 ka), symmetrical 800-meter-high cone which rises above the floor of an older caldera (Ivanov et al., 1991). A single summit vent is the source of both the lava flows and explosive degassing. Typical composition of recent Karymsky lava flows is 62.20 weight percent silica (Ivanov et al., 1991).

Sangay Volcano, located in Ecuador’s eastern volcanic cordillera, has been continuously active since 1628 (Hall, 1977). However, due to its remote position, fluctuations in eruptive vigor may go largely unnoticed. During the spring of 1998, volcanic activity was at a relative ebb, with explosive gas releases occurring only twice an hour. According to local observers, typical activity is manifested by more powerful explosions, including significant incandescant ejecta and extrusion of lava. During 1998, volcanic bombs and some summit incandescence indicated a continued, though slight, flux of magmatic material through the vent. Although the composition of Sangay lavas are widely variable, they commonly lie between 55 and 57 wt% silica (Monzier et al., 1999). The 1800-meter-high Sangay edifice is a 14 ka accumulation of lava flows, debris flows, and pyroclastic flows, atop remnants of older, collapsed volcanic structures (Monzier et al., 1999). At present, four craters are aligned along a 700 m summit ridge. During the 1998 field work, fumaroles were active in all craters, but a single central crater was the source for all explosions.

In all experiments at Karymsky and Sangay, we recorded the regular explosions with Guralp CMG-40T broadband seismometers as well as bandpassed (2 s to 30 Hz) electret condenser microphones. At both volcanoes, microphones and seismometers were deployed within 1.5 km of the active vent. At each volcano, digital recording was continuous for at least 100 h. Seismic signal-to-noise is excellent, while acoustic quality is variable and dependent upon low wind conditions. At both volcanoes, we were able to record at least 24 h of high signal-to-noise acoustic explosion signals.

3. Data overview

We conducted field work at Karymsky during August 1997 (Johnson et al., 1998), and September 1998. In 1997, we deployed three 3-component broad-

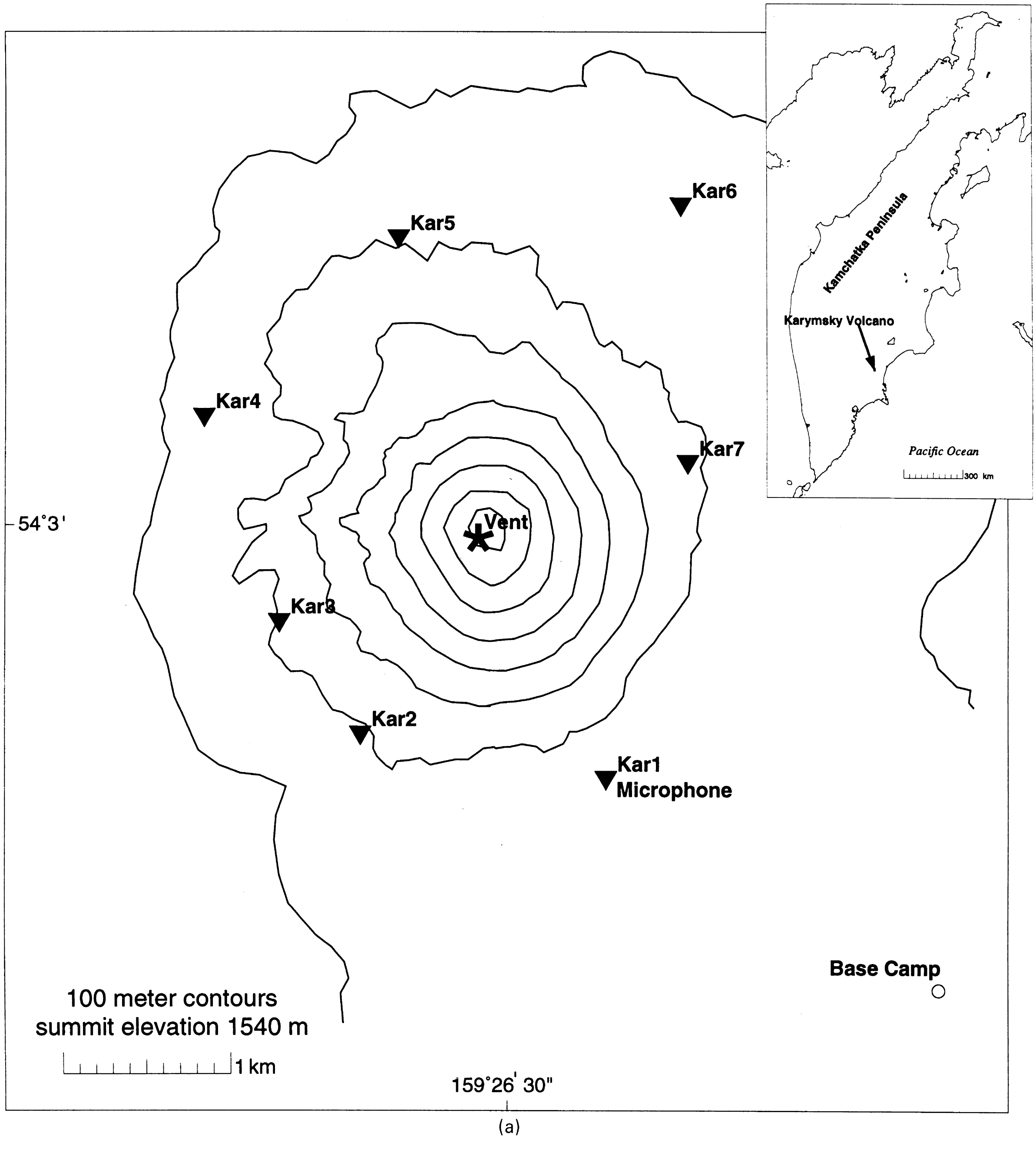
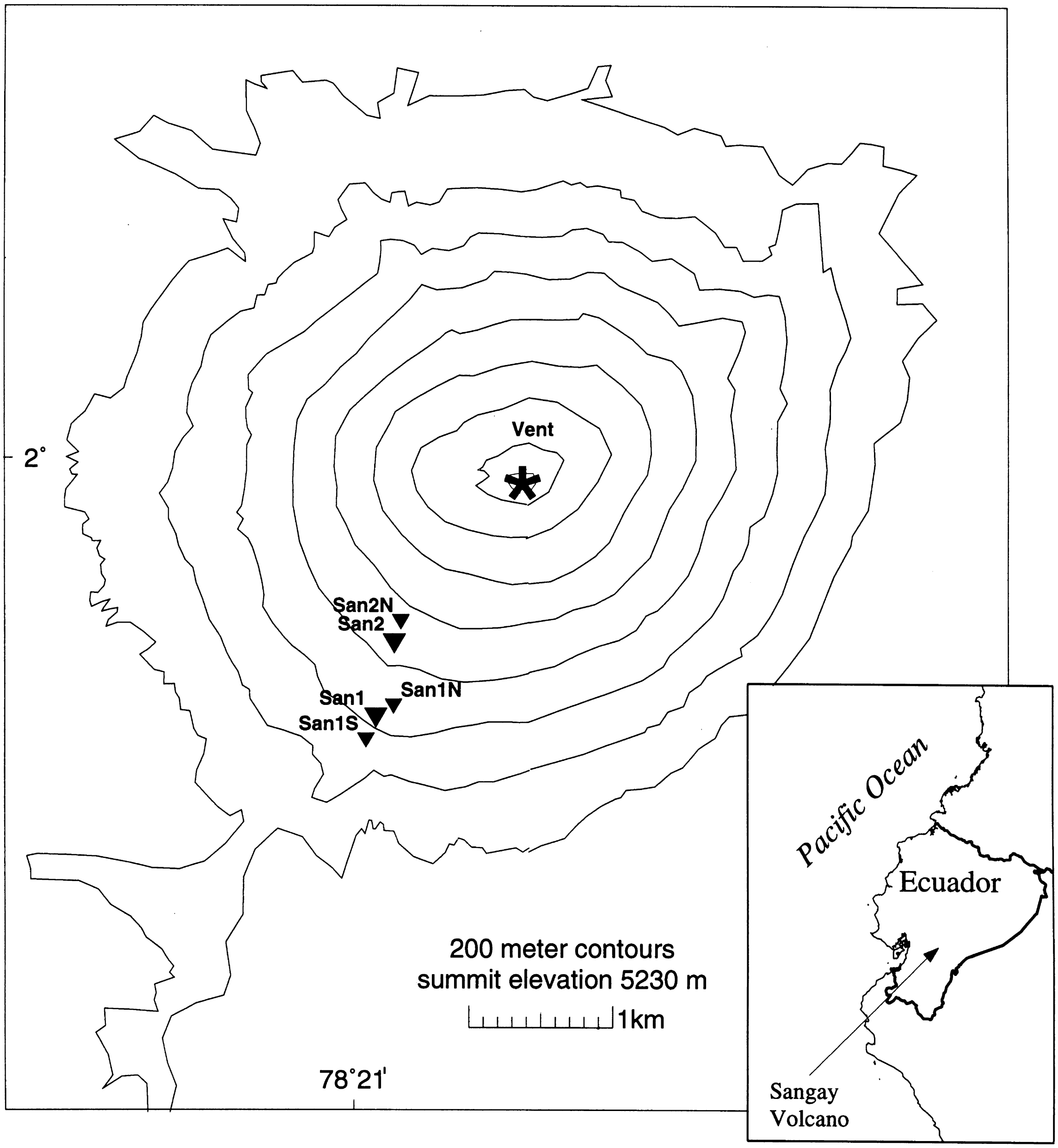


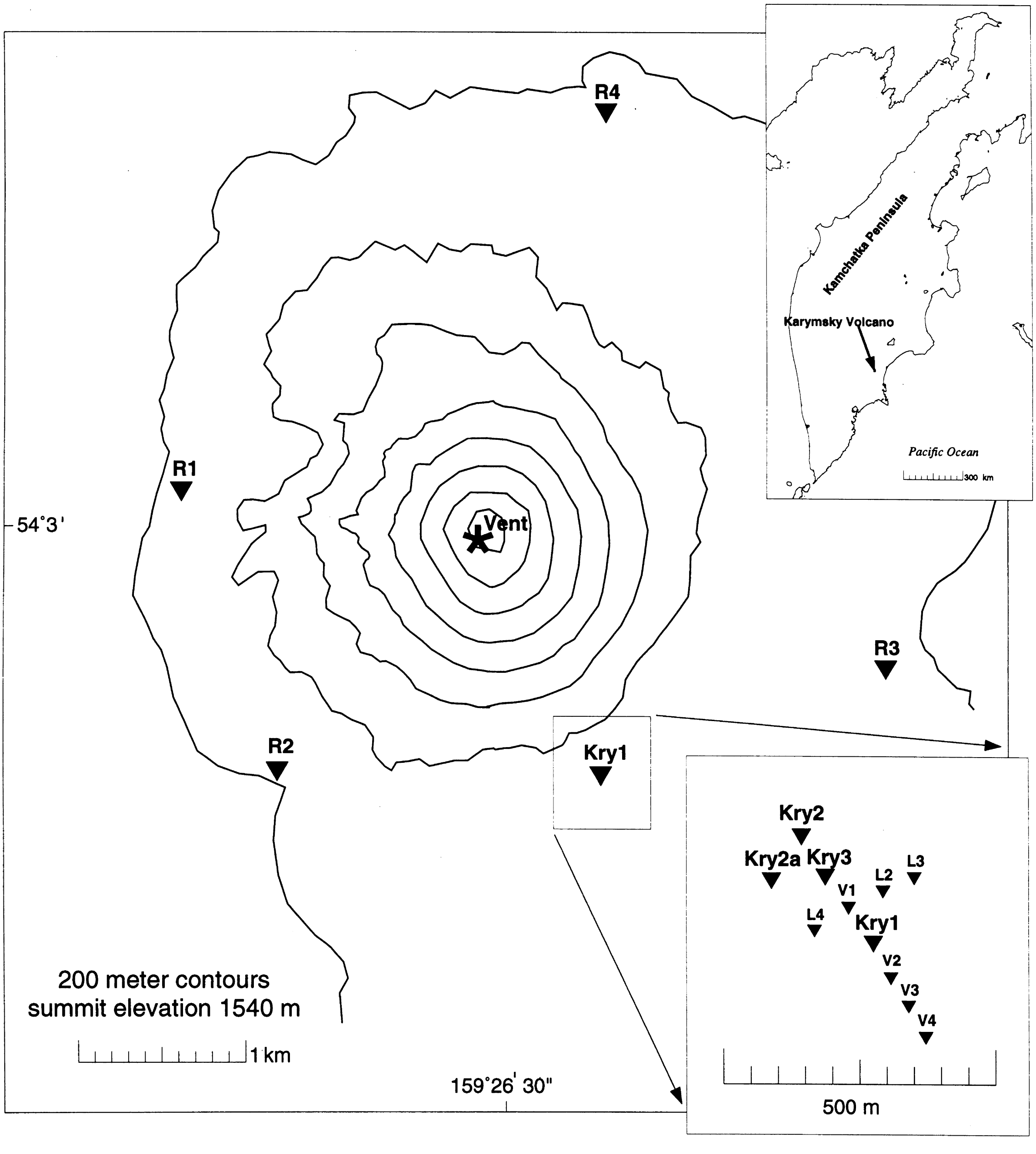
Fig. 1. (a) Map of Karymksy station installations, 1997. Station KAR1 operated for 9 days and contained a broadband seismometer and low-frequency microphone. Stations Kar2 through Kar7 contained broadband seismometers and recorded for two days each. Inset map shows location of Karymsky Volcano within the Kamchatka Peninsula. (b) Map of Sangay and station installations in 1998. Stations San1 and San2 (large triangles) contained broadband seismometers and low-frequency microphones. Small triangles indicate locations of single-component short period sensors. Inset map shows location of Sangay within South America. (c) Map of Karymsky and station installations in 1998. Station Kry1 operated for 6 days and was the site of the Larsen–Davis precision infrasonic pressure sensor. Stations Kry2, Kry2a, and Kry3 each contained broadband seismometers and low-frequency microphones. StationsR1, R2, R3, R4, L2, L3, L4, V1, V2, V3 and V4 operated in one-day or two-day long campaigns and consisted of short-period instruments and low-frequency microphones.



(b)

Fig. 1. (*continued*)

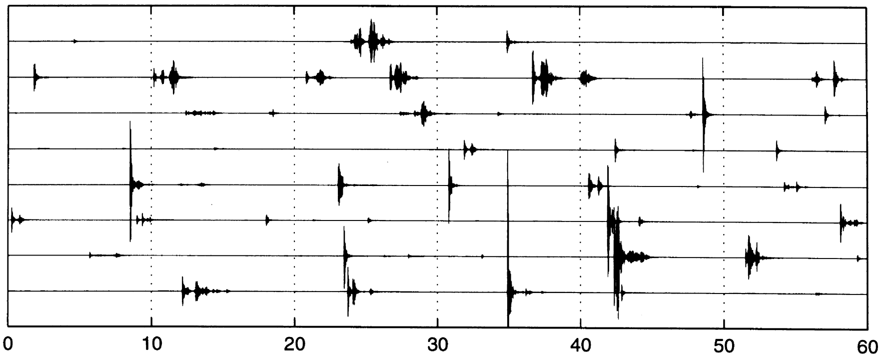
band seismometers on the flanks of the cone (Fig. 1a). Station Kar1, located 600 m below and 1500 m south of the vent, consisted of a seismometer and a low-frequency acoustic microphone. Two other broadband stations were moved about the volcano every two days in order to record seismic energy propagating through various sections of the cone. In 9 days, we recorded about 1000 explosions, and more



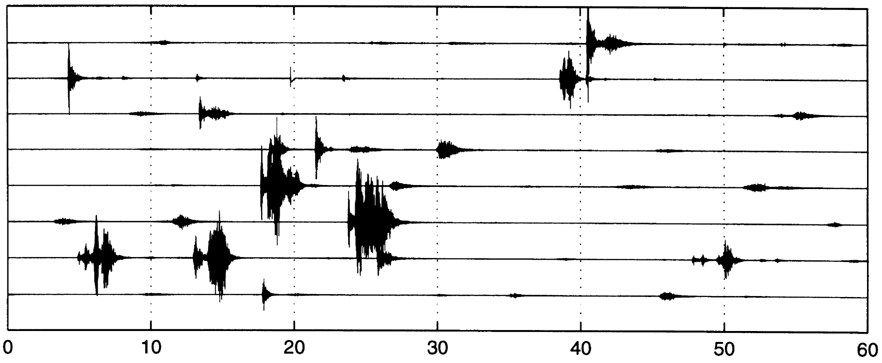
(c)

Fig. 1. (*continued*)

a) Karymsky Eight Hour Seismogram (1997:233:15:00 to 1998:233:23:00)



b) Sangay Eight Hour Seismogram (1998:115:17:00 to 1998:116:01:00)



c) Karymsky Eight Hour Seismogram (1998:249:08:00 to 1998:249:16:00)

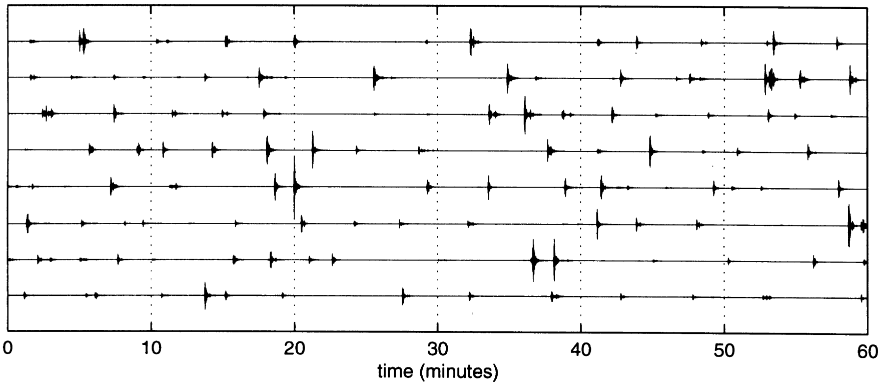


Fig. 2. (a) Vertical 8-hour velocity seismogram for station Kar1 at Karymksy (21 August 1997). (b) Vertical 8-hour velocity seismogram for station San1 at Sangay (25–26 April 1998). (c) Vertical 8-hour velocity seismogram for station Kry1 at Karymsky (6 September 1998).

than 100 high-quality acoustic signals. In 1998, we returned to Karymsky with three broadband instruments, four short period instruments, seven low-frequency microphones, and one Larsen–Davis free field precision microphone. Station Kry1 reoccupied the site of Kar1 and was active for the duration of the experiment. Six other seismo-acoustic stations were deployed in variable geometries in day-long

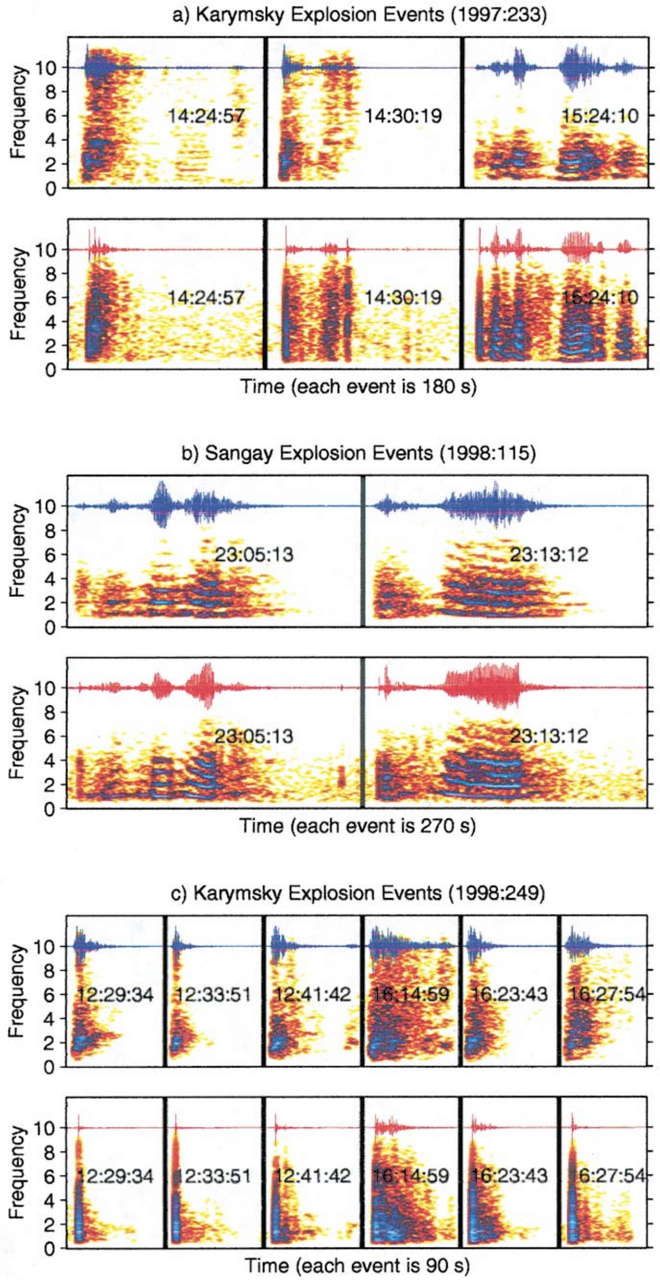


Fig. 3. Spectrograms of seismic and acoustic traces for typical events at: (a) Karymsky in 1997 (recorded at Kar1); (b) Sangay in 1998 (recorded at San1); and (c) Karymsky in 1998 (recorded at Kry1). Harmonic tremor is evident in both seismic and acoustic channels. It is present in some events from Karymsky 97, common in the Sangay 98 record, and absent at Karymsky in 98.

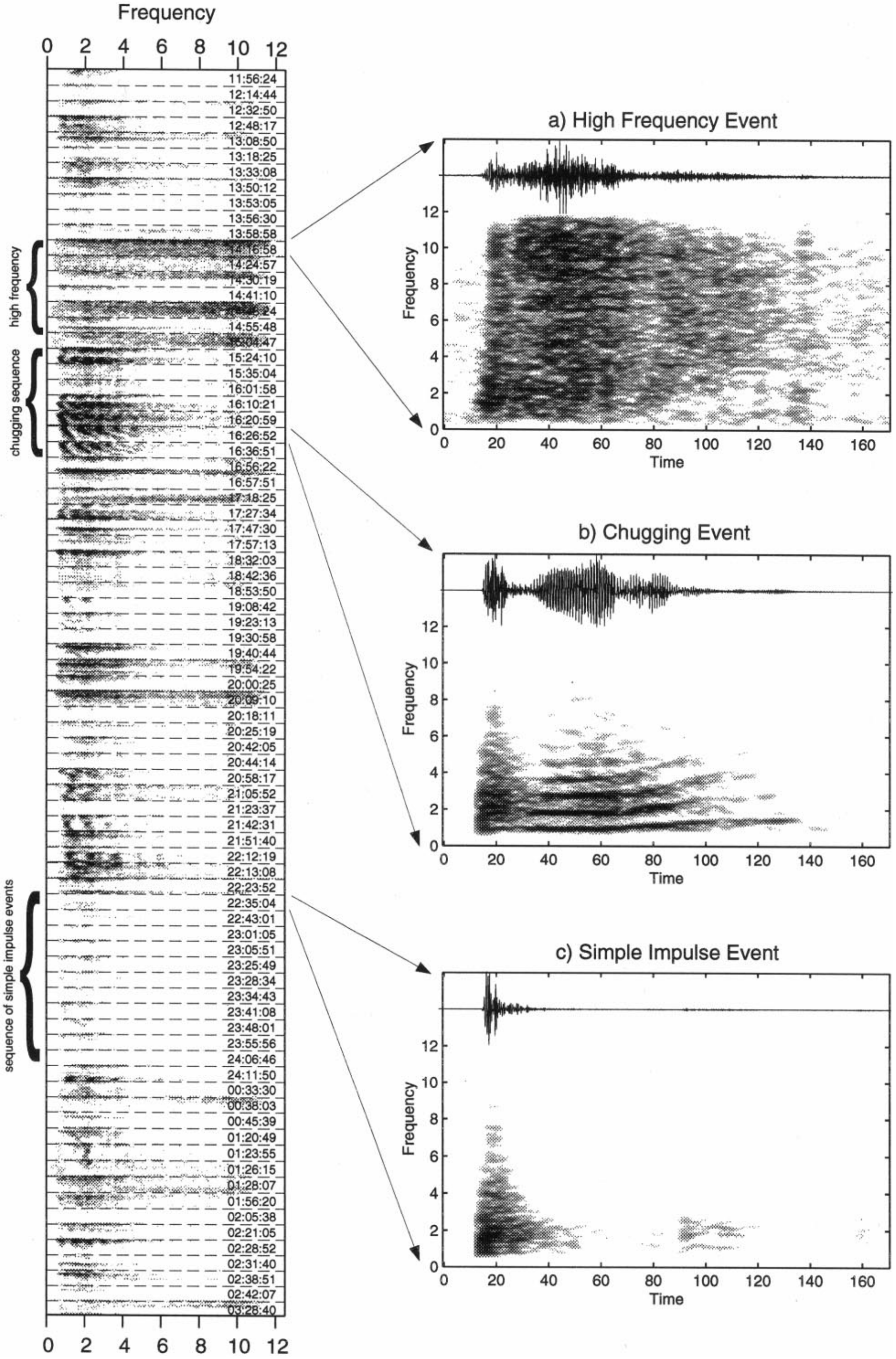


Fig. 4. Seismic traces and spectrograms for three characteristic event types at Karymsky in 1997: (a) high-frequency event; (b) chugging (harmonic tremor) event; (c) simple impulse event. The spectral evolution plot to the left demonstrates how specific event types tend to cluster in time for the Karymsky 97 record. Spectrograms were calculated for 80 consecutive events and used time windows 30–90 s after the explosion onset.

campaigns (Fig. 1c). Due to elevated eruptive vigor, we recorded about 2000 explosions and 1000 high-quality acoustic signals in 6 days.

We conducted field work at Sangay during April 1998. Two stations (San1 and San2), containing broadband seismometers and low-frequency microphones, were situated on the southern flank of the volcano, 1200 and 1600 m from the vent (Fig. 1c). In addition, three short period vertical Mark Products L22 sensors were deployed linearly at 300 m intervals. In total, we recorded about 300 explosions, more than 50 of them associated with high-quality acoustic records.

During our field work at Karymsky and Sangay, eruptive activity consisted of distinct, frequent explosions with largely aseismic recharge intervals. The lack of background tremor contrasts with observations at many other volcanoes with Strombolian-type activity (McNutt, 1986; Hagerty et al., 1997; Dawson et al., 1998). Our seismic records also show no evidence of very long period seismicity associated with mass transfer (Neuberg et al., 1994; Chouet and Dawson, 1997).

Seismograms (Fig. 2a–c) and acoustograms reveal significant similarities and some differences in eruptive behavior among the three datasets. Virtually every discrete seismic event can be associated with an acoustic counterpart (Fig. 3a–c), indicating

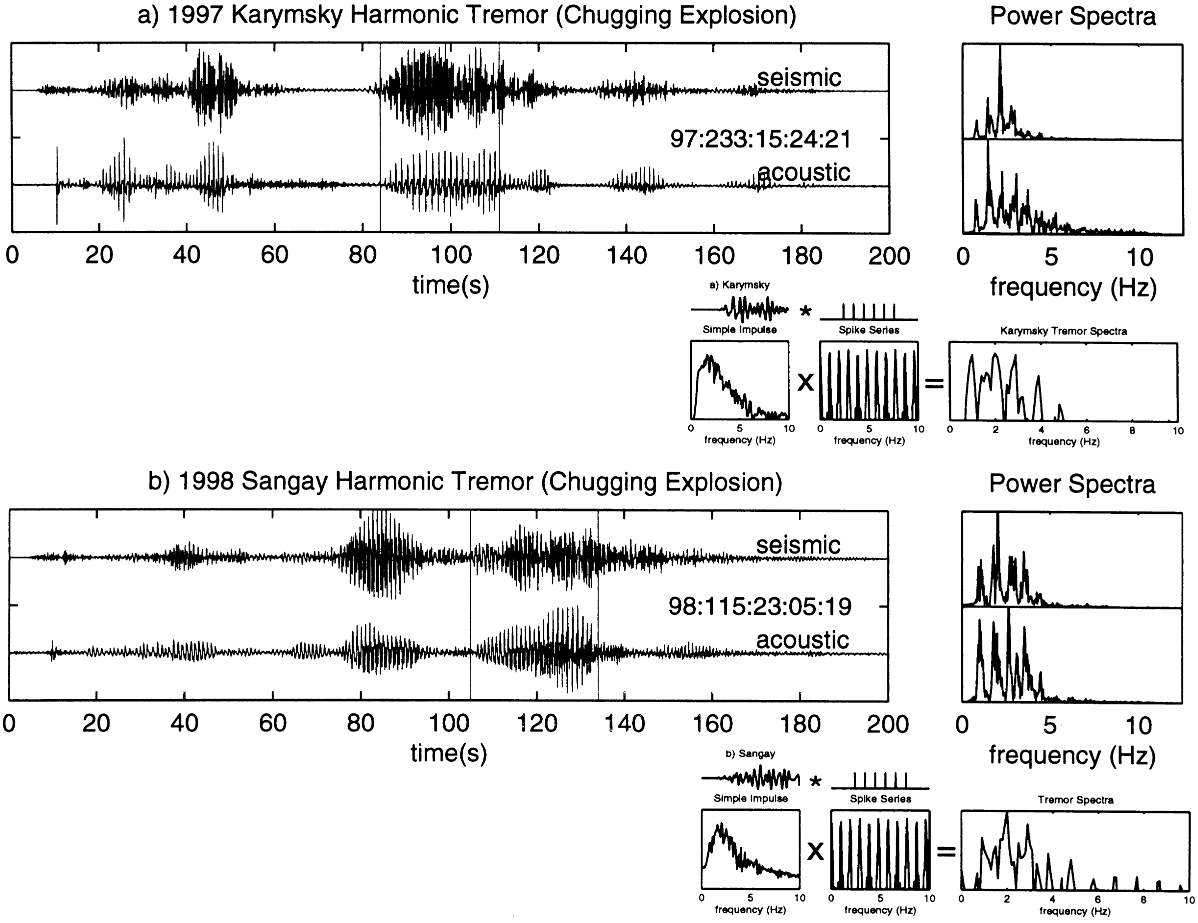


Fig. 5. Similarity of chugging (harmonic tremor) events at: (a) Karymsky in 1997 (recorded at Kar1); and (b) Sangay in 1998 (recorded at San1). Acoustic harmonic tremor is manifested as a regular series of impulsive gas bursts. The presence of more integer overtones in the Sangay harmonic tremor can be explained by a higher corner frequency for composite simple impulse events.

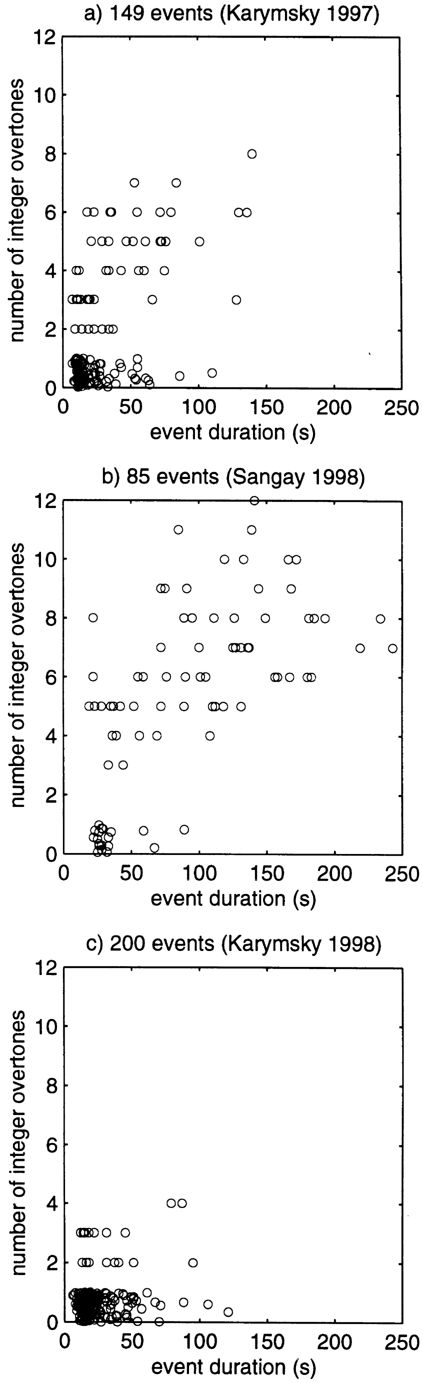


Fig. 6. Qualitative event classifications for: (a) Karymsky 97; (b) Sangay 98; and (c) Karymsky 98. The quantity of integer overtones was assessed through visual inspection.

explosive degassing at the primary vent. Both volcanoes possess a variety of explosion types including short-duration seismic wavelets (simple impulses) which taper to background in less than 1 min, and longer-duration ground motions (tremor) which last as long as 5 min.

4. Analysis

At Karymsky and Sangay, we define distinct explosion events as short-term seismic energy (10 s mean squared velocity) which is greater than the daily mean energy and separated from a previous event by at least 30 s. According to these criteria, we document 149 explosions in 27 h at Karymsky in 1997 (5.5 per hour, average event length 31 s), 85 explosions in 49 h at Sangay in 1998 (1.7 per hour, average event length 91 s), and 200 events in 15 h at Karymsky in 1998 (13 per hour, average event length 25 s). Explosion frequency was greatest at Karymsky in 1998, least at Sangay in 1998, and appears to be inversely proportional to the length of the degassing events. We attribute heightened explosion frequency and shortened event duration (most pronounced in the Karymsky 1998 dataset) to heightened magma and gas flux (see Section 5).

The spectral and temporal character of explosion signals reveals several broad categories of event types at Karymsky and Sangay. We refer to the first category (Fig. 4c) as a simple impulse, or short-duration explosion, because of the absence of sustained ground motion. This event type represents the shortest possible seismic signal associated with visible degassing at the vent. The associated acoustic signal consists primarily of a short, simple 2.5 Hz impulsive pressure pulse. The second category is comprised of extended degassing events. These events begin as simple impulse events, with an accompanying impulsive acoustic pulse, but ground motions and acoustic signals are longlasting. Many of the extended degassing events contain well-defined integer overtones (Figs. 4b, 5a and b). We refer to these harmonic tremor signals as ‘chugging events’ because the tremor is accompanied by audible exhalations which sound like a locomotive. Another type of extended degassing signal contains significant energy above 6 Hz (Fig. 4a). Visual observations indicate that this

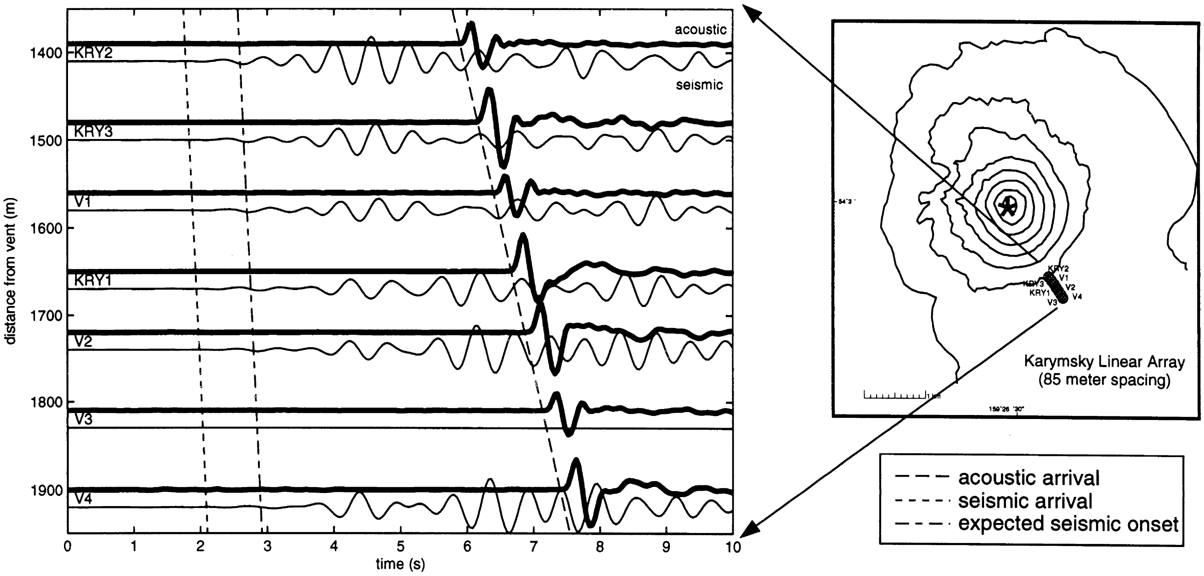


Fig. 7. A selected Karymsky 98 explosion recorded by a tight (85 m spacing) linear array. The seismic channel has been bandpassed between 2 s and 2 Hz. The first detectable seismic energy (dashed line) crosses the array at an apparent velocity of 1645 m/s. Acoustic arrivals cross the array at 336 m/s. A concurrent seismo-acoustic impulsive source at the vent that might be responsible for the acoustic arrival would produce seismic energy that would cross the array (dash-dot line) later than the observed seismic first arrival.

high-frequency component results from energetic 'jetting' of material through the vent. Though many extended degassing events are easy to classify as either harmonic or high-frequency hybrid combinations are also common. Spectrograms of consecutive explosions at a particular volcano (Fig. 4) reveal a tendency for specific event types to cluster in time.

A qualitative map of event types (Fig. 6) reveals general differences in the three datasets. In general, Karymsky possesses proportionately fewer tremor events than Sangay. Tremor at Karymsky tends to be of shorter duration with less-developed integer overtones than at Sangay. The relative quantity of integer overtones in the Karymsky 97 and Sangay 98 datasets can be attributed either to the stability of the resonance phenomena or to the propagation filter within the two volcanoes. Because seismic simple impulses are consistently more broad-band at Sangay than at Karymsky, we should expect a greater quantity of integer overtones in Sangay tremor (Fig. 5). Extreme examples of integer overtones in tremor signals, such as the 30 observed at Lascar Volcano in Chile (Hellweg, 1997a), may be explained by the convolution of a very broadband seismic impulse with a comb function. However, the absence of harmonic tremor events at Karymksy in 1998 must be attributed to a lack of a resonance mechanism (this will be discussed later).

Unless obscured by wind noise, all seismic explosion signals are accompanied by an infrasonic pressure pulse which follows the seismic signal by 3–7 s at vent distances of 1.2–3 km. Though the onset of each acoustic signal is impulsive, the corresponding seismic signal is very emergent. The emergent signals may be partially explained by weak transmission between a low-velocity fluid-filled conduit and the wall rock (Dibble, 1994), or alternatively by a diffuse or emergent source within the conduit.

Indeed, we observe evidence for source motions prior to the actual explosion at Karymsky. A tight array (85 m spacing) at Karymsky in 1998 (Fig. 7), reveals apparent velocities of 1645 m/s for seismic first arrivals and 336 ± 4 m/s for acoustic arrivals. However, the travel time separation between these two phases is too lengthy to be explained by a concurrent seismo-acoustic impulsive energy source at the vent. In many explosions, we are able to observe up to

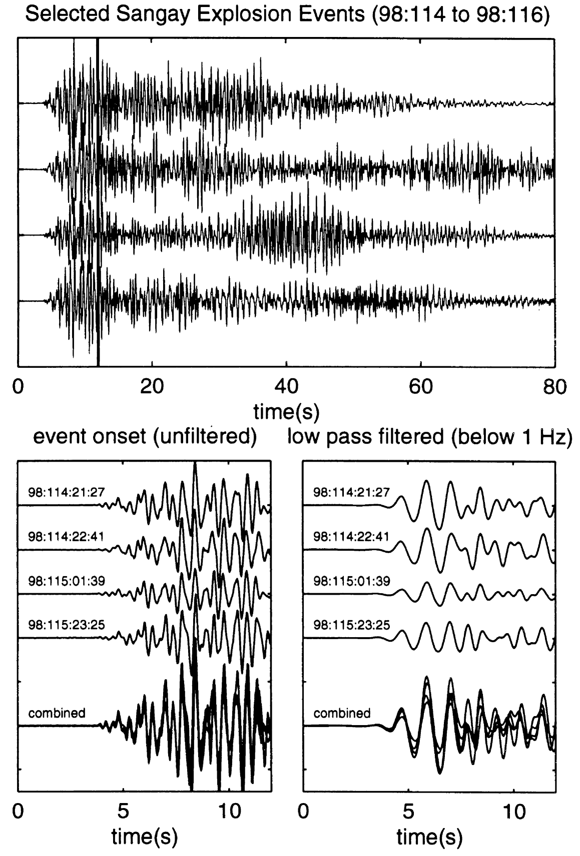


Fig. 8. Repetitive explosion source locations and mechanisms are evidenced by the self-similarity of explosion waveforms recorded at a single station.

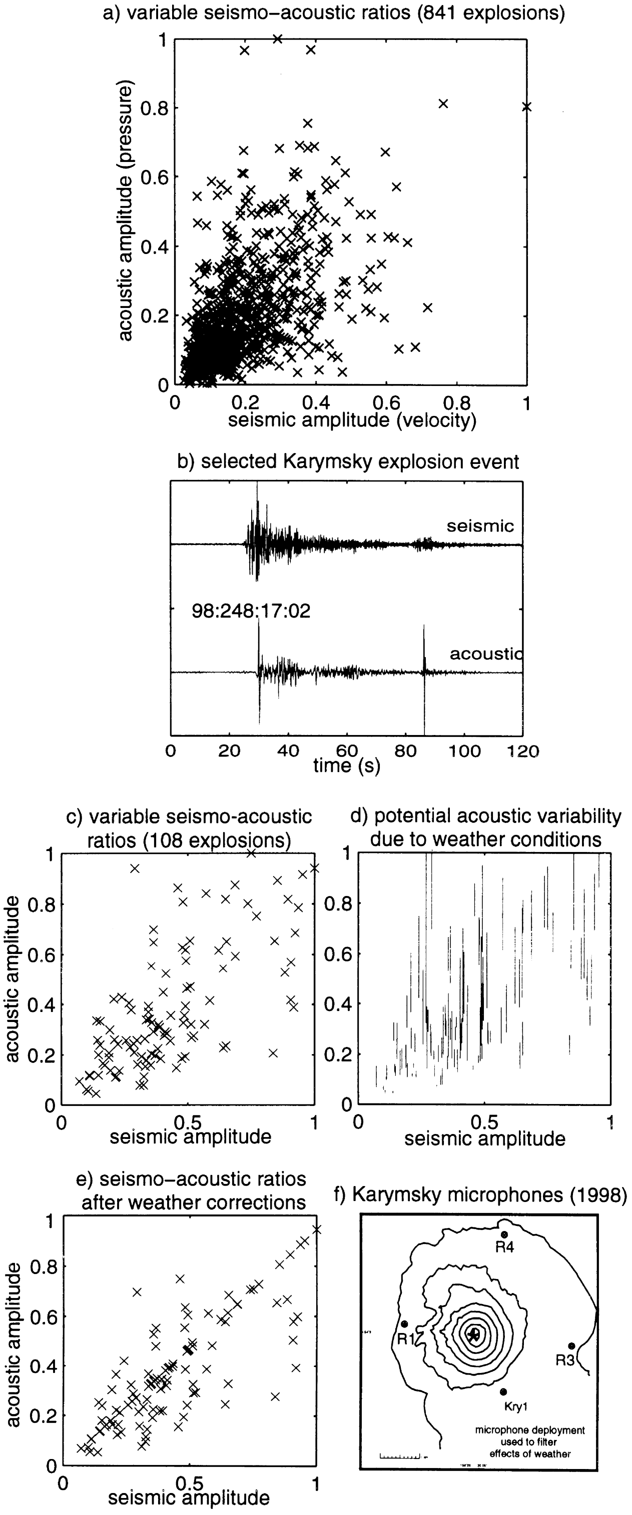
2 s of pre-explosion seismicity, which may reflect fracturing or movement of material in the conduit just prior to gas release. These motions are slight compared with motions which occur several seconds later. The bulk of the seismic energy is generated by the response of the volcano to the thrust of material ejected through the vent (Brodsky et al., 1999).

Even simple explosion events generate seismic signals, which are tens of seconds long. This coda should be attributed to interactions of body and surface waves caused by path effects (reflections, scattering, near-field effects) within the structurally complicated volcanic edifice (Chouet et al., 1998). Despite complicated propagation filters, we observe a high degree of self-similarity for the first ten seconds of most seismic waveforms, indicating that a similar explosion mechanism is responsible for each event (Fig. 8). Waveform correlation is much higher for two different events than for a single explosion recorded at two stations only 85 m apart. By reciprocity, we infer that source location within the conduit varies by considerably less than 85 m vertically.

Though seismic waveforms may appear similar for many different explosions, the ratio of seismic-to-acoustic energy generated by different explosions is extremely variable (Fig. 9a and c). Weather, including wind and a temperature-dependent velocity structure, has considerable impact on the atmospheric propagation of acoustic energy. On the basis of raypaths and traveltimes for infrasonic energy propagating in a stratified atmosphere (Garces et al., 1998), we can determine bounds for amplitude enhancement and attenuation upwind and downwind (Fig. 9d). At Karymsky in 1998 we deployed microphones north, south, east and west of the vent (Fig. 9f) with the intent of filtering out the effects of weather from the acoustic records. Even after removing conceivable impacts of weather, we still observe considerable scatter in the plot of seismo-acoustic amplitudes (Fig. 9e). Rapid changes in seismo-acoustic amplitudes that occur during the course of a single explosion event (Fig. 9b) are further evidence that changing weather is not the sole cause of variable seismo-acoustic amplitudes.

We acknowledge several mechanisms, besides weather (Fig. 10a), which may be responsible for variable seismo-acoustic ratios. The depth of the explosion source within the conduit could affect the amount

Fig. 9. (a) Scatter in the normalized seismic and acoustic amplitudes for a suite of 864 distinct explosion events from Karymsky 98 (recorded at Kry1 and Kry2). (b) A selected Karymsky explosion event with dramatic changes in seismo-acoustic amplitude ratios (notice double pulse). (c) Scatter in the normalized seismic and acoustic amplitudes for a suite of 108 explosions (recorded at Kry1). (d) Potential variability in acoustic amplitudes for 108 explosions recorded at Kry1. Error bars are determined through analysis of acoustic records from stations R1, R3, and R4. (e) Scatter in the normalized seismic and ‘corrected’ acoustic amplitudes for a suite of 108 explosions. Acoustic amplitudes are forced to remain within the error bars (d), but are migrated to obtain a best linear fit. Considerable scatter remains and must be attributed to factors other than weather. (f) Map of microphone stations used for assessing the effects of weather at Karymsky.


a) variable seismo–acoustic ratios (841 explosions)
acoustic amplitude (pressure)
seismic amplitude (velocity)
0
0.2
0.4
0.6
0.8
1
b) selected Karymsky explosion event
seismic
98:248:17:02
acoustic
time (s)
0
20
40
60
80
100
120
c) variable seismo–acoustic ratios (108 explosions)
acoustic amplitude
seismic amplitude
0.5
d) potential acoustic variability due to weather conditions
seismic amplitude
e) seismo–acoustic ratios after weather corrections
acoustic amplitude
seismic amplitude
f) Karymsky microphones (1998)
R4
R1
R3
Kry1
microphone deployment used to filter effects of weather

of energy able to propagate into the atmosphere (Fig. 10b). Similarly, debris, atop the explosion source, would muffle the acoustic signal by absorbing explosion energy as mechanical energy (Fig. 10c) (Mori et al., 1989). Finally, preferential coupling of seismic energy into the air and into the ground might depend on the impedance of the magma (Fig. 10d) (Hagerty et al., 1997). This last method requires that a seismo-acoustic source be located within the magma and does not seem appropriate at Karymsky and Sangay, where we associate acoustic and seismic signals with gas expansion at the vent.

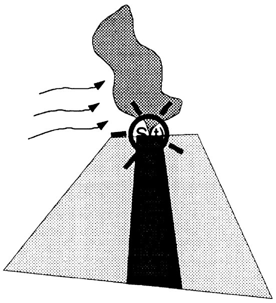
5. Discussion

Inhibited gas flux during the intervals between degassing explosions suggests that either gas flow is unsteady through the upper conduit or a plug temporarily prevents continuous gas escape. Unsteady gas flow has been considered as a mechanism for regular explosions at many Strombolian systems (Kilauea, Stromboli) where vents appear entirely open (Jaupart and Vergniolle, 1989; Vergniolle and Jaupart, 1990; Manga, 1996). However, because the vents at Karymsky and Sangay appear to be choked with rubble and rising viscous lava, we consider the possibility that the upper section of conduit is depleted of exsolved volatiles and acts as a ‘plug’. Though solidified lava is likely to possess open fractures through which gas can continually escape, we believe that a section of conduit in the shallow subsurface could temporarily serve as a barrier to rising gas (Johnson et al., 1998). When gas pressure reaches a critical threshold determined by the weight and cohesion of the loading material, an explosion breaches the plug. Following the initial outburst, a lowered lithostatic pressure promotes further gas exsolution. Detritus that does not clear the vent can settle into the conduit atop volatile-depleted magma, setting the foundation for the next plug.

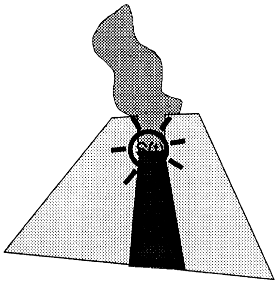
In many explosions at Karymsky in 1997 and at Sangay in 1998, degassing is not a single isolated burst from the vent, but a sequence of regular, impulsive gas releases, which is manifested as seismic and acoustic tremor. We identify four models that are able to generate periodic signals and have been offered as explanations of harmonic tremor at Strombolian-type volcanoes. The first model, used to explain ‘chugging’ oscillations at Arenal (Garces and McNutt, 1997) and Semeru (Schlindwein et al., 1995) is the presence of a fluid body in the upper portion of the volcano edifice. In this model, excitation causes the chamber to resonate, much as the standing waves in a vibrating organ pipe. A second model involves the generation of von Karman vortices on the lee side of an obstruction in a conduit. Vortex shedding has a specific periodicity that can be predicted by the properties of the fluids and dynamics of the flow (Hellweg, 1997b). A third mechanism capable of generating regular oscillations is conduit-wall resonance produced by non-linear fluid flow through a pipe (Julian, 1994). A final model, which is physically similar to conduit-wall resonance, involves a pressurized system of mixed phase gases and magmatic fluids trapped beneath a plug. The plug acts like a valve on a pressure cooker, allowing the release of gas as a series of regular impulsive events (Lees and Bolton, 1998).

Several mechanisms are theoretically capable of producing regular source pulses, which can propagate through the atmosphere and ground as harmonic tremor. At this juncture, we admit that we cannot identify a unique source for the harmonic tremor at our volcanoes. However, we currently favor gas release through a near-surface valve (plug resonance) because of the following reasons: (1) we regularly observe material choking the volcanic vent at Karymsky; (2) tremor is a transitory feature which may be governed by a continuously evolving plug; (3) tremor events appear to cluster in time; (4) tremor was virtually absent at Karymsky in 1998, when magma flux was elevated and a cold viscous debris plugs had little time to develop.

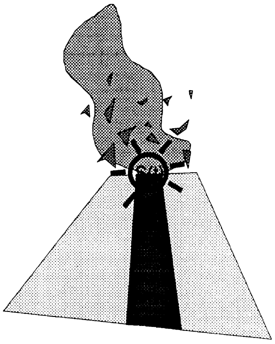
We believe that a pressure-cooker analog offers a reasonable mechanism for both trapping gas between explosions and producing occasional tremor events. Even during a vigorous explosion, when an entire plug might be ejected from the conduit, calving of the conduit walls and crater floor allows material to fall back into the conduit. When the conduit remains unobstructed by debris, gas may escape easily as a high frequency jetting. Lower-frequency and harmonic tremor events are produced when debris is not completely ejected through the vent during the initial impulse. Material is able to settle in the upper portion of the conduit and inhibit continuous gas release. The relatively rare incidence of tremor at Karymsky (compared with Sangay) may be attributed to a more vigorous material flux through the vent, which keeps the conduit open. However, other variables, such as magma viscosity, volatile content, and conduit geometries, may also play a significant roll.



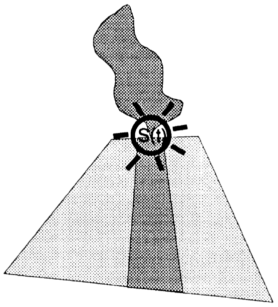
a) Wind (weather)



b) Variable Explosion Depth



c) Mechanical Dissipation of Acoustic Energy



d) Changing Impedance of Magma

Fig. 10. Cartoon of four possible mechanisms which could produce variable seismo-acoustic ratios: (a) weather variability; (b) location of explosion source within a conduit; (c) dissipation of acoustic energy as mechanical energy; (d) variable melt impedance.

6. Conclusion

This largely observational paper describes seismic and acoustic signals associated with explosions at Karymsky and Sangay Volcanoes. In the spectrum of possible eruptive mechanisms, those of degassing at Karymsky and Sangay appear to be very similar. At both sites, seismo-acoustic sources are located near the vent and degassing occurs frequently and impulsively. Volcanic material and debris choking the upper conduit are responsible for temporarily blocking gas flow through the vent. The source of the harmonic tremor, which is nearly identical at the two volcanoes, may result from gas release through a plug, which acts as a valve. We consider the greater quantity of tremor events at Sangay (compared to Karymsky) to be related to a lower gas and magma flux.

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