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Degassing Explosions at Karymsky Volcano, Kamchatka

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Abstract. During the summer of 1997, Karymsky Volcano produced summit explosions about six times each hour. Typical explosive episodes lasted between 30 seconds and three minutes, produced gas and ash columns several hundred meters high, and ejected some incandescent material. To better understand the physical source mechanisms responsible, we recorded hundreds of explosions with a three component broad-band seismometer and microphone located 1650 meters from the active vent. Nearly every explosion is recorded as an emergent yet identical seismic wavelet which is followed 4.15 s later by an impulsive acoustic arrival. We interpret the signals as a near-surface gas volume burst which fractures the vent 'plug,' lowers the lithostatic pressure within the magma column, and often induces further degassing. When degassing continues, it is generally manifested as either a series of regular one second 'chugging' explosions, steady higher frequency 'jetting', or a hybrid combination. We believe that the seismic signature for 'chugs,' short duration harmonic tremor with integer overtones, is the result of repeated gas volume bursts at the vent. In contrast, seismograms for jetting are non-harmonic and contain higher frequencies. We believe that the competing degassing behaviors are influenced by the gas flux as well as the plug/conduit characteristics. We propose that a plug exists due to a viscosity gradient caused by volatile depletion in the upper conduit.

Introduction

Strombolian-type volcanoes such as Karymsky are excellent laboratories for investigating volcanic processes because explosions and the associated seismicity repeat regularly. A variety of seismic signals, including volcanic tremor, may be observed and studied here. At Karymsky Volcano, we have applied seismic, infrasonic, and visual observations to determine reasonable source processes responsible for the regular explosions and associated tremor. We believe that activity at Karymsky Volcano shares similarities with activity at a host of other volcanoes, some of which have been the focus of studies: Arenal [*Benoit and McNutt*, 1997; *Garces et al.*, 1998], Langila [*Mori et al.*, 1989], Ruapehu [*Hurst*, 1992], Semeru [*Schlindwein et al.*, 1995], Spurr [*Garces and McNutt*, 1997], Stromboli [*Chouet et al.*, 1998]. A comparison of our data with that collected at other volcanic centers is vital for determining the mechanisms at differing eruptive centers.

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Background

Karymsky Volcano is a frequently active stratovolcano located in the central part of the Kamchatkan volcanic belt. Its most recent eruptive period began on January 1st, 1996 after 14 years of quiescence. The eruption was preceded by earthquake swarms, indicating magma intrusion, which culminated in a local tectonic earthquake (M7.0) [*Gordeev et al.*, 1997]. This large event opened conduits for magma migration which led to concurrent eruptions at Karymsky Summit and Karymsky Lake, 5 km to the south [*Gordeev et al.*, 1997]. Though activity at Karymsky Lake ceased after several days, the Strombolian activity at Karymsky Summit has continued until present (September, 1998).

Initial activity at Karymsky Summit was marked by vigorous Vulcanian eruptions. Ash and projectiles were ejected continuously, forming dark columns several kilometers in height. Eight months after the eruption onset, activity had declined to periodic explosions which occurred about twelve times each hour and an active andesitic block lava flow which extended one kilometer from the summit vent. Twenty months after onset (during the summer of 1997), eruptive vigor had decreased further. Six explosions occurred each hour and plumes rose several hundred meters. Incandescent ejecta was visible during some of the explosive episodes and the lava flow of 1996 was silent.

Current activity at Karymsky appears to be typical for the 4700 year-old volcano which has been in eruption 28 of the past 50 years [*Simkin et al.*, 1994]. During the previous eruptive interval (1970-1982), Karymsky also exhibited low-level Strombolian behavior after a paroxysmal onset. Total material added during the 12 year period was $\sim$0.01 km^3 and composition of the primary lava flow was $\sim$62.20 weight percent silica [*Ivanov et al.*, 1991]. The current eruptive interval has already produced a comparable volume of andesite, most of it during the first year.

Data

In August 1997, we deployed 3 broad-band Guralp CMG-40T seismometers at Karymsky Volcano (Figure 1). Over a period of 9 days, we recorded more that 1000 high-quality seismic events associated with summit vent explosions. A low frequency (2 to 32 hz bandpassed) microphone situated

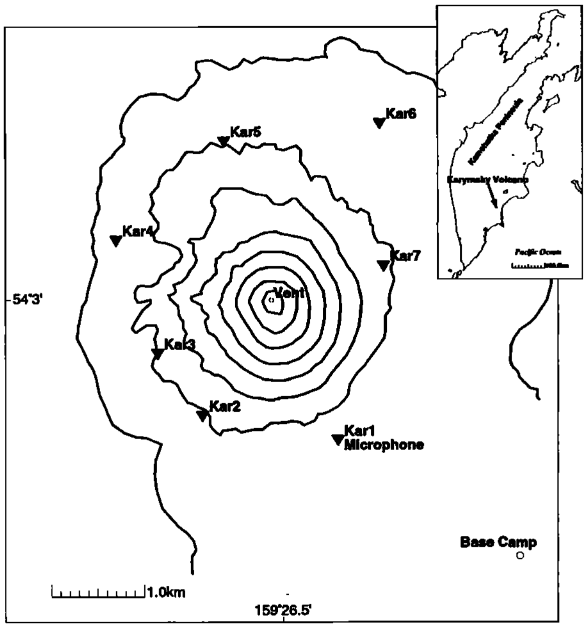

Figure 1. Map of Karymsky showing locations of the broadband stations deployed in 1997. Station KAR1 included a broadband microphone as well as a broadband 3-component seismic station. At any given time, only 3 stations were operating. Contours are at 100 m intervals starting at 1000 m. The outer boundary is the rim of a caldera. The inset shows the location of Karymsky on the Kamchatka Peninsula.

at Station KAR1, 1650 meters from the vent, operated for three days and recorded over 300 explosions. In general, the acoustic signal-to-noise ratio was especially good at night during low wind conditions.

For each explosion, both ground-propagating and atmosphere-to-ground coupled energy was observed in the seismic records at all station locations. Nearly all the high frequency energy (greater than 6 Hz) arrived simultaneously on the seismic and acoustic channels, indicating that there is significant coupled (acoustic-to-seismic) energy. High frequency ground-propagating seismic energy is severely attenuated in the unconsolidated volcanic cone.

Because acoustic energy appears to be present for all shallow seismic events, we assume that first arrivals on both seismic and acoustic channels share a common seismo-acoustic source. For virtually every explosion recorded at Station KAR1, an emergent collection of seismic waves precedes an impulsive acoustic pulse by 4.15 s $\pm$ 0.1 s. Variation in the travel time differences can be accounted for by reasonable variations in atmospheric sound speed. We assume the seismo-acoustic source is stationary because of the high degree of similarity between the first few seconds of all seismic explosion waveforms which are recorded at a single station (Figure 2a). If the seismic and acoustic sources are synchronous, first arrivals through the volcanic edifice travel at a phase velocity of 2300 to 2800 m/s (calculated with a sound speed of 343 m/s and allowing +/- 50 m uncertainty in the vent location).

Following the initial impulsive onset, Karymsky explosive events display three general behaviors (Figure 2a). In half of the explosions, the seismic signal tapers to near background level within 30 s regardless of initial amplitude. We refer to this most basic type of explosion as 'a simple impulse event.' In 10% to 20% of the events, the explosion is characterized by a 1 to 3 minute interval of low frequency harmonic tremor. Because this tremor is often accompanied by audible, steam-engine-like exhalations, we refer to these signals as 'chugging events' [*Benoit and McNutt*, 1997]. Other long-duration explosions contain a combination of higher frequencies and non-harmonic tremor. These 'hybrid events' sometimes evolve into harmonic tremor.

Interpretation

Periodic explosions at intervals of minutes or hours are common at many basaltic and andesitic centers worldwide. Some mechanisms for regular explosions have previously been suggested as coalescence of bubble foams in a conduit constriction [*Jaupart and Vergniolle*, 1988] or as waves of bubbles formed through nonlinear upward flow [*Manga*, 1996]. In silica-rich volcanic systems, it has been shown that periodic dome explosions may be caused by pressurization due to microlite growth and volatile loss [*Sparks*, 1997].

At Karymsky we believe that the regular explosions occur when steadily increasing gas pressure reaches a critical threshold beneath a volatile-depleted, high-viscosity plug. When the bubble pressure surpasses a confining pressure determined by the weight and cohesion of the plug, the plug is shifted or 'uncorked' allowing immediate escape for a certain quantity of gas. The initial explosion of gas is recorded as a $\sim$2.5 Hz impulsive pressure pulse at the microphone (a simple impulse). The same impulse, scattered in the loose, heterogeneous volcanic edifice, is filtered to a 30 s coda, with waveforms which vary dramatically at the different stations.

Though seismic and acoustic amplitudes vary and probably correspond to different volumes of escaped gas, the scaled seismic waveforms for initial explosions are very similar at a single station (Figure 2a). We thus believe that the initial source process and location are the same for all Karymsky explosive events, whether degassing continues or not. This consistent explosive onset is frequently, but not always, followed by a sustained, more variable period of degassing. We believe that continued degassing occurs when the initial explosion partially reopens fractures and reduces the pressure which is necessary for gas to escape from the top of the magma column. As gas and solid material is blasted away from the vent, it is also likely that reduced lithostatic pressure within the conduit promotes increased gas exsolution.

The isolated simple impulse event may either indicate a general deficit of volatiles in the upper portion of the conduit, or a vent configuration that closes itself after the initial explosion, preventing further escape of gas. By inspecting the lapse times between explosions, it appears that when isolated simple impulses follow each other, they occur relatively frequently. Since simple impulse events are short in duration and indicate a smaller total gas release, more frequent explosions would be expected in order to sustain a constant gas flux.

Chugging events are extended gas release events characterized by a series of regular ($\sim$1 s interval) impulsive bursts which continue for as long as three minutes. We believe chugging events occur when the vent does not completely seal itself after the initial, vent-'uncorking' simple impulse. Because the acoustic waveform of each individual chug is identical to the acoustic waveform of a simple impulse, we

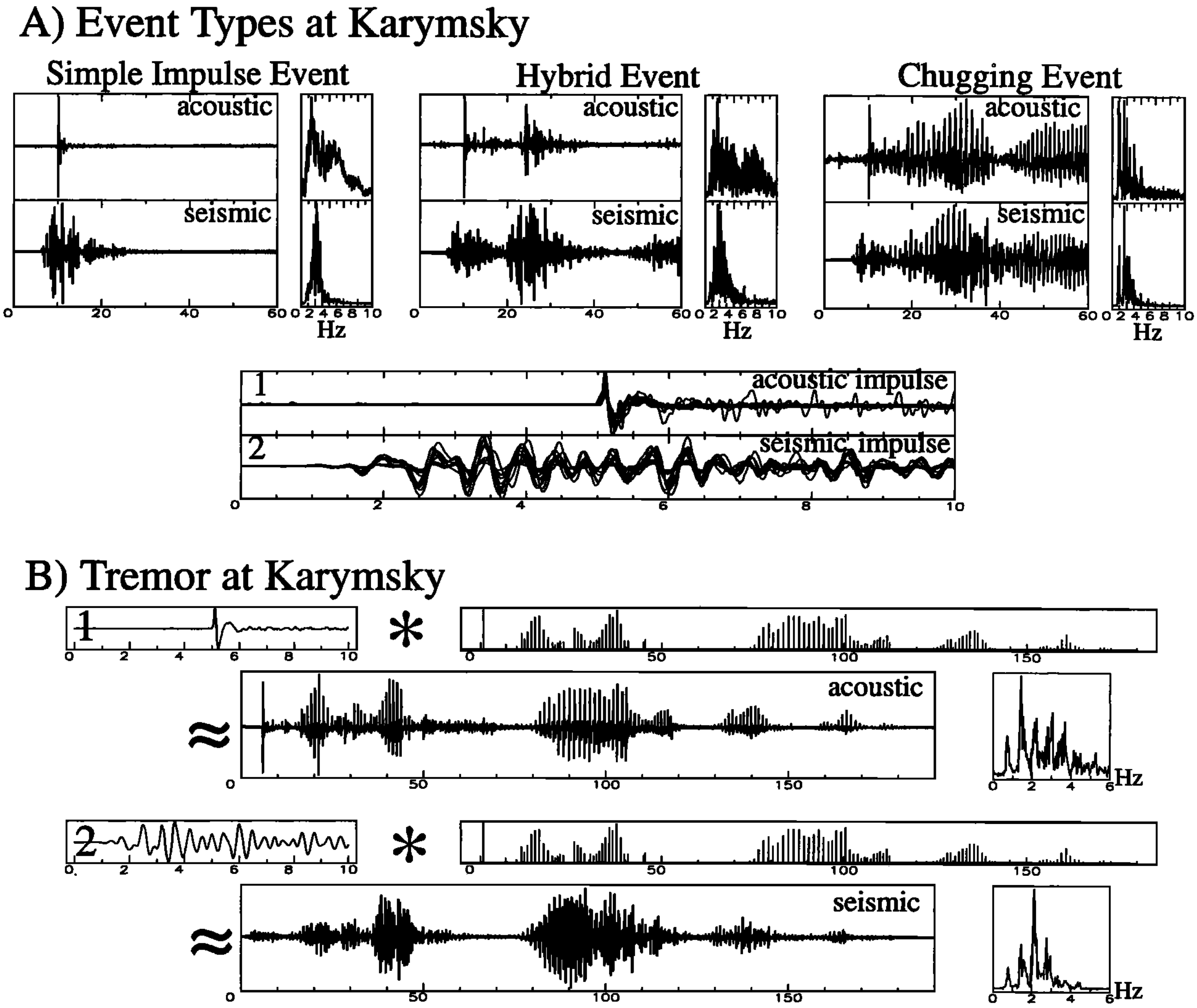

Figure 2. a) Acoustic and vertical seismic traces and frequency spectra for 3 typical Karymsky explosive events (Simple Impulse, Hybrid, and Chugging) are shown at the top. At the bottom, waveforms from 12 different explosions are superimposed to show the high degree of correlation among the onsets of Karymsky explosions. b) Harmonic tremor at Karymsky (chugging events) may be a convolution of the simple impulses with a spike series. Envelopes of waveforms produced in this manner are very similar to the recorded waveforms. Frequency spectra for a 30 second window of recorded tremor shows clear integer harmonics.

assume that each chug also represents a rapid, explosive release of gas. Such gas releases (chugs) are sustained for tens of seconds, often tapering off and on several times before completely stopping. The associated seismic signal, a short duration harmonic tremor, can be constructed as a superposition of repeated identical sources (Figure 2b). Traditionally such harmonic tremor has been attributed to the characteristic resonance of a bounded fluid volume. It has been suggested that the fundamental resonance frequency is caused by a decompression which arises when energy reflects off a lower impedance contrast, determined by a 'bubble exsolution front,' and then returns to the surface (S.R. McNutt, personal correspondence). Though this model is capable of producing regularly spaced acoustic pulses, we do not see it as a unique solution. We envision the possibility for alternative mechanisms, such as repeated gas volumes released through a narrow closeable pressure cooker-type valve.

Hybrid events are identifiable by less well-defined integer harmonics and a general abundance of higher frequencies. Like chugging events, they also last for one to three minutes and are analogous to short duration, non-harmonic tremor. Often the high frequency component tapers off as the signal evolves into a lower frequency harmonic tremor. These signals may result from a combination of regular gas releases and continuous gas escape. If after the initial, impulsive, vent clearing event, fractures for gas escape remain relatively open or gas flux remains high, these hybrid events may result.

Clustering of event types (whether impulsive, chugging, or hybrid) is evidence that the vent configuration or magma characteristics change slowly over the course of many explosions. For instance, it is common for chugging events to dominate for several hours, then to be absent for several hours. Reports from Karymsky in late fall of 1997 indicate that chugging events had become the dominant event type (E.I. Gordeev, personal correspondence, 1997). In the summer of 1996, no chugging events were observed (J.M. Lees, personal correspondence, 1997). This transition to chugging behavior may be attributed to changes is magma viscosity and/or gas flux.

Discussion

Determination of physical processes in the conduit is hampered by many unknowns. Further field observations must be made before we can do more than speculate on such parameters as the conduit width, magma viscosity profile, gas bubble concentration, volume, and distribution, and gas flux through the vent. Over the course of 3 years, we have observed that the flux of andesite through the Karymksy vent has all but stopped while gas emissions have merely slowed. As a result, we believe that gas bubbles are rising through a vertical magma column faster than the liquid phase.

The rise velocity of small bubbles in a Newtonian fluid is proportional to bubble surface area and the density difference between the gas and the fluid, and inversely proportional to fluid viscosity [*Clift et al.*, 1978]. Viscosities for silica-rich magmas are heavily influenced by the quantity of dissolved volatiles and may increase by three orders of magnitude for a 2% by weight drop in water content [*Lange*, 1994]. Since water solubility falls off as the square root of lithostatic pressure [*McMillan*, 1994], we can expect an enormous viscosity gradient in the shallow portions of a volcanic conduit. If magma viscosity increases faster than the decrease in lithostatic pressure, we would expect rise velocities to decrease as gas bubbles climb towards the vent. Here viscous and static resistance against bubble expansion govern the pressure within individual bubbles. Though we simplify the pressure accumulation by considering a gas foam which collects beneath an immovable, impermeable, high viscosity plug, pressure buildup is probably integrated over a conduit section.

It has been shown that very small changes in dynamic or static stresses can excite activity at volcanic systems which are 'primed' [*Hill et al.*, 1995; *Rydelek et al.*, 1988]. After a Karymsky initial explosion, we expect continued degassing can be influenced by slight changes in the vent configuration, as well as a small pressure drop throughout the conduit. The repeated, explosive gas releases (chugs) may result from accelerated gas exsolution caused by such a pressure drop. Each release of gas reduces the pressure directly beneath the high viscosity plug. At the same time an increased rate of gas exsolution might presssurize the conduit quickly enough to generate chugs at 0.8 s to 1.2 s intervals. Higher frequency events, which indicate continuous as opposed to chugging gas emissions, may result from a different gas flux or a vent configuration which does not entirely close itself after it is opened. The common evolution from high frequencies to chugging style, within a single event (hybrid events), may mean that gas flow is tapering off or that the plug has already begun to 'heal.'

Conclusion

We propose a model for the source of periodic explosions and the nature of the tremor at Karymsky. The periodic explosions, which occur on an average of six times each hour, are attributed to the sudden release of gas which has accumulated beneath an impermeable vent plug. If the gas flux up through the conduit is steady, an explosion results when a threshold pressure is reached. If degassing continues after the explosion, it is manifested either as a series of explosive pulses (chugging) or continuous jetting (hybrid). These relatively brief events (one to three minutes) appear to be abbreviated versions of harmonic and non-harmonic tremor, generated by pressurized gas as it escapes to the free surface.

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