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# Non-linear explosion tremor at Sangay, Volcano, Ecuador

Q1 Jonathan M. Lees [a,*], Mario Ruiz

[a] *University of North Carolina, Department of Geological Sciences, CB#3315, Mitchell Hall, Chapel Hill, NC 27599-3315, United States*

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**Abstract**

A detailed analysis of discrete degassing pulses, chugs, at Sangay volcano, was performed on seismic and infrasonic records to determine the physics of the conduit. Infrasonic chugging signals appear as repetitive pulses with small variations in amplitude and time lag. An automated time-domain analysis was developed to measure with high precision time intervals and amplitudes at different wave arrivals, reducing the possibility error associated with hand picking. Using this automated method, a strong positive correlation of acoustic amplitude with repose time between individual pulses on chugging signals of Sangay was found on numerous oscillating sequences. Frequency gliding of apparent harmonic frequencies generally trends from high to low frequency at Sangay, in contrast to trends at Karymsky Volcano, Russia. A new description of chugging events using wavelet transform methods, appropriate for non-stationary signals, shows subtle changes in the waveforms relate to physical processes in the volcano. A system of non-linear feedback, based on choked flow at the vent, is postulated as the most likely source of this volcanic tremor.


*Keywords:* volcanoes; explosions; Strombolian activity; infrasound; seismo-acoustic; non-linear; wavelet transform; harmonic tremor; quasi-periodic

## 1. Introduction

Volcanic "chugging", a specialized tremor observed at several exploding volcanoes, is currently being used to understand the physics and structure of volcanic conduits during low level Strombolian style activity. Chugging has been identified most clearly at Arenal Volcano, Costa Rica, (Benoit and McNutt, 1997; Garces et al., 1998; Hagerty et al., 2000), and Karymsky Volcano, Kamchatka, (Johnson et al., 1998; Johnson and Lees, 2000; Lees et al., 2004) as a sequence of puffing or explosions following an initial explosion which apparently triggers the sequence. The quasi-periodic chugging sequence consistently exhibits an inter-pulse period varying from 0.7–2 s and produces a series of pulses in the infrasonic frequency band. Chugging sequences are not restricted to the low frequency bands and can often be heard in audible frequency ranges, although we know of no documented cases of researchers visually observing gas or other emissions associated directly with chugging. This maybe due to the fact that chugging usually follows a larger Strombolian style explosion and pulsations that occur in the aftermath are obstructed by the larger amounts of gas and ash remaining from the initial blast. The individual infrasonic chugging signals appear to be discrete and time limited, often evolving over the length of the chugging sequence. Corresponding seismic signals, distorted because they are convolved with the intervening earth structure, display more complex signals

Q2 * Corresponding author. Tel.: +1 919 962 0695; fax: +1 919.
*E-mail address:* jonathan.lees@unc.edu (J.M. Lees).
*URL:* http://www.unc.edu/~leesj (J.M. Lees).

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associated with path effect and site response, as well as the source time function of individual tremor pulses. Since the acoustic signals do not suffer significant distortion from path effects, we concentrate primarily on analysis of the infrasonic signals in this study.

From April 21–26, 1998, two portable, broadband, seismic stations including infrasonic microphones were deployed on the southern flanks of Sangay to monitor activity and record infrasonic acoustic waves as well as seismic emission from the vents (Fig. 1). During this survey, 38 chugging signals were recorded on seismic and acoustic stations. Johnson and Lees (2000) provide a detailed description of the 1998 deployment and show that chugging events of Sangay and Karymsky have, in general, similar waveforms, although differences in occurrence, duration and spectral content were cited. Prior to the 1998 deployment, long-period, hybrid and tremor events (about 5/day) were recorded in 1995 on a short period seismic station 4.3 km from the summit. The 1995 events exhibited characteristics similar to the 1998 recordings. Some of the 1995 events were associated with audibly and visually observed explosions followed by roar-like, pulsating, rhythmic exhalations (GVN, 1996). Because of the remoteness of Sangay, the volcano is not monitored

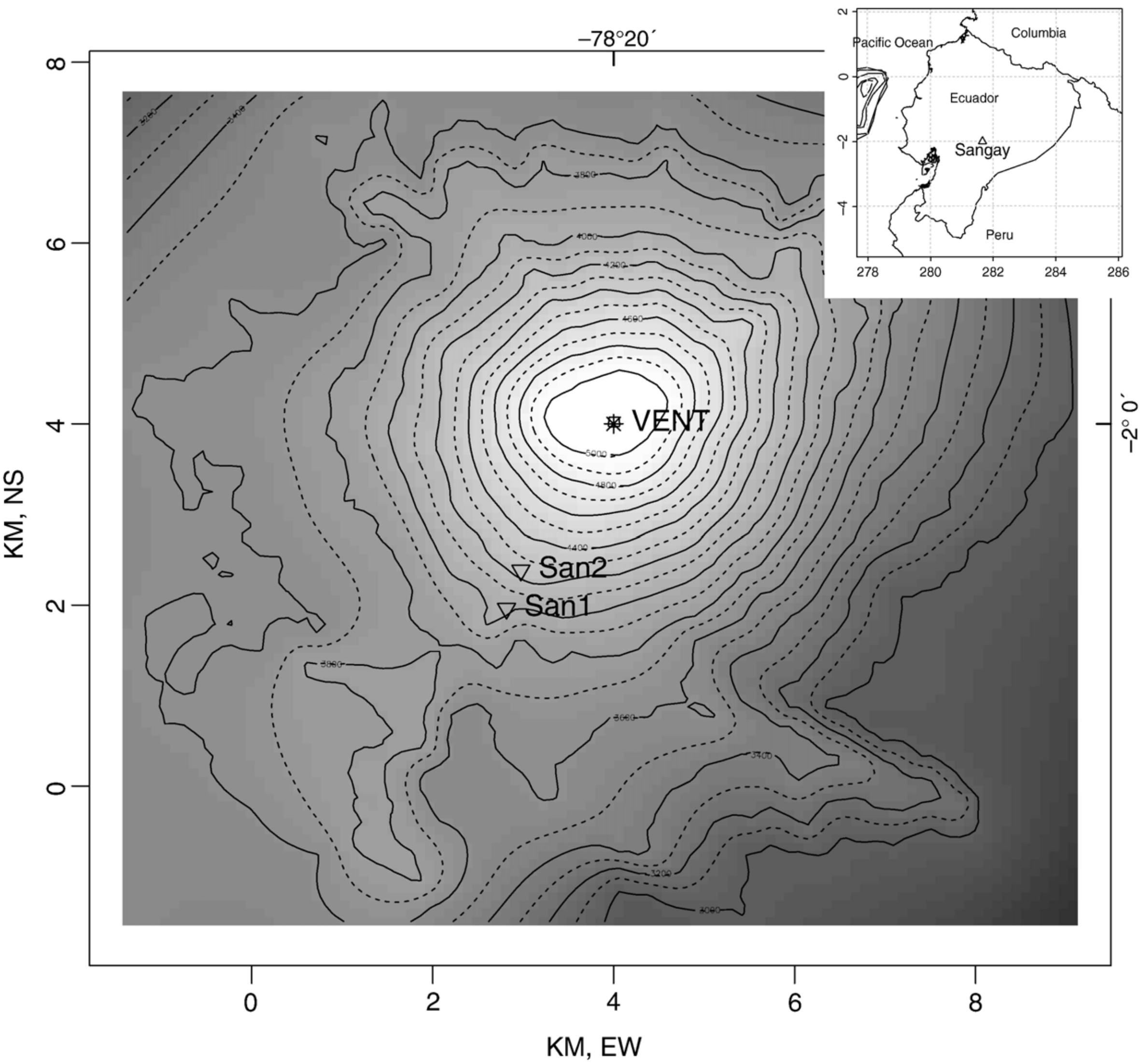


Fig. 1. Topographic map of Sangay showing station location and vent region. Contours are drawn at 200 m intervals. Stations were located down slope from the active vent. Data presented in this paper are from station San2 1200 m from the vent.

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regularly, although we expect this low level activity, including pulsating tremor, is ongoing and persistent.

Sangay is the most active volcano in the Northern Andes. It has been in a state of continuous eruption for as long as historic accounts are available. Large eruptive activity, including high ash columns, has been reported on more than 16 occasions between 1728 and 1980 (J. Egred, pers. comm.). A detailed review of the geology, petrology and descriptions of the volcano can be found in Monzier et al. (1999). Ongoing activity at Sangay consists primarily of low level Strombolian explosions with block and ash explosions, occurring, on average, 1–2 times per hour. In the past few years activity has migrated across the vents at the summit. This paper uses data collected solely from the 1998 deployment.

At Sangay, the summit complex of vents contains several craters with a WSW–ENE trend, although at the time of the field experiment, only a crater at the NE edge was erupting. Time delays between acoustic and seismic arrivals have a mean value of 4.02 s ($\sigma=0.105$ s) at station SAN2, the closest to the vent. Based on the consistency of these time delays, we are confident that the sources studied here are derived from only one of the active vents. Onsets of acoustic and seismic waveforms of explosions recorded at Sangay are remarkably similar despite the emergent nature of seismic signals (Johnson and Lees, 2000). These observations support the hypothesis of repeatable sources at stable locations for this type of event at Sangay.

Of all volcanoes that exhibit "chugging" behavior Sangay and Karymsky share seismo-acoustic characteristics that are more similar to each other than others studied by the authors. It is worthwhile noting that these two volcanoes differ in their size and tectonic setting. Sangay vents are located at 5000 m elevation as compared to Karymsky's 1600 height. Each volcano is conical in shape, located in a subduction zone setting, although Sangay is situated at the southern terminus of volcanism in the Northern Andes whereas Karymsky is far from potentially disturbing edge effects associated with slab termination. Each volcano exhibits an array of whole rock geochemistry ranging from silicic to mafic character, although for the most both volcanoes are dominated by andesitic eruptions and lava flows (Zobin and Levina, 1998; Monzier et al., 1999; Eichelberger and Izbekov, 2000; Ozerov et al., 2003; Lees et al., 2004).

Analysis in the earlier paper (Johnson and Lees, 2000) used spectrogram analysis of signals to show effects of harmonic tremor and gliding, the time-varying fluctuations of the fundamental mode and harmonics of chugging series. Although Sangay and Karymsky volcanoes share physical similarities in their eruption activity parameters (eruptive scale time, magma viscosity, volatile content, and mass flux though the vent) chugging events at each exhibit broad differences in duration, occurrence, and frequency content. In this paper we extend the analyses described earlier and show that activity at Sangay is much more similar to Karymsky behavior than previously understood. Using an automatic time-domain analysis of amplitude–time lapse ratios, we show that chugging amplitudes recorded on infrasonic sensors appear to be correlated with time between individual chugs, as observed at Karymsky in 1997 (Lees et al., 2004). This observation has important implications for modeling volcanoes in general, regarding the interaction of vent and ascending combinations of mixed-phase mass prior to expulsion from the volcano orifice (Ozerov et al., 2003). Our analysis is related to the non-linear analyses of chaotic processes, although in this study we base our conclusions on much more detailed observations of the chugging time series. Finally we present a new description of chugging events using wavelet transforms methods appropriate for non-stationary signals.

## 2. Data analysis

Eleven episodes of high signal–noise sequences of chugging were isolated at Sangay in the period of observation in 1998. These were extracted from the full data set and analyzed as described below. At least two sequences were complex series known as 'intermittent chugging'(Lees et al., 2004), i.e. sequences that were modulated by a much longer wavelength process, so those were broken down and investigated in parts. For each of the selected episodes, detailed analysis of the time intervals between individual chugs and the amplitudes of individual chugs was recorded (Fig. 2). To be as consistent as possible, automation of time and amplitude determinations was implemented. All time picks were made by selecting the maximum amplitude in a window surrounding each chug signal on the raw acoustic records. This approach eliminated the possibility of bias associated with decision making by an analyst. To provide estimates of the error in the automated picks, we used the following procedure: after arrival times were determined, a small window surrounding the maximum of each chug was selected and low-pass filtered using a Gaussian Nadaraya–Watson kernel regression smoother with central frequencies at 6 and 2 Hz respectively (R Development Core Team, 2006). The difference between the 2 Hz filtered maximum arrival-time/amplitude versus the 6 Hz arrival-time/amplitude represents an estimate of the quality of the arrival time

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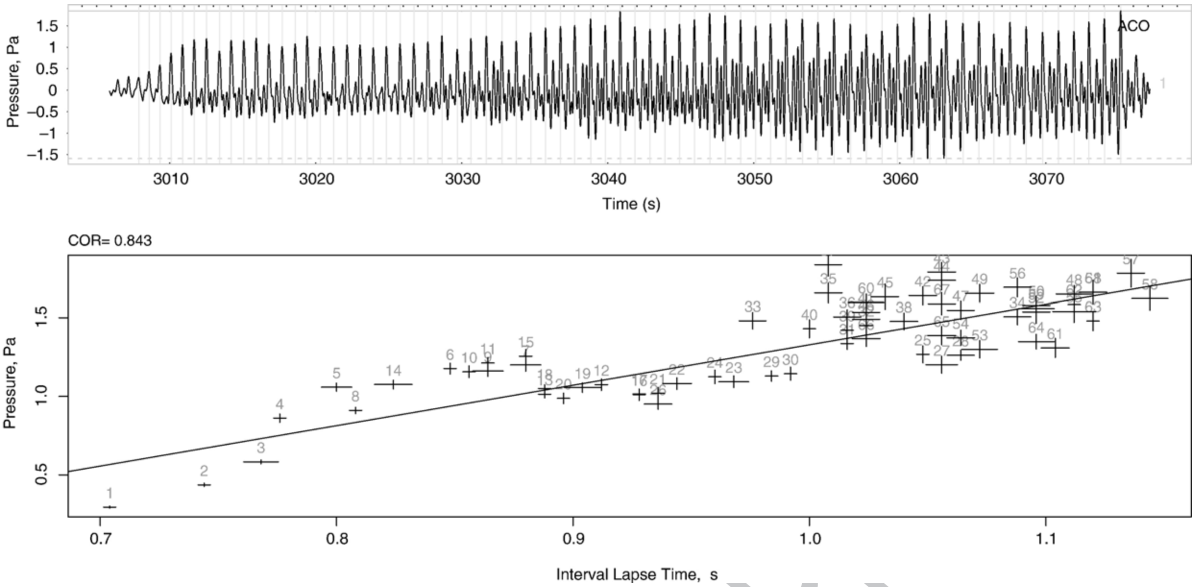


Fig. 2. Chugging Event #4. Each pulse is measured at its peak and errors of timing and amplitudes are estimated by comparing estimates with filtered versions of the pulses. Linear regression of time interval and amplitude is computed for each chugging sequence separately and error estimates are used to weight the linear models. The slope for Event 4 is 2.6 Pa/s with a correlation coefficient of 0.84. The number labels are the sequence of each pulse in the chugging series such that larger indices arrive later in time.

determination (Fig. 3). Uncertainty estimates rely on the choice of smoothing parameters, naturally, so an effort was made to design the filters that increase error bars when the peak region of the chug is multi-modal, or noisy. This method seemed to provide reasonable error bounds in amplitude and time on the individual chugs, with maxima of 4.9% and 1.7% error variation, respectively.

The advantage of measuring time intervals so precisely over conventional spectrum methods is clear: estimates of frequency spectra generally mix signals over

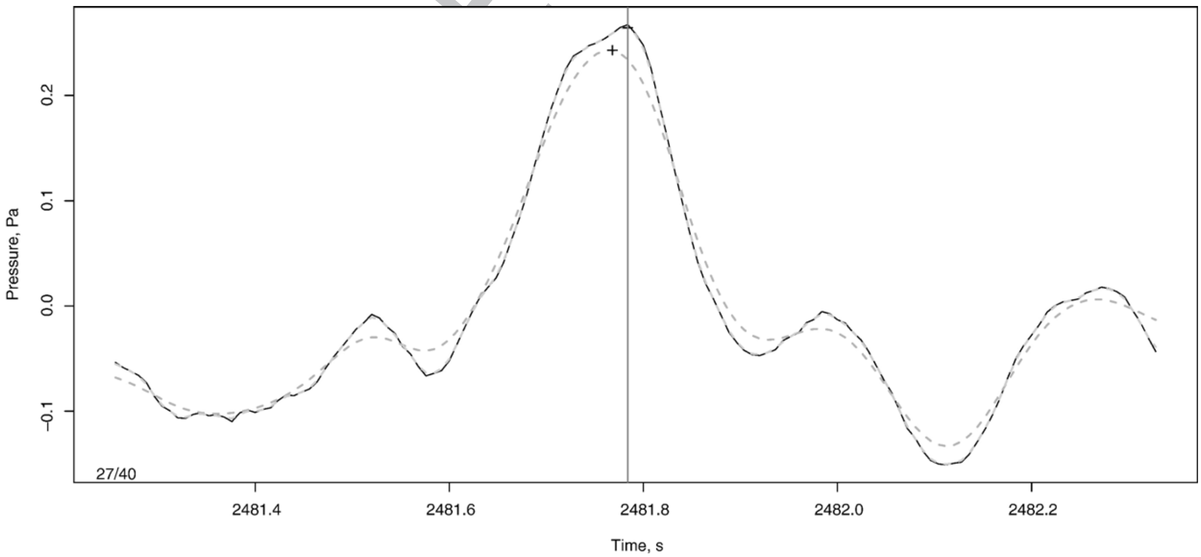


Fig. 3. Example chug illustrating estimates of error in time and amplitude. Arrival times are estimated by the peak amplitude in a short window surrounding the chug pulse. The pulse is smoothed at two different frequencies (dashed, grey lines) and the difference between the amplitude and arrival time of each (plus symbols) provides an automated method to extract the uncertainty of times and amplitudes. Uncertainties are used to weight the linear regression presented in Fig. 2.

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several wavelengths to extract the frequency–amplitude information (Lees et al., 2004). The time-domain approach taken here preserves details of the structure of the sequence that cannot be obtained using a spectrogram. The apparent relation between amplitude and time interval between chugs is further obscured by inconsistent estimation of the time arrivals, as would be the case if arrivals were determined by eyeball estimation. By developing an automated algorithm to extract this information, the method can be applied to and compared with other datasets with general reliability.

## 3. Amplitude–time lapse analysis

We isolated eleven sequences of chugging activity and applied the automated time-domain analysis described above. Uncertainties in pulse arrival-time and amplitude estimates were used to weight linear regressions between lag (lapse) times and amplitudes. In nearly all the chugging sequences studied, there is a statistically significant positive correlation between amplitude and time interval between chugs (Fig. 4). While this observation is not universal, i.e. there are sequences which do not show a strong correlation, in those instances where chugging is relatively simple, the rule holds. Occasionally chugging sequences are complex, i.e. they are modulated by a longer period envelope that regulates amplitude fluctuations. In these cases, the chugging series were broken down and analyzed individually. The mean slope for sequences which had a statistically positive slope was 2.2 Pa/s. We note that accurate and stable calibration of the Venema electret microphone sensitivity is not available for data recorded at Sangay in 1998 (Johnson et al., 2003). In this paper we used an estimated 30 mV/Pa to convert volts to pressure. The critical observation here is the positive relation between amplitudes and time lags whereas the absolute value of the slope is of lesser concern.

## 4. Frequency gliding

Frequency gliding occurs when the fundamental and corresponding harmonic frequencies fluctuate in time (Benoit and McNutt, 1997; Garces et al., 1998; Hagerty et al., 2000; Lees et al., 2004). At Langila volcano tremor related to puffing sounds of emissions exhibited frequency variations greater than 50% over a time span of about 1 min (Mori et al., 1989). The tremor at Langila had an

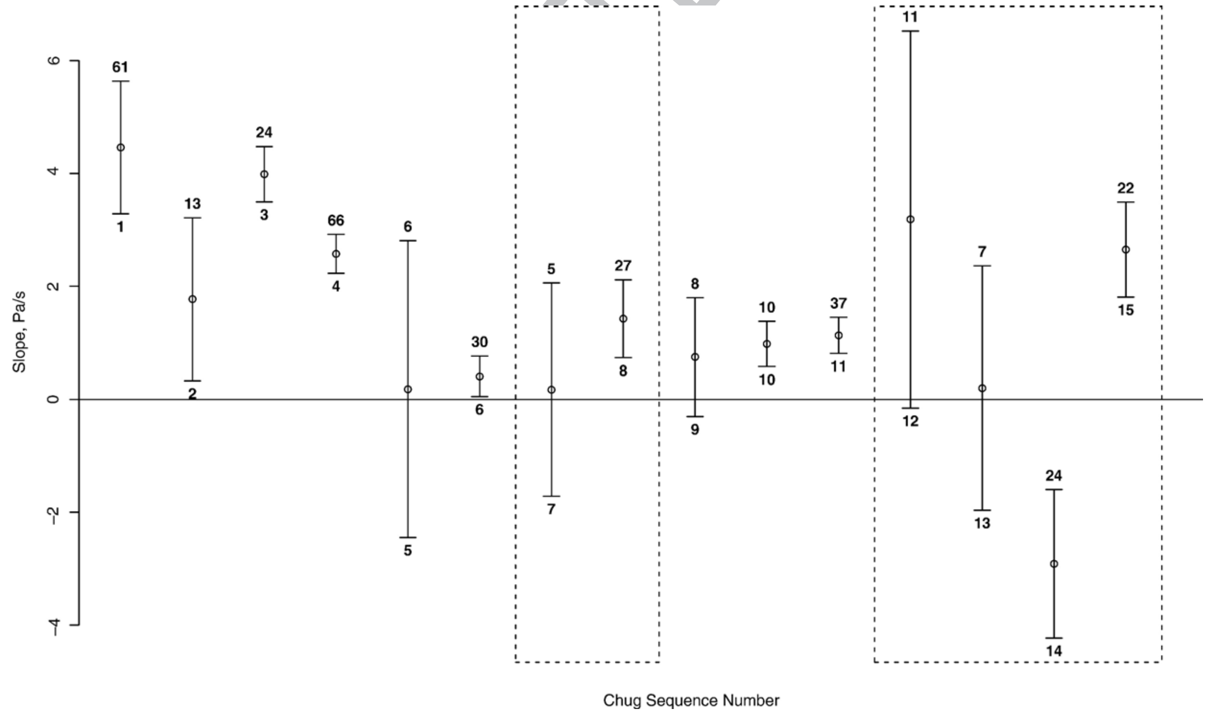


Fig. 4. Summary of regression analyses. Error bars are 95% confidence bounds formally estimated from linear regression. Each sequence is numbered (lower number) and shows the number of chugs per sequence (upper numeral). Sequence number 4 is presented in Fig. 2. Dashed boxes enclose sequences of intermittent chugging that were broken down into subsets and analyzed individually. The majority of chugging events at Sangay show a positive correlation between pulse interval time and amplitude.

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increasing period for increasing amplitudes (Julian, 1994). Frequency increments of about 100% over about 10 min have been noted at Sakurajima volcano (Kamo et al., 1977). At Sangay we found that gliding often trends from higher to lower frequencies (Fig. 5), although occasionally chugging sequences appear to have the opposite trend. In some cases, however, gliding shows an increase and later a decrease in frequency over the time span of the sequence. Where chugging is interpreted as a superposition of standing waves, gliding has been viewed as a time varying change in the physical medium (for example, density fluctuations) which produce a drifting of the fundamental frequencies. Benoit and McNutt (1997) attributed frequency variations to changes in the dimensions of magma bodies or gas content. In linear oscillators, damping lowers the natural frequency of oscillation, in non-linear oscillators, damping can also have the opposite effect (Julian, 2000).

It has been established that volcano chugging cannot be modeled by a simple linear system of superposed oscillations (Lees et al., 2004). Since observations at Sangay appear to corroborate the conclusion that the underlying physical mechanism is non-linear, we propose that the observed frequency gliding is related to feedback loops in the vent-gas storage system near the opening of the conduit. As chugging progresses, the aperture where gasses are released undergoes slight modification, coupled with fluctuations of internal pressures within the uppermost conduit. In nearly all cases where there was significant correlation between amplitude and interval time, higher amplitude pulses have longer times. This implies that the mechanism for releasing gasses is related to an increase of pressure associated with a larger volume of gas in the conduit chamber.

We found no correlation between isolated explosion event amplitude (non-chugging or chugging) and lapse time since the previous event. The physical mechanisms that control initial or isolated blasts are most likely different from those governing chugging signals. During the 1998 field deployment, initial blasts at Sangay occurred once per hour, on average, producing hundreds of events (over this same period fewer than 20 sequences of chugging were observed, 11 of which are discussed here). All reports of activity from Sangay suggest that this activity has been ongoing since 1628 (Monzier et al., 1999). This is in marked contrast to Karymsky where Strombolian activity is intermittent with a decadal cycle that includes vigorous explosion cycles during the active phases. In spite of the differences in physical structure and geologic composition, the two volcano chugging sequences are remarkably similar in frequency content and amplitude range. We speculate that the physical processes governing all chugging signals is a feedback loop controlled by the geometry of the vent opening and

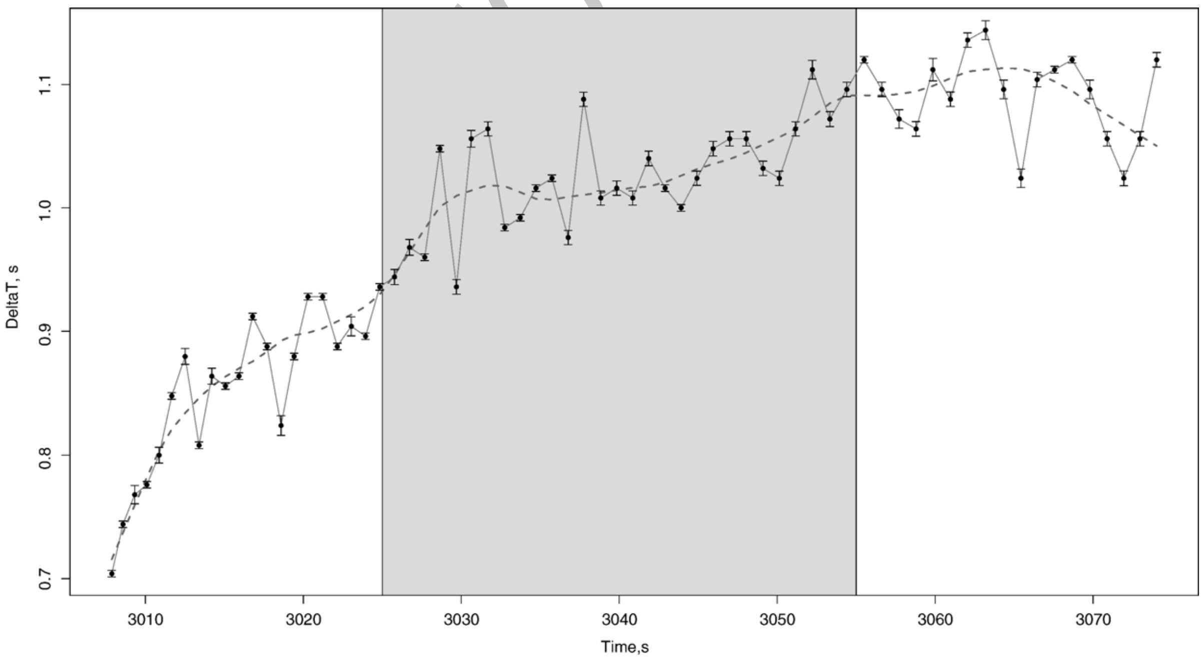


Fig. 5. Gliding interval time between chugs versus time from chugging sequence presented in Fig. 2. In this example the period between chugs increases, so the frequency decreases over the 60 s span of the chugging event. The shaded region corresponds to time periods discussed in the text where frequencies and particle motion vary. The dashed line is a smoothed representation of the points. Error bars for the timing are estimated as in Fig. 3.

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the flux of gasses near the surface. For chugging at Karymsky and Sangay volcanoes parameters controlling gas flux appear to be similar. The vent at Karymsky during the times of observation was on the order of tens of meters with debris packing into the crater following each explosion. The aperture extent of the active vent at Sangay in 1998 is unknown because visual observations could not be made at that time. Gliding provides information into the internal dynamics of the conduit physical state and we next invoke powerful processing tools to investigate it further.

## 5. Wavelet transforms

Application of the wavelet transform on the chugging sequence shown above reveals internal temporal variation of the time history of the tremor. In this case we use the Morlet wavelet (Carmona et al., 1998; Addison, 2002; Lees, 2005) as it is appropriate for Ricker type wavelets often observed in seismic records. The mathematical form of the Morlet wavelet is a sinusoidal oscillation modulated by a Gaussian window function:

$$\psi\left(\frac{t-b}{a}\right) = \frac{1}{\pi^{1/4}} e^{i2\pi f_0[(t-b)/a]} e^{-\frac{1}{2}[(t-b)/a]^2} \qquad (1)$$

where $t$ is time, $a$ is a scaling factor, $b$ is shifting parameter, $f_0$ is the center frequency for the wavelet, and $i$ is the complex number.

An example wavelet transform is presented in Fig. 6 with scale factor 1 and center frequency 5. The Morlet wavelet used in this study is designed so that the first two side lobes of the wavelet are approximately half the amplitude of the central peak (Carmona et al., 1998; Addison, 2002). We present the wavelet transforms of all four recorded signals, three seismic and one infrasound. Details of the wavelet transform of the infrasonic channel from Fig. 6 are presented in Figs. 7 and 8.



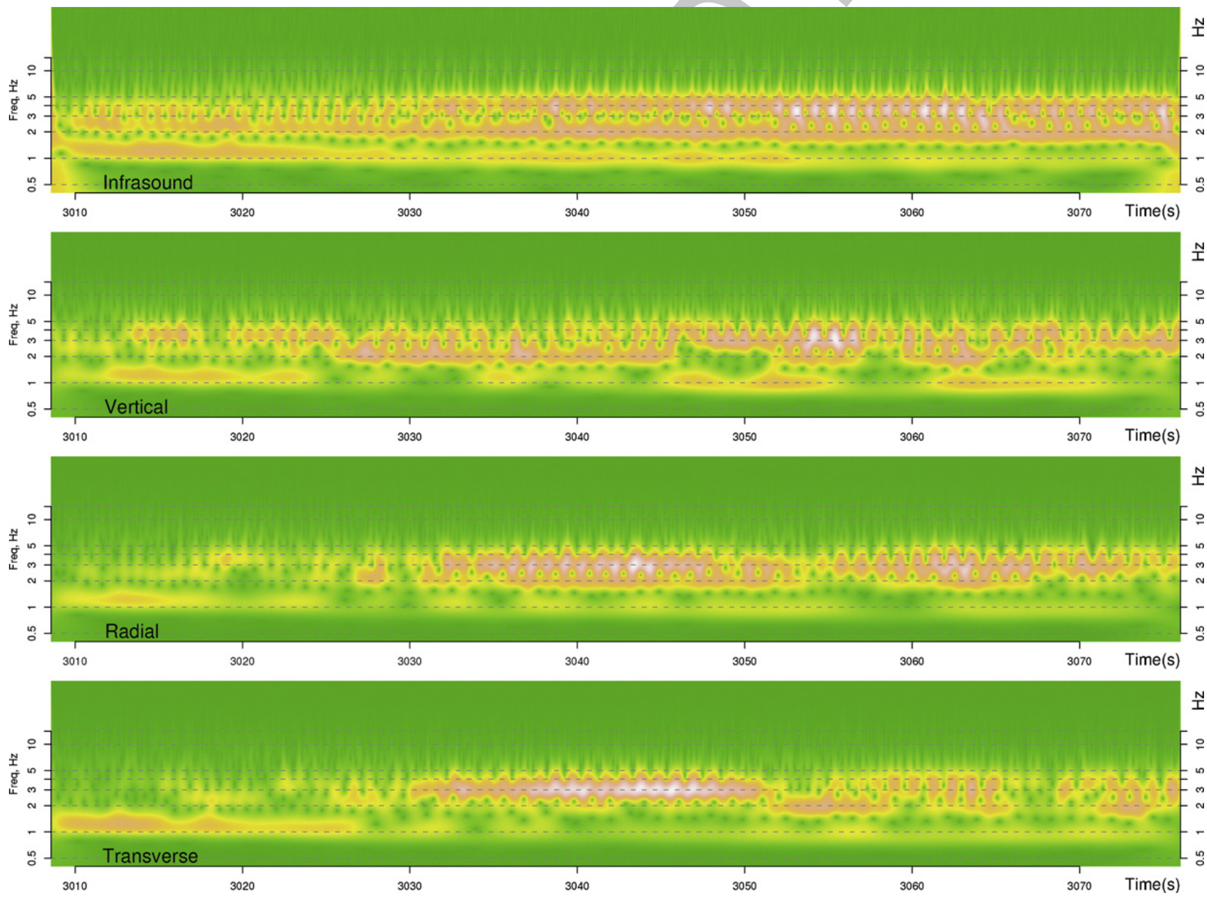


Fig. 6. Wavelet transform of chugging sequence #4. The figure shows all four channels: one infrasound and three-component seismic. The wavelet transform is designed to accentuate time varying frequency changes during the sequence of chugging tremor. The amplitude of the wavelet transform is based on a cross-correlation and has no units.

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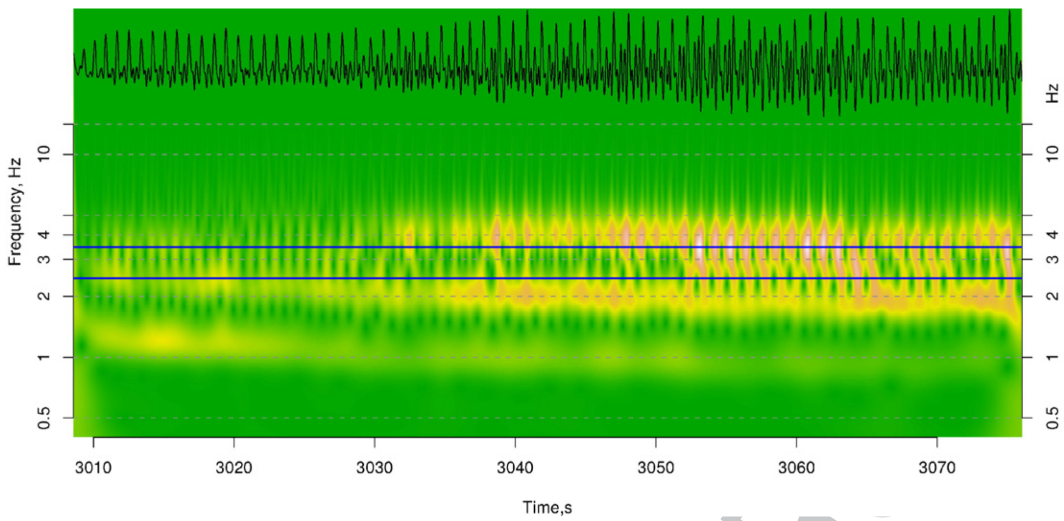


Fig. 7. Detail of wavelet transform of infrasonic component from Fig. 6. Two lines are drawn at frequencies 2.4 and 3.4 to illustrate the frequency-time varying behavior of the vent explosions during a chugging sequence. These rows are extracted in present in Fig. 8.

The wavelet transform can illuminate transient features in the signal that standard spectrograms, commonly used in seismology, do not show. In the example presented in Fig. 7 the wavelet transform accentuates individual pulses and relates information on how these pulses change with time and frequency. By focusing on details of the wavelet transform we can narrow down specific temporal variations in the chugging sequence. Consider two frequencies 3.4 Hz and 2.4 Hz in Fig. 7. Near time 3055 s there appears a slight bifurcation of the frequency content: pulses of 3.4 Hz are augmented by a series of 2.4 Hz wavelets. If we extract the rows of the wavelet transform at these frequencies (Fig. 8) the structure become more apparent: around 3055 s the 2.4 Hz signal is time shifted relative the 3.4 Hz wave by about 1.3 s, on average. This frequency time shift represents a new input at the source region where the infrasound pulses originate. Prior to 3055 the two frequencies are in phase, and then, rather abruptly, they are tuned out of phase.

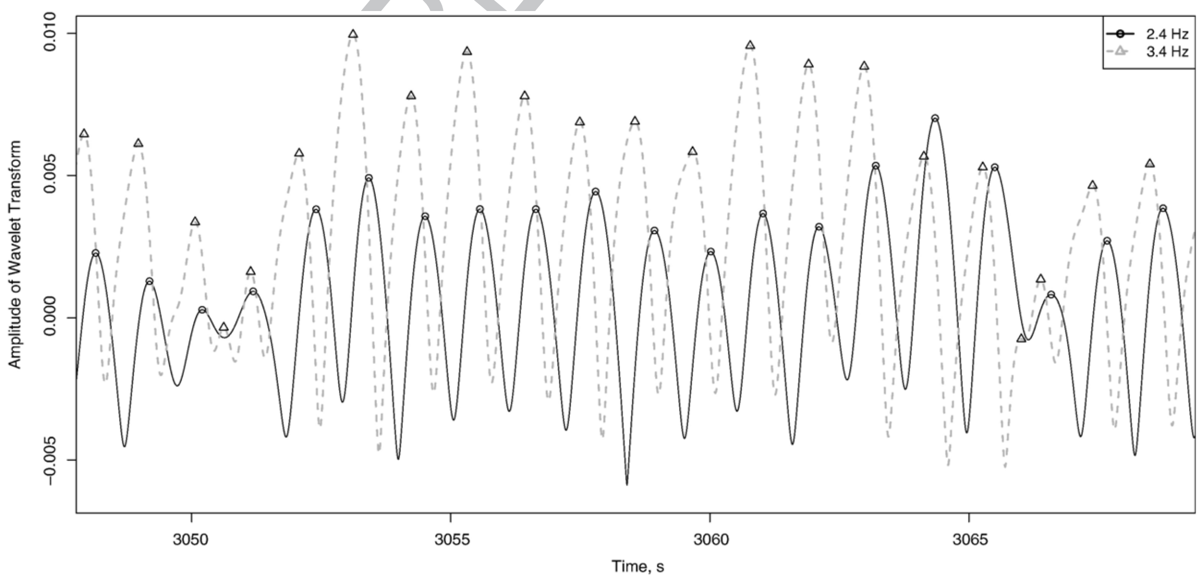


Fig. 8. Two rows of the infrasound wavelet transform extracted from Fig. 7 at 2.4 and 3.4 Hz. The marked peaks are measured in time and an average delay of 1.3 is estimated.

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Analysis of particle motion during chugging sequences is not commonly used, but in this case of chugging it reveals an interesting result. We speculate that particle motion orientation recorded at Sangay in 1998 is most heavily influenced by source effects rather than a path effects, i.e. waves arriving at the station are polarized at the source due to vent characteristics such as geometry, viscosity, or even directional and temporal source variations which produce peculiar radiation patterns.

To analyze temporal variations in chugging particle motion, the three component seismic sequence is broken down into windows of 100 samples long (100/125 s) and eigenvectors of the point clusters for each window are calculated as the window migrates along the trace with 75% overlap (Fig. 9, see (Lees, 2004) for a description of the methods). Measures of cluster quality are monitored along with the incident angle and azimuth of arrival. In this example (Fig. 9) there is good coherence in the initial part of the chugging sequence, during the first 20 s (time 3000–3020 s), where the apparent motion of the particles at the seismometer is apparently 90° rotated from the direction to the vent (Fig. 10). Then, at around 3025 s into the start of the sequence, a higher frequency wave arrives at the station and the particle motion shifts approximately 30° northward. We note that this effect is accompanied by a slight change in the acoustic signal, but a more significant change occurs at around time 3055 s where lower frequencies appear to shift as illustrated in the previous paragraph (Figs. 7, 8, 9 and 10). It is clear that the dynamics of the chugging sequence varies over the time duration of the tremor, representing possible variations in explosion sources at the vent. The fact that the acoustic record changes in coordination with the seismic particle motion, suggests that particle motion variations originate at the source, since the acoustic waves do not share the same path effects as the seismic waves. A simple model consisting of superposition of standing waves in a column of rising magma or in a relatively shallow, mixed-phase conduit cannot explain these variations in behavior without invoking changes of the conduit geometry and/or physical characteristics over time periods of seconds or fractions thereof. On the

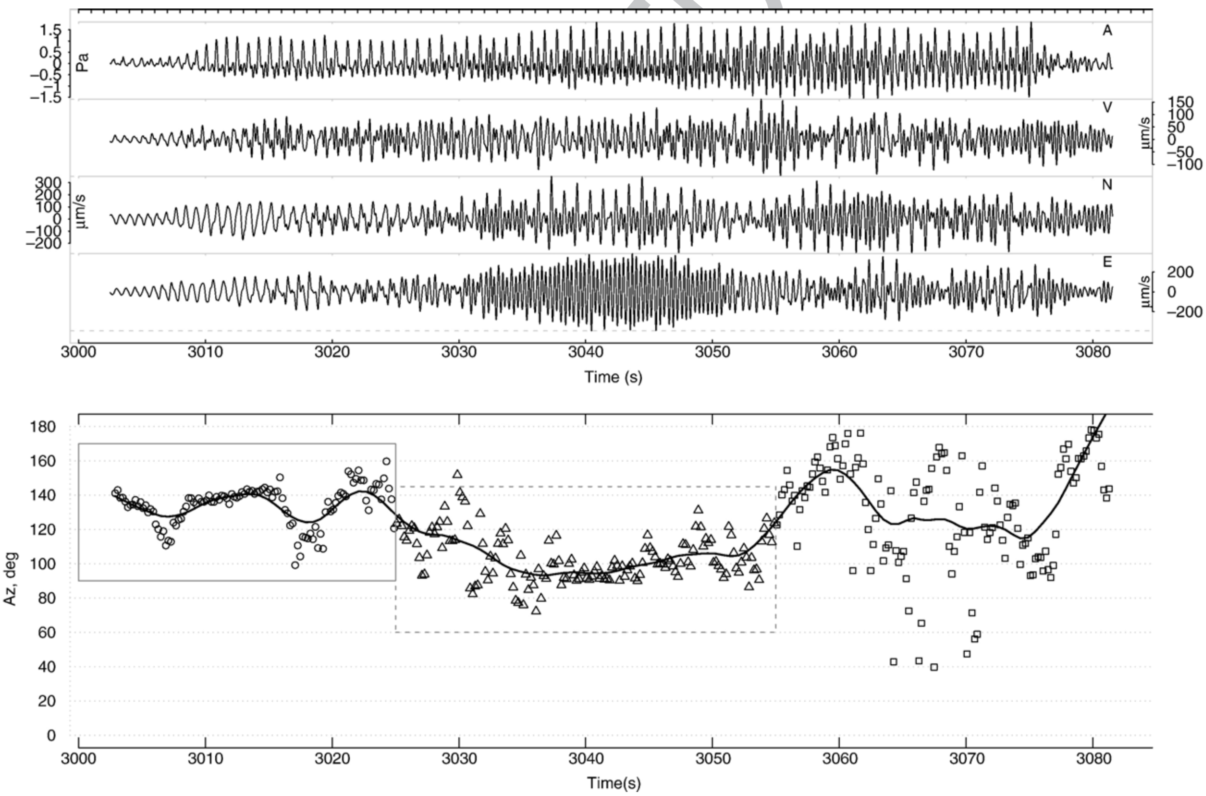


Fig. 9. Particle motion of chugging sequence. The upper panel shows the infrasound and the three components of the particle motion. The lower panel shows the azimuthal direction of particle motion estimated over moving windows of 100 samples (sample rate=0.008 s) with 75% overlap. The directions are derived from eigenvalue decomposition of velocity vectors, followed by projection onto the horizontal plane. The left box (3000–3025 s, circles) exhibits a significantly different orientation of particle motion than the central box. The central box (3025–3055 s, triangles) corresponds to the zone where the frequencies are shifting as described by the infrasound wavelet analysis.

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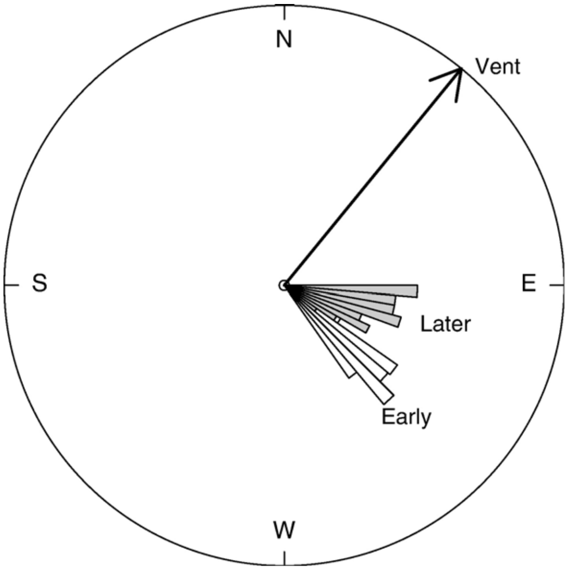


Fig. 10. Azimuthal distribution of particle motion relative to the vent direction. The "early" (white) period corresponds to time span 3000–3025 s (circles) in Fig. 9, the "later" (grey) period corresponds to time 3025–3055 s (triangles). A slight shift northward is seen in the orientation of the chugging signals over time corresponding to a change in explosion source orientation.

other hand if the extrusion of gases changes directions because of adjustments at the vent during the course of a chugging sequence, we may speculate that the shear waves arriving at the station rotate their orientation, producing the observed polarization shift.

## 6. Discussion

Lees et al. (2004) found a strong, apparently linear, correlation between chugging time intervals and corresponding signal amplitudes at Karymsky Volcano. Visual observations of Karymsky Volcano explosions in 1997/1998 suggest that, during chugging activity, Karymsky produced gas/ash explosions from a single eruption vent at the summit. The lone vent acted as the sole source of infrasonic activity, both for chugging and non-chugging events. Video recordings of explosions at Karymsky in 1998 showed that at least two, distinct and separate plumes were evident during explosions (Johnson, in press). The plumes appeared to emanate from the same vent nearly simultaneously; a smaller, lighter colored cloud along with a darker, much larger plume of ash, pyroclastics and debris. We presume that the smaller, white plume consisted primarily of water vapor. During the 1998 deployment at Sangay, only one vent was observed and the presence or absence of multiple plumes is unknown.

Using a new technique in the time domain, a statistically significant positive correlation between time delays and pressure amplitudes of chugging events was found on Sangay's infrasound data. This fact shows that chugging events at Karymsky and Sangay have more similarities than previously was noticed. The fact that amplitudes appear to be correlated with time intervals between chugs is significant. It suggests that it is highly unlikely that the process governing the chugging phenomenon can be modeled as a (simple, linear) superposition of waves in the conduit. This observation cannot be easily deduced from standard spectral analysis of the chugging sequences. Frequency gliding has been observed at Arenal volcano, although the relation of amplitude to pulse frequency was not readily observed until it was noted at Karymsky (Lees et al., 2004). In this study we introduce the wavelet analysis to probe the time–frequency relation of the chugging sequences because standard spectrogram analysis smears information in time. The wavelet analysis has better time resolving power than traditional spectrograms and thus shows details of frequency evolution. During the sequence where frequency splitting and abrupt changes occur over time spans of seconds (or less) the wavelet transform provides insight into time variations of the volcanic explosion source.

Konstantinou and Lin (2004) found that chugging signals from Sangay have a low correlation dimension (1.8–2.4) and a Lyapunov exponent in the range of 0.013–0.022. From these results, they inferred that chugging events can be modeled by non-linear processes (positive Lyapunov exponent) with a low number of degrees of freedom given by a small fractal dimension. Theoretical process mechanisms can be generated by simple sets of non-linear, differential equations such as the Van der Pol or Duffing equations (Julian, 2000; Konstantinou and Schlindwein, 2003). While these equations retain some of the very gross characteristics of the tremor observed we have found simulations based on these simple assumptions seriously lacking.

A variety of non-linear, physical models have been postulated for harmonic tremor on Strombolian style explosive volcanoes, including: a) fluid flow through cracks (Julian, 1994, 2000); b) pressure cooker model (Lees and Bolton, 1998); and c) generation of Von Karman vortices related to obstructions in a conduit (Hellweg, 1999, 2000) and crack vibrations (Chouet, 1986, 1988; Chouet et al., 2003). For now, we cannot speculate on the appropriateness of such models for illuminating the observations reported here, although it should be noted that it is possible to design sets of differential equations that produce sequences of signals similar to those discussed here. Lees and Bolton (1998)



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proposed a set of non-linear differential equations relating choked flow with feedback mechanisms, although these models are still being explored to determine the best parameter estimates and their relation to physical volcanoes. Details of time series produced by these sequences of pulsations will have to be recorded with high fidelity at numerous stations before we can formulate reliable inverse procedures to determine the underlying physical processes. Furthermore, it is most probable that non-uniqueness of parameters sets defining small sets of differential equations proposed to simulate these phenomena will preclude a single, geologically significant, solution. Cross-disciplinary observations (thermal, visual, chemical, etc...) may offer hope to narrow model space of parameter sets that potentially satisfy the seismo-acoustic data, and some efforts along these lines are currently being investigated, although concrete results are not available as yet (Harris et al., 2003; Neuberg, 2006).

The correlation of particle motion variations and infrasonic frequency shifting suggests that the underlying geometry of the source is changing over the time span of one chugging event. At this point we do not have enough constraints to determine if changes in the source occur at depth (tens to hundreds of meters) or at the surface where the infrasound is generated. We speculate that it is unlikely that the variations observed here are produced by deep sources in the vent. Rather we suggest that perturbations shown above most probably result from rapid modifications of the near surface vent during the evolution of the chugging sequence. The modification maybe a slight opening or closing of the aperture or ablation of the edges of the vent which drives the frequency modulation and longer term gliding. A simple feedback mechanism that controls the pressure in the near surface conduit and the aperture of the vent can provide the necessary non-linear behavior required by the amplitude/repose time phenomena shown in Fig. 5. This model has been proposed by others (Johnson et al., 1998; Lees et al., 2004), although a strict mathematical formulation has not been worked out formally (Lees and Bolton, 1998).

## 7. Conclusions

By working in the time domain to estimate arrival times of pulses during tremor events we have reduced the error and increased the precision of time–amplitude observations of explosions at Sangay and Karymsky volcanoes. Sangay volcano exhibits quasi-periodic sequences of pulses following explosions which are known as chugging. Numerous sequences were analyzed and shown to have a statistically significant positive correlation between amplitude and interval repose time. The strong correlation between pulse amplitude and repose time interval suggests feedback mechanisms and chaotic behavior similar to other volcanological phenomena where fluids are assumed to flow through narrow conduits and excite non-linear oscillatory vibration. The close association of particle motion variations and frequency-phase shifts estimated from wavelet transforms indicates modifications of the source/vent geometry rather than a deep seated variation. At the interface between the volcano and the atmosphere this phenomena leads to audible chugging that is prominent in the infrasonic bandwidth (0.7–2 Hz) and can be modeled as choked flow from a relatively shallow conduit chamber.

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