Resonances of a volcanic conduit triggered by repetitive injections of an ash-laden gas

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[1] A swarm of long-period (LP) seismic events was recorded in December 2001 before heightened eruptive activity of Tungurahua Volcano, an andesitic stratovolcano in Ecuador. The LP events showed simple decaying harmonic oscillations with frequencies ranging from 2 to 3.5 Hz and quality factors (Q) significantly larger than 100. Our spectral analysis of the LP events identified systematic temporal variations in both frequency and Q of the LP events. Assuming a crack resonator at the source of LP events, the temporal variations can be consistently explained by increasing the ash content within the resonator, which may be caused by repetitive injections of an ash-laden gas into a pre-existing crack in the conduit as a preparatory process for eruptions. *INDEX TERMS:* 7280 Seismology: Volcano seismology (8419); 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280); 8434 Volcanology: Magma migration; 8439 Volcanology: Physics and chemistry of magma bodies. **Citation:** Molina, I., H. Kumagai, and H. Yepes (2004), Resonances of a volcanic conduit triggered by repetitive injections of an ash-laden gas, *Geophys. Res. Lett.*, *31*, L03603, doi:10.1029/2003GL018934.

1. Introduction

[2] Long-period (LP) volcano seismicity, including LP events and tremor with typical oscillation periods in the range 0.2–2 s, is a manifestation of pressure-induced acoustic vibrations of fluid-filled resonators in magmatic and hydrothermal systems, that provide glimpses of the internal dynamics of volcanic systems [*Chouet*, 1996]. Differences between LP events and tremor may be attributed to their temporal excitation, which is time-localized for LP events and sustained for tremor. Decaying harmonic oscillations in the tail of the LP waveform represent the impulsive response of the resonator system and provide useful information about its characteristic properties. Although various geometries have been proposed for the sources of LP events [e.g., *Chouet*, 1996; *Neuberg*, 2000], recent studies based on waveform inversions of LP events [*Kumagai et al.*, 2002a; *Nakano et al.*, 2003] suggest that a crack geometry is the most appropriate for the LP source. It has been widely recognized that the complex frequencies (frequency and quality factor, Q) of LP events show temporal variations [e.g., *Gil Cruz and Chouet*, 1997; *Aoyama and Takeo*, 2001; *Kumagai et al.*, 2002b]. Such variations are of particular importance for diagnosing the state of fluids inside resonators.

[3] Tungurahua Volcano (5023 m high) is located near the center of the Ecuadorian Andes (Figure 1), and is one of the most active volcanoes in Ecuador. Tungurahua Volcano is an andesitic stratovolcano with eruptive episodes approximately every century for the last 1300 years. Each eruptive episode was typically characterized by ash emissions and pyroclastic and lava flows [*Hall et al.*, 1999]. Beginning in October 1999, Tungurahua entered into activity characterized by ash emissions and vulcanian and strombolian activity. In addition to other seismic activity, a swarm of LP events showing long-lasting harmonic oscillations (Figure 2) occurred beneath this volcano between 5 and 11 December 2001, which was observed by a network of 1 Hz seismometers on the volcano (Figure 1). The LP swarm was preceded by a three-month-long quiescent period. After the swarm, no seismicity was recorded between 11 and 18 December. The different type of LP events showing incoherent oscillating signatures began to occur on 19 December. Ash emissions from the summit crater began on 23 December, and the first explosion occurred on 30 December. Between 15 and 20 January 2002, an incandescent glow was constantly observed in the crater, and magmatic eruptions began on 4 February. The LP swarm activity, therefore, may be related to a key issue for understanding the preparatory processes for the eruption activity inside the volcano.

2. Complex Frequencies of LP Events

[4] We analyzed the LP waveforms recorded at seismic station RETU during this swarm activity. This station, which featured a 1 Hz vertical seismometer, was closest (~2 km) to the crater (Figure 1) and provided the best quality continuous data in the Tungurahua seismic network. We did not use the LP waveform data from other stations, since the tails of the LP waveforms were not adequately recorded in triggered data at CUSU, ULBA, AREV, and ARA2 and the LP waveforms from continuous data at PATA, RUN2, and JUI5 were generally noisy because of larger distances from the source and local site conditions.

[5] We used the Sompi method [*Kumazawa et al.*, 1990], which is a spectral analysis method based on an autoregressive (AR) model, to determine the complex frequencies of decaying oscillations in the tail of the LP waveform. The complex frequency is defined as $f - ig$, where f is the frequency, g is the growth rate, and $i = \sqrt{-1}$, and accordingly, Q is defined as $-f/2g$. Figure 3 shows the result of Sompi analysis of the LP event that occurred on 8 December 2001 (Figure 2) in the form of frequency-growth rate (f–g) diagrams, where we plot the complex frequencies of wave elements for all the trial AR orders

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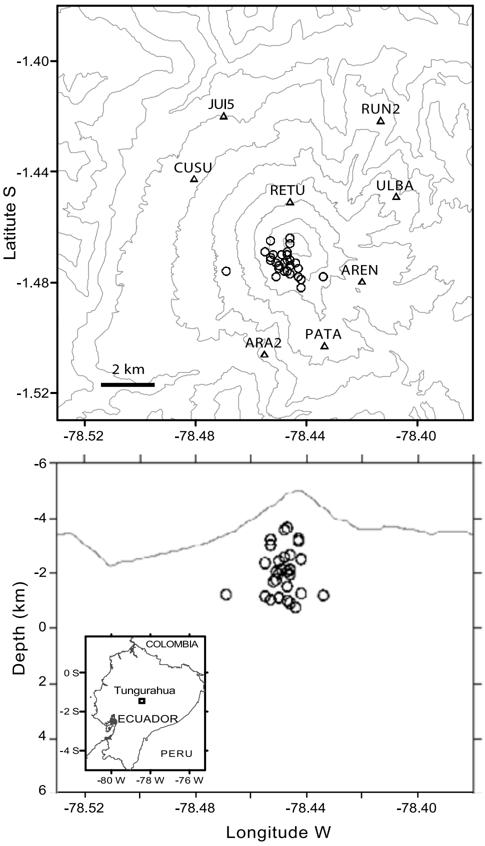

Figure 1. Hypocenters (open circles) of the LP events and location of seismic stations (open triangles) operated by the Instituto Geofísico, Escuela Politécnica Nacional. The inset shows the location of Tungurahua Volcano in Ecuador.

between 4 and 60 (see *Kumazawa et al.* [1990] and *Kumagai and Chouet* [2000] for details of the theory and procedure). Densely populated regions in the *f*–*g* diagrams represent signals for which the complex frequencies are stably determined for different AR orders, while scattered points represent incoherent noise. The complex frequency of each waveform was conventionally determined by taking the mean value of the estimates of ten successive AR orders that contained the least variance. The errors in the complex frequency were estimated from the variance of the estimates of the ten successive AR orders. We analyzed 57 LP events to determine the complex frequencies of the dominant spectral peaks, and their temporal variations are shown in Figure 4. Both the frequency and *Q* show systematic trends during the swarm. The frequency gradually decreased from 3.5 to 2 Hz, whereas *Q* gradually increased from 100 to 400 with wide scattering along this trend. In view of the smooth trend in the observed frequency, it may be reasonable to assume that repeated triggering of a single resonator was the source of the LP events during this swarm, while the scatter of *Q* may be attributed to errors and instabilities that stem from fitting exponentially decaying oscillations in the spectral analysis.

3. The Crack Model

[6] In order to interpret the observed temporal variations in the complex frequencies of the LP events, we have used the acoustic properties of a crack containing various types of magmatic and hydrothermal fluids [*Kumagai and Chouet*, 2000, 2001]. To obtain long-lasting oscillations with *Q* significantly larger than 100 in the crack model [e.g., *Chouet*, 1986, 1988], a large velocity contrast between the surrounding rock and fluid is required. Such a large velocity contrast is achieved between an ash-gas or water droplet-gas mixtures in a crack and the surrounding solid rock. The LP events, especially in the late stage of the swarm, show *Q* values around 400. Based on the results presented by *Kumagai and Chouet* [2000, 2001], such very high *Q* values may only be achieved by an ash-gas mixture. We performed hypocenter determinations of the LP events using first-arrival times of relatively clear onsets recorded at more than 5 stations, which suggest that the source of the LP events may be located at a depth below 1 km from the summit (Figure 1). In the hypocenter determinations, we used the one-dimensional layered *P*-wave velocity model obtained by *Molina* [2001] with a slight modification, in which the *P*-wave velocity ranges from 3 to 5.5 km/s down to the depth of 6 km below the sea level. Our hypocenter determinations show scattered positions over almost 3 km

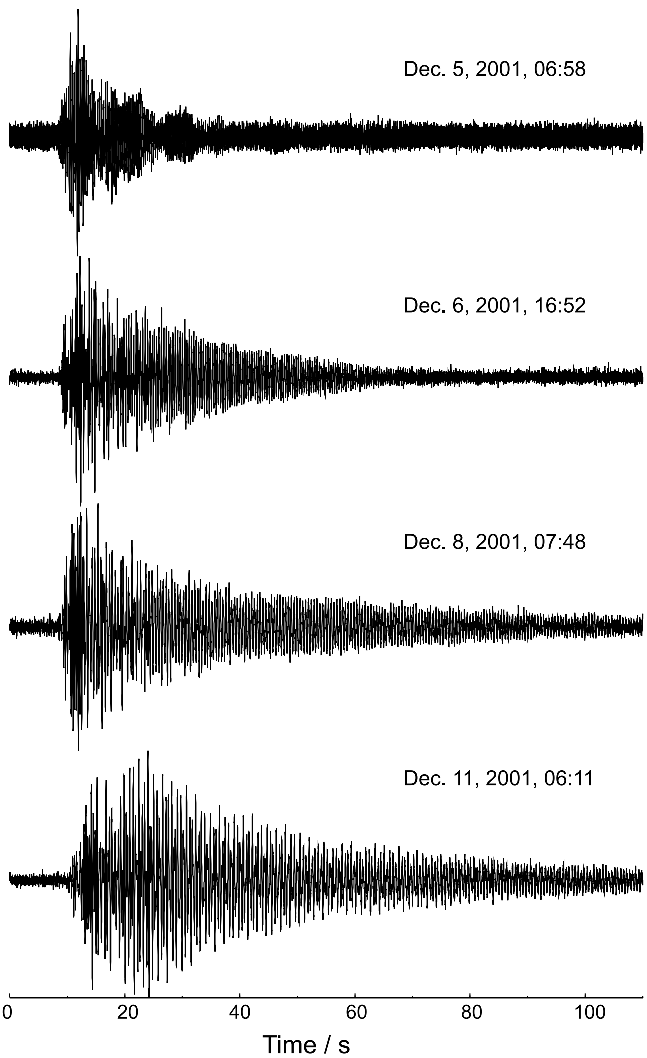

Figure 2. Waveforms of LP events observed at RETU. The event times are based on the Greenwich Meridian Time (GMT).

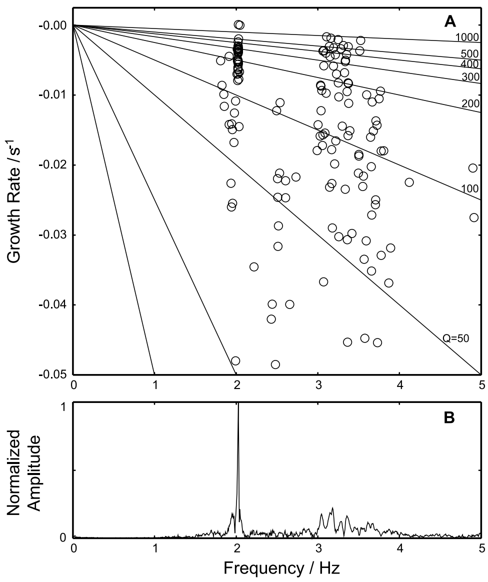

Figure 3. (A) Plots of the complex frequencies of individual wave elements for all the trial AR orders (4–60) estimated for the LP event that occurred at 7:48 (GMT) on 8 December 2001 shown in Figure 2. (B) Amplitude spectrum estimated for this event.

vertically (Figure 1), which may be attributed to the errors originated in the difficulty to read emergent onsets of the LP events. A water droplet (liquid water) may not exist at the estimated source depth, since the critical pressure and temperature of water are 22 MPa (roughly 1 km depth) and 646 K, respectively. We may therefore reasonably assume that the fluid at the source of the LP events is an ash-gas mixture.

[7] We estimated the dimensionless frequency (ν) and Q of the crack resonance containing the ash-steam mixture following the technique presented by *Kumagai and Chouet* [2000], with a mixture temperature of 1200 K and rock density and P-wave velocity (α) 2600 kg/m^3 and 4000 m/s respectively, and possible source depths 1–3 km beneath the summit (see Figure 1). Ash particles are assumed to be 10 μm in diameter, with density of 2200 kg/m^3 and the specific heat of 954 J/(kg K). The sound speed and density of the ash-gas mixture were calculated by the dusty-gas theory elaborated by *Temkin and Dobbins* [1966]. This theory assumes no collisions between particles, and therefore may be applicable to the mixture with gas-volume fraction larger than 50%. We used the crack geometrical parameters $W/L = 0.5$ and $L/d = 10^4$, where L, W, and d are the crack length, width, and aperture, respectively, and the transverse mode with wavelength $2W/5$ [*Kumagai and Chouet*, 2000] for our interpretation of the complex frequencies of LP events.

[8] The resultant ν and Q as a function of gas-volume fraction were used to fit the observed temporal variations in f and Q assuming a proportionality between the gas-volume fraction and time by trial and error, in which we used the relation $f = \nu\alpha/L$ [e.g., *Chouet*, 1986]. The fits are shown in Figure 4. Assuming the value of L ranging from 200 and 240 m in the possible source depth range, the decreasing and increasing trends in observed f and Q are fairly reproduced by f and Q of the crack resonance (Figure 4). The basic decreasing and increasing trends of f and Q against the gas-volume fraction as shown in Figure 4 are stable features for a crack containing the ash-gas mixture [*Kumagai and Chouet*, 2001], although the actual range of the gas-volume fraction or ash content in the crack and sizes of the crack depend on the assumed resonance mode and crack parameter values (e.g., P-wave velocity and density for the rock matrix and crack geometries). Note also that the effect of particle collisions in the ash-gas mixture should be fully examined, since the estimated gas-volume fraction of the mixture in the late stage of the LP swarm activity is less than 50%, which may be outside of the limit of the dusty-gas theory. This point is open to future studies.

[9] On the other hand, the decreasing trend of the observed frequency may be interpreted as a gradual increase of the crack size under fixed acoustic properties of the fluid in the crack. However, a change in the crack size with fixed L/d does not affect Q [*Kumagai et al.*, 2002b], and therefore does not explain the increasing trend of the observed Q. It may be also possible to assume a change in L/d under fixed acoustic properties. As L/d increases in the crack, f decreases but Q also decreases [*Kumagai and Chouet*, 2001], which is not consistent with the observations. Therefore, the crack model suggests that the observed temporal variations may only be explained by a gradual increase of the ash content in the crack at the source of the LP events, although the range of the ash content and sizes of the crack depend on the assumed mode and parameter values.

4. Discussion

[10] We thus interpret the LP activity as follows. As a magma intrudes into a shallower part of the volcano, a

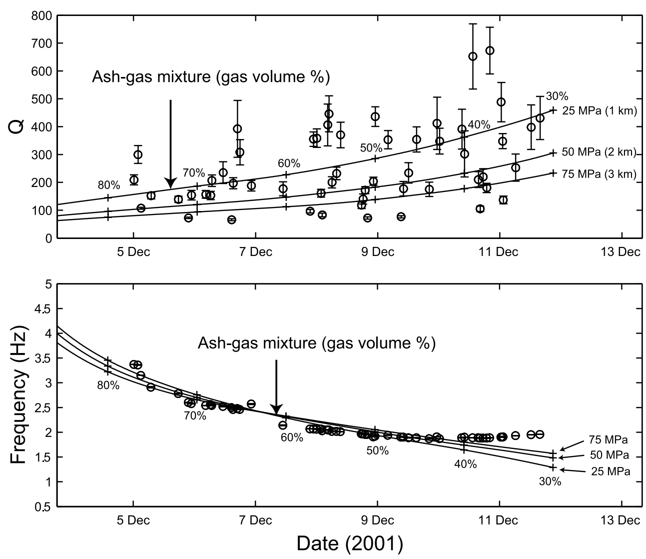

Figure 4. Temporal variations in frequency and Q determined for LP events. The solid lines show the best fits of frequency and Q calculated for a crack containing the ash-gas mixture at various pressures between 25 and 75 MPa corresponding to the source depths between 1 and 3 km below the summit, in which we assumed the crack lengths of 200, 230, and 240 m at the depths of 1, 2, and 3 km, respectively.

pressurized condition is reached in the magma through decompression-induced degassing and vesicle growth, which begins to produce ash particles with gases. The released ash-laden gas is rapidly injected into a pre-existing crack in the conduit just above the magma system, inducing the resonance of the crack or an LP event. This process, which is similar to one proposed for LP events in Galeras Volcano, Colombia [*Gil Cruz and Chouet*, 1997], occurs repeatedly and accumulates ash particles in the conduit, which results in the temporal variations in the frequency and Q of the LP events. Finally, the conduit is almost filled with ash particles, and accordingly the resonance of the crack is no longer excited. The fact that the eruption activity of Tungurahua intensified after this LP activity suggests that further pressurization of the magmatic system eventually opens the entire conduit, resulting in the ash emissions followed by magmatic eruptions.

[11] Recently, *Tuffen et al.* [2003] proposed a possible mechanism for the repetitive generation of ash-laden gas from a magma. They consider a viscoelastic vesiculated magma, which is under pressurization due to sustained bubble growth inside the magma. As stress due to the pressurization reaches the shear strength of the magma, a brittle fracture occurs, releasing ash-laden gas from the fracture. Subsequent viscous deformation of the magma leads to rapid welding and healing of the fracture, and then this process repeats itself. This self-trigger mechanism due to the viscoelastic behavior of a magma may therefore explain the repetitive occurrences of the LP events in Tungurahua.

[12] It should be noted that the source process proposed in this study is quite different from the one associated with similar LP events showing long-lasting oscillations at Kusatsu-Shirane Volcano, Japan, which are interpreted as the resonances of a hydrothermal crack in the aquifer system [*Kumagai et al.*, 2002a, 2002b; *Nakano et al.*, 2003], suggesting a wide variety of the source processes associated with LP events. The complex frequencies of LP events and their temporal variations are thus particularly useful to diagnose the state of fluids and probe processes within volcanic systems. Further links to experimental, theoretical, and geological studies will provide a better physical understanding of the source dynamics associated with LP events as a useful indicator of impending eruptions, thereby helping our efforts to predict eruptive behavior and mitigate volcanic hazards.

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