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Monochromatic infrasonic tremor driven by persistent degassing and convection at Villarrica Volcano, Chile

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[1] Infrasonic data collected at Villarrica volcano (Chile) in March 2009 show a sustained, continuous, infrasonic oscillation (tremor) with a monochromatic low frequency content at ~0.75 Hz. This tremor is extremely stable in time both at the summit and at a distal (~4 km) small aperture array. Infrasonic tremor is characterized by discrete high amplitude bursts with a cyclic recurrence time of ~40 s and is well correlated (0.93) with seismic tremor. These new data are compared with previous datasets collected in 2002 and 2004 during different levels of activity. All data show the same persistent infrasonic tremor and have the same strong correlation with seismic tremor. The stability and correlation of infrasonic and seismic tremor indicate the existence of a sustained and continuous process, which we suggest is related to the gravity-driven bubble column dynamics responsible for conduit convection. **Citation:** Ripepe, M., E. Marchetti, C. Bonadonna, A. J. L. Harris, L. Pioli, and G. Ulivieri (2010), Monochromatic infrasonic tremor driven by persistent degassing and convection at Villarrica Volcano, Chile, *Geophys. Res. Lett.*, *37*, L15303, doi:10.1029/2010GL043516.

1. Introduction

[2] Activity at Villarrica (Chile) is dominated by continuous degassing of a basaltic-andesitic magma from a persistently active summit vent. The depth of the free surface within the conduit changes with time from ~20 m to >150 m, with activity associated with the continuous degassing process being characterized by gas bursting and explosive activity from vents that are 5 to 20 m in diameter [*Gurioli et al.*, 2008; *Palma et al.*, 2008], as well as by occasional lava lake activity [*Witter et al.*, 2004].

[3] Measurements of SO_2 flux at Villarrica by *Witter et al.* [2004] and *Palma et al.* [2008] indicate a highly variable SO_2 flux with mean values of ~200 t/d. *Witter et al.* [2004] suggest that the persistent (excess) degassing is consistent with magma column convection. Seismic activity at Villarrica is quite well described and consists mostly of persistent seismic tremor [*Fuentealba et al.*, 2000; *Ortiz et al.*, 2003; *Calder et al.*, 2004; *Palma et al.*, 2008], with a frequency content of 0.9 to 2.3 Hz [*Fuentealba et al.*, 2000]. The amplitude is modulated by emergent transients lasting <60 s, which are associated with mild Strombolian explosions or discrete outgassing pulses [*Fuentealba et al.*, 2000; *Palma et al.*, 2008]. This degassing process also generates infrasonic transients hinting at a sustained sequence of bursting gas slugs occurring every 90 to 100 s [*Johnson et al.*, 2004; *Gurioli et al.*, 2008; *Marchetti et al.*, 2009]. All investigations point to efficient two-phase flow dynamics where degassing of the free surface drives both seismic and infrasonic activity.

[4] We present here the first evidence of a monochromatic infrasonic signal at Villarrica. Our data provide new insights into the conduit dynamics feeding the degassing activity at Villarrica, with implications for other similar persistently degassing systems. The frequency content of the infrasonic "tremor" is near-stable through time and shows the same amplitude modulation of the seismic tremor. The persistency of the infrasonic tremor indicates the presence of a constant, gas-bubble-driven, dynamic process whose variation is forced by changing gas flux regimes.

2. Instrument Setup and Volcanic Activity

[5] Geophysical experiments at Villarrica volcano were performed during three field surveys in December 2002, November 2004 and March 2009 [*Johnson et al.*, 2004; *Gurioli et al.*, 2008]. As part of these campaigns, seismic, infrasonic and thermal sensors were installed on the crater rim to provide an integrated analysis of the degassing activity (Figure 1). During the December 2002 experiment, data were collected continuously at the summit for a 10-day-long period. Instead, during the November 2004 and March 2009 experiments, summit-based acquisition periods lasted between 3 and 6 hours. At the same time, seismic and infrasonic stations located at the base of the volcano (~4 km from the vent) ran for 6–9 days. In March 2009 infrasound was also recorded using a four-element infrasonic array with an aperture of 170 m. This was deployed at an elevation of ~1500 m. a.s.l. on the north-west flank of the volcano at a distance of ~4 km from the summit crater (Figure 1).

[6] Pressure sensors deployed both on the summit and at distal stations consisted of *All Sensors* pressure transducers in March 2009, with a sensitivity of 25 mV/Pa and resolution of 0.02 Pa in the 0.1–50 Hz frequency band. In November 2004, *MKS* differential pressure transducers were used, with a sensitivity of 38 mV/Pa in the 0.01–50 Hz frequency band, with electret microphones having a nominal sensitivity of 7 mV/Pa being deployed in December 2002. While seismic signals were recorded in 2004 and 2009 with a Guralp CMG 40T (30 s) broad-band seismometer, in 2002 a vertical short-period Mark (1 s) seismometer was deployed at the summit crater.

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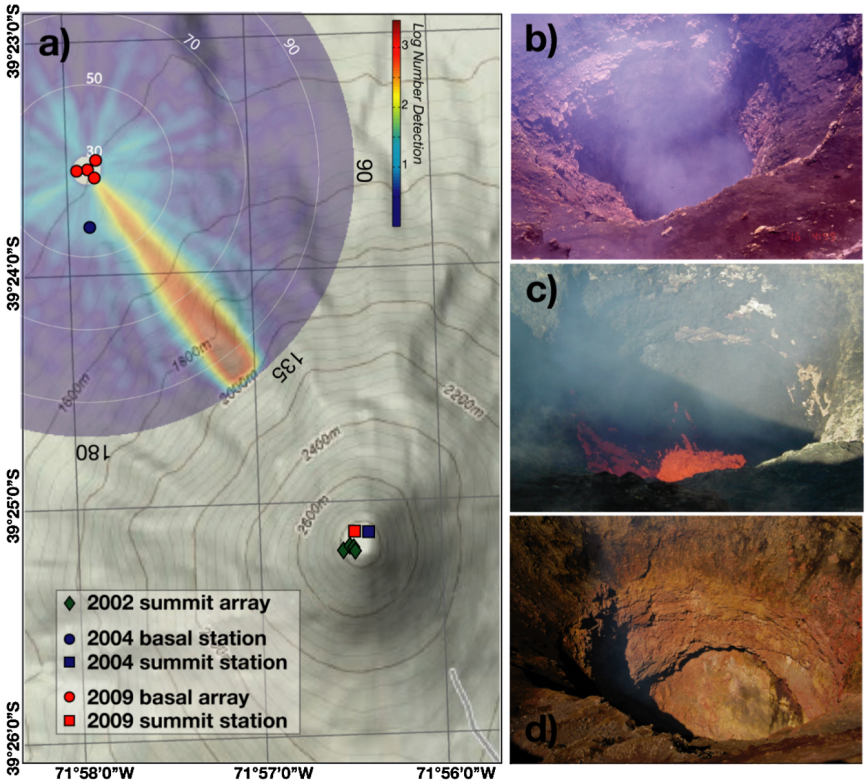

Figure 1. (a) Map of Villarrica showing the position of the stations deployed during the three field experiments, and the number of detections (log scale) of coherent infrasound across the 2009 array (06-11/03/2009) as a function of multi-channel semblance (ray) and infrasonic back-azimuth, showing that infrasound is coming from the summit of Villarrica (~140°N). Pictures of the summit crater at Villarrica during the (b) 2002, (c) 2004 and (d) 2009 experiments taken from the rim.

[7] The level of the free surface during each experiment was ~60 m below the crater rim in November 2004, and somewhat deeper (>150 m) in November 2002 and March 2009 (Figure 1). Degassing and explosive activity were also very different between the three periods. November 2004 was a period of relatively high activity [*Palma et al.*, 2008], characterized by mild Strombolian explosions and lava spattering from a ~20 m wide vent [*Shinohara and Witter*, 2005; *Gurioli et al.*, 2008]. While gas bursting and emissions of scoria and bombs that rose and fell within the crater characterized activity in December 2002, degassing in March 2009 was weak with no visible or audible explosions.

3. Monochromatic Infrasonic Tremor

[8] During the March 2009 experiment, the small-aperture infrasonic array detected a persistent low frequency (from 0.5 to 2 Hz) infrasonic signal characterized by a sustained, monochromatic (0.75 Hz) oscillation with a large amplitude modulation (Figure 2a). This signal was highly coherent across the array (Figure 2a) and the multi-channel semblance analysis [*Ripepe and Marchetti*, 2002] revealed that all of the infrasonic energy (>0.3 Hz) arrived from the direction of the summit (Figure 1a). The infrasonic waveforms recorded by the summit system were near-perfectly correlated (>0.98), in the 0.3–3 Hz band, with the data from the array at a distance of ~4 km (Figure 2a). The high correlation between the two stations demonstrates that the monochromatic spectrum of this persistent infrasonic oscillation is not due to an atmospheric path effect, but is generated by the shallow system (conduit) dynamics. Waveforms recorded at 200 m and 4000 m show a time delay consistent with a sound speed of 340 m/s and an amplitude decay explained by geometric spreading (1/r). This shows that infrasound can maintain unaltered information (Figure 2a) on the source process when collected at a distance of several kilometers from the vent, and suggests that infrasonic activity at Villarrica can be easily monitored from a few kilometers.

[9] This infrasonic oscillation (tremor) was continuously recorded during the entire six-day-long duration of the 2009 experiment, showing no significant frequency changes, harmonics or gliding effects (Figure 2b), as have been observed at Arenal [*Hagerty et al.*, 2000]. From this point of view infrasonic tremor recorded at Villarrica is somewhat unique and indicates a highly stable source process. To explore this spectral stability, we analyzed the infrasonic records collected during the experiments of December 2002 and November 2004. Once corrected for the frequency response of the different pressure sensors used during the experiments, spectral analysis revealed that also in 2002 and 2004 infrasound was characterized by a similar low frequency signal with the same monochromatic behavior (Figure 2b). The spectral peak was at 0.75 Hz in 2002 and ~1 Hz in 2004.

4. Seismo-acoustic Tremor

[10] Seismic data collected at the summit during the three experiments show mostly tremor (Figure 2a) with a stable

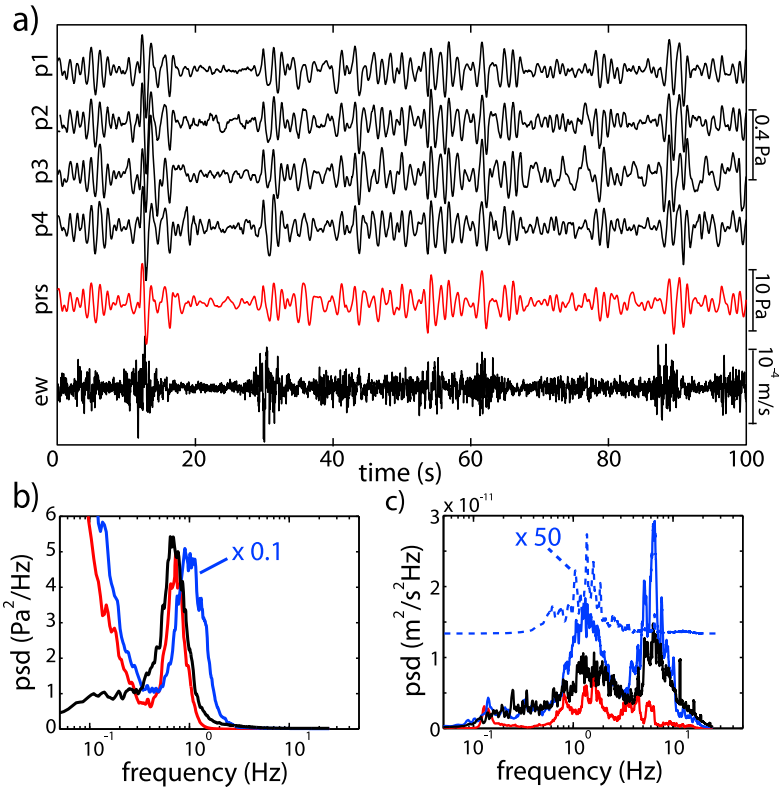

Figure 2. One-hundred-second-long samples of infrasonic data recorded in 2009 at the summit of Villarrica (*prs*) and seismo-acoustic data recorded by the four-elements of the array (*p1-p4*) and co-located seismometer (ew). (a) Infrasonic data are 0.3–3 Hz band-pass filtered and summit infrasound is delayed by 11.8 s. Power spectral density for (b) infrasonic and (c) seismic data sets recorded at the summit during 2009 (red), 2004 – reduced by a factor of 10 - (blue) and 2002 (black). Tremor recorded at the distal station (~4 km) shows a peaky spectrum (dashed line) concentrated in the low (0.6 to 3 Hz) frequency band.

spectral content within two major spectral bands spanning the 0.6 to 3 Hz and 5 to 10 Hz ranges (Figure 2c). However, at the distal stations the high-frequency component is lost (Figure 2c) and tremor is characterized by the low-frequency content (0.6–3 Hz), which typically dominates the volcano-seismicity at Villarrica [*Fuentealba et al.*, 2000] and falls within the same frequency range (0.5–2 Hz) of the infrasonic tremor. Spectral amplitude also varies according to the intensity of the observed activity, being larger during the relatively vigorous explosive (or degassing) phase of November 2004, and lower in March 2009 and December 2002 when the free surface was relatively deep inside the conduit and activity levels were lower (Figure 1b and 1d). This is a quite well-known behavior at Villarrica [*Palma et al.*, 2008] and other open-vent volcanic systems characterized by persistent magma degassing such as Stromboli, Etna and Masaya [e.g., *Ripepe et al.*, 1996, 2001; *Métaxian et al.*, 1997]. Spectral stability and amplitude changes of the low-frequency component point to a stationary source intimately related to the dynamics of the magma degassing in the shallow system.

5. Seismo-Acoustic Periodic Energy Oscillation

[11] At a longer time scale of hours to days, the amplitude of the low-frequency (<3 Hz) component of the seismic tremor is modulated by discrete transients or bursts of high amplitude phases. Such high-amplitude phases have already been described Villarrica and are explained as being produced by gas bursting at the free surface [*Fuentealba et al.*, 2000; *Palma et al.*, 2008]. We have emphasized this amplitude modulation by calculating the root mean square (RMS) of the amplitude distribution in 10-second-long windows on the seismic signals filtered in the 0.5 to 3 Hz band (Figure 3). The RMS is a proxy for the instant energy release and provides a simple, but effective, picture of the energy fluctuations of the source. Such RMS seismic tremor fluctuations at Villarrica have been already reported and explained as related to the degassing activity [*Palma et al.*, 2008], a hypothesis supported by our infrasonic records. In fact, RMS of seismic tremor is well-correlated (0.93) with the RMS calculated on the infrasonic signal revealing that these two parameters are responding to the same source process (Figure 3). The spectral analysis of the seismic and infrasonic RMS amplitude for the 2009 data set shows that the source is radiating energy at quite a regular interval of ~40 s (Figure 3f). This well correlated, periodic, behavior of the energy released as seismic and infrasonic tremor is also confirmed by the analysis of the 2002 (Figure 3a) and 2004 (Figure 3b) experiments. Spectral analysis of both seismic and infrasonic RMS show a clear periodicity of ~100 s in 2002 and of ~60 s in 2004 (Figure 3d and 3e).

6. Discussion

[12] Correlation between seismic and infrasonic tremor amplitude fluctuations has been reported at other open-vent

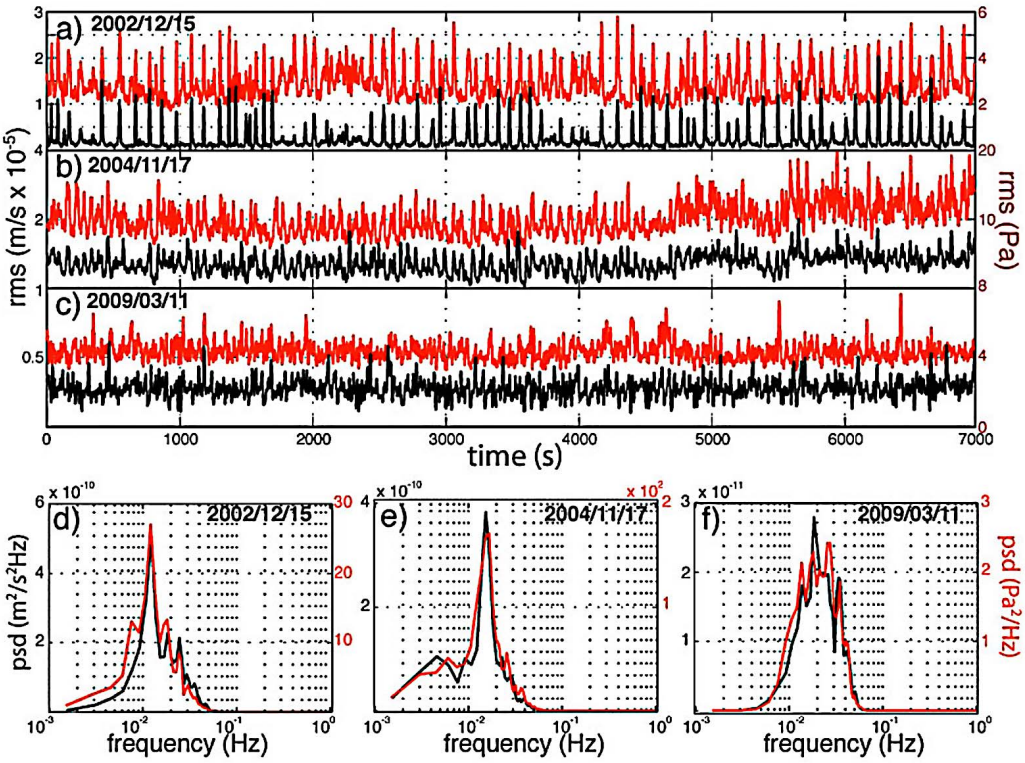

Figure 3. (a–c) RMS amplitude, evaluated using 10-second-long windows, for a 2-hour-long sample of seismic (black) and infrasonic (red) tremor recorded during the three experiments in Dec. 2002, Nov. 2004 and March 2009. (d–f) Power spectral density of the same RMS amplitude of seismic (black) and infrasonic (gray) tremor.

degassing volcanoes such as Stromboli [*Ripepe et al.*, 1996], Karymsky [*Lees et al.*, 2004], Arenal [*Hagerty et al.*, 2000] and Etna [*Ripepe et al.*, 2001] and indicates a link to a common source process. In some cases, infrasonic tremor is characterized by small transients repeating at short time intervals (within seconds) and is associated with small bursting of gas at the surface in non-equilibrium conditions (active degassing). In contrast, at Villarrica, there is no evidence of clear transients in the infrasound records that could be related to an active degassing process driven by gas bursting. The monochromatic infrasonic tremor at Villarrica thus appears not to be driven by slug flow dynamics, as traditionally evoked for degassing and explosion dynamics at the other systems listed above, but instead by a more stationary and less explosive process. The monochromatic infrasound could result from resonance of the air column above the persistently degassing magma column. However, assuming a 100 m wide conduit, the observed 0.7 and 1 Hz spectral peaks could result only if the magma level was at a depth of 370 and 220 m, respectively. This is much deeper than observed. Conduits with smaller diameters will only result in deeper magma levels. We thus think air column resonance is unlikely as an explanation for our infrasound.

[13] SO_2 degassing involves a far greater magma volume than the volume of magma ejected at Villarrica, suggesting an efficient convective process within the conduit to remove the unerupted degassed volume from the shallow system [*Witter et al.*, 2004]. In addition, SO_2 flux at Villarrica is well linked to tremor amplitude and to changes in activity [*Palma et al.*, 2008]. This points to conduit convection dynamics characterized by a constant recycling of degassed magma. Within this model, the very stable, monochromatic infrasonic signal likely reflects flow instability in the upward rising bubbly column within the conduit.

[14] Our infrasound shows striking similarities with unimodal frequency pressure oscillations observed in two-phase flow analogue experiments [e.g., *Drahos et al.*, 1991; *Pioli et al.* 2009]. In this two-phase flow regime model, small gas bubbles ascend the conduit. For low gas flow regime, bubbles ascend through a quasi-static liquid. At higher gas flow rates, bubbles tend to cluster leading to a non-uniform bubble number density in the liquid. Gravity will act differently according to the density changes in the two-phase fluid inducing inhomogeneity in the distribution of the bubble number density in the column. This gravity-induced inhomogeneity leads to an oscillatory circulation with the gas bubbles mainly concentrating and flowing upwards in the central part of the column, and the liquid moving downwards in convective cells close to the conduit wall (Figure 4). This phenomenon is quite well-known in the engineering literature, local changes in the gas hold-up (void fraction) induces pressure oscillation of the bubble column with periods becoming shorter for higher superficial gas velocities [*Buwa and Ranade*, 2002]. We suggest that such conduit degassing and convection dynamics apply to Villarrica, and that different amplitude and periodicities for 2002, 2004 and 2009 correspond to variations of degassing rates.

7. Conclusions

[15] Analysis of infrasound collected at Villarrica in 2009 reveals a sustained and continuous low frequency (<1 Hz)

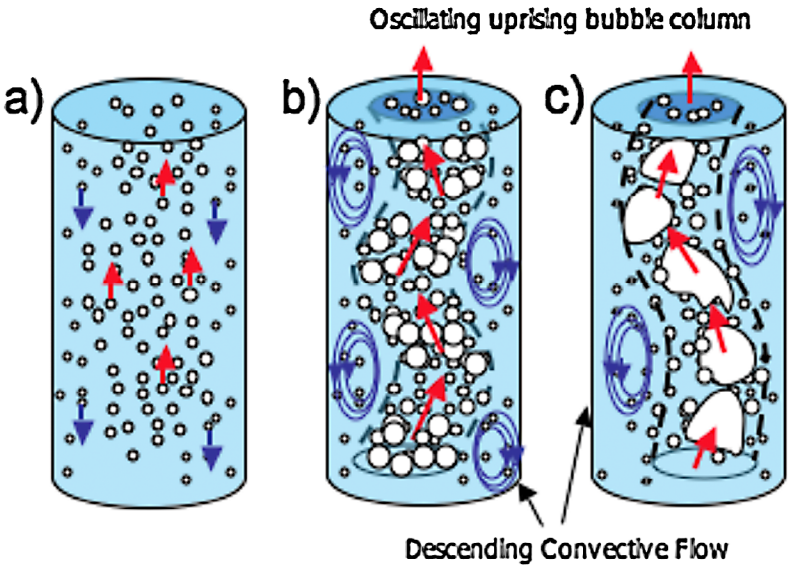

Figure 4. Sketch of the gas flow in a bubble column (redrawn from *Mudde* [2005]). (a) At low gas flow rates buoyant small bubbles rise in a static liquid column. When the gas flow rate increases, (b) while rising bubbles tend to cluster in the center of the column, circulation cells of liquid descend at the margins. (c) At higher gas flow rates unstable bubbly flow develops.

oscillation modulated by high amplitude bursts spaced at quite regular (~60 s) intervals. Seismic and infrasonic tremor shows the same amplitude changes indicating a cyclic energy release induced by a common source process. The lack of clear transients in the infrasonic tremor is evidence for a degassing process that differs from that operating at other open-system volcanoes such as Stromboli where most of the degassing is generated by the bursting of small gas bubbles at the surface of the magma column. Infrasound at Villarrica suggests that degassing occurs very close to the equilibrium condition, perhaps the result of efficient magma convection.

[16] Stable monochromatic oscillations have been observed in two-phase flow analogue experiments and are explained as the density-driven oscillation of the bubble column as the result of a variable distribution of the gas fraction within the liquid [e.g., *Mudde*, 2005]. We suggest that the vigorous recycling of degassed magma drives gravity-driven oscillation in the bubbly column, which is recorded as seismic and infrasonic tremor. However, spectral differences between the seismic (0.6–3 Hz) and infrasonic (0.5–2 Hz) tremor point to a different coupling of the oscillating bubbly column with the ground and the atmosphere. While infrasound could be directly related to oscillation of the magma level in response to oscillations in the column degassing dynamics, seismic tremor could result from a more complex interaction between the magma column and the conduit walls, and/or to the scattering properties of the ground, as suggested by the peaky spectrum of tremor recorded at greater distances (Figure 2c).

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