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Volcanic eruptions observed with infrasound

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[1] Infrasonic airwaves produced by active volcanoes provide valuable insight into the eruption dynamics. Because the infrasonic pressure field may be directly associated with the flux rate of gas released at a volcanic vent, infrasound also enhances the efficacy of volcanic hazard monitoring and continuous studies of conduit processes. Here we present new results from Erebus, Fuego, and Villarrica volcanoes highlighting uses of infrasound for constraining quantitative eruption parameters, such as eruption duration, source mechanism, and explosive gas flux. *INDEX TERMS:* 0394 Atmospheric Composition and Structure: Instruments and techniques; 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280); 8494 Volcanology: Instruments and techniques. **Citation:** Johnson, J. B., R. C. Aster, and P. R. Kyle (2004), Volcanic eruptions observed with infrasound, *Geophys. Res. Lett.*, *31*, L14604, doi:10.1029/2004GL020020.

1. Introduction

[2] Understanding volcanic eruptions requires robust estimation of fundamental physical parameters such as the detailed history of gas flux. Seismograms are often ineffective for such analyses because they are typically complex superpositions of source processes and wave propagation phenomena in strongly scattering media [*Chouet*, 1996]. However, the acoustic airwaves produced by eruptions and radiated to distances of a few km tend to exhibit comparatively low atmospheric scattering/dissipation, and experience predictable (and frequently minor) echoing, site, or weather-dependent effects. For these reasons infrasound monitoring much more readily enables quantitative assessment of eruptive degassing. In basic monitoring situations, high-amplitude airwaves provide unequivocal evidence of eruptive degassing in progress. Such infrasound is also largely unaffected by cloud cover and does not rely on line-of-sight view of vents, as is the case with ancillary satellite or other visual/infrared observations. For these reasons, acoustic monitoring and quantitative analysis of infrasonic pressure waves is becoming increasingly well established at active volcanoes worldwide (Table 1).

[3] An illustrative example of the merits of infrasound can be shown at Fuego Volcano, Guatemala, where pyroclastic explosions occurred several times each hour during January 2003. At a monitoring site 2.6 km from the summit crater, explosion plumes were first visible about 1.5 s before the first emergent seismic arrivals and 8 s before the first impulsive infrasonic arrival (Figure 1). Though the seismicity associated with these events tended to be complex and drawn out in time, the acoustic records depicted an initial high-amplitude pressure pulse (compression/dilatation) followed by lower-amplitude 'rumbling' continuing for tens of seconds. The primary pulse of the Fuego infrasound often exceeded 40 Pa ($\sim$126 dB) 2.6 km from the vent and was accompanied by an audible boom that sounded like distant thunder (<100 dB). As observed at other volcanoes [*Vergniolle et al.*, 1996; *Johnson*, 2003], the Fuego infrasonic bandwidth appears to have several orders of magnitude greater spectral energy than the audible bandwidth.

[4] Volcanoes may efficiently generate long-wavelength (17 to 340 m) near-infrasound (20 to 1 Hz) because the vent source dimension, considered here to be the area of vigorous free surface degassing, is frequently much larger than typical sonic wavelengths. Though debate remains as to whether some volcanic infrasound can be generated internally (e.g., within a volcano's magma conduit [*Buckingham and Garcés*, 1996; *Garcés and McNutt*, 1997]), or due to vibrational modes of large intact gas bubbles [*Vergniolle and Brandeis*, 1994; *Vergniolle et al.*, 1996], the majority of high-amplitude volcanic infrasound is explicable by the eruptive acceleration of compressed volatiles from vents [*Reed*, 1987; *Firstov and Kravchenko*, 1996; *Yamasato*, 1997; *Ripepe and Gordeev*, 1999; *Gabrielson*, 1998; *Johnson*, 2003]. Such infrasound may result from either a long-period acceleration of erupted gas at a compact vent or from an impulsive source distributed over a large region. In both cases, it is possible to model infrasound generation based upon the linear theory of sound [*Lighthill*, 1978; *Dowling*, 1998] where the acoustic wavefield is composed of a superposition of n volumetrically expanding monopole point sources. For a fixed source at the surface of a rigid half space radiating into a homogeneous atmosphere of velocity c, the excess pressure recorded at x (located distances r_i from each source) is $p(x, t) = \sum_{i=1}^{n} \frac{Q_i(t - r_i/c)}{2\pi r_i}$, where each Q_i is proportional to the time derivative of the associated mass flux. For a monopole point source, with negligible propagation effects, a first-order flux estimate is thus $q(t) = 2\pi r \int p(t + r/c)dt$ [*Firstov and Kravchenko*, 1996; *Johnson*, 2003].

2. Volcano Infrasound Case Studies

[5] Volcano infrasound may be modeled by either a series of sources distributed over a diffuse vent region, or in special cases, as a single point source from which a gas or fluid volume is erupted. A point source model is suitable for single-bubble bursts at the intermediate viscosity ($\sim 10^4$ Pa-s) phonolitic lava lake at Mount Erebus, Antarctica [*Dibble*, 1994], where infrasonic wavelengths are large relative to source dimension, and the source history is

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Table 1. Summary of Some Volcanoes With Infrasound Studies

Volcano	Chemistry	Associated Activity	Reference	Year	Pa[a]
Arenal	andesite	Strombolian/Vulcanian activity	*Hagerty et al.* [2000]	1997	100
Volcán de Colima	andesite	Vigorous Vulcanian activity	unpublished	2003	10
Erebus	phonolite	infrequent large bubble bursts from lava lake	*Rowe et al.* [2000]	1997–98	200
Etna	basalt	lava lake degassing explosions	L. Evers (unpublished manuscript, 2001)[b]	2001	?
Fuego	basaltic-andesite	discrete Vulcanian explosions	this paper	2003	100
Guagua Pichincha	dacite	dome explosions/dome collapse?	*Johnson et al.* [2003]	1999	?
Karymsky	andesite	discrete Strombolian explosions	*Johnson and Lees* [2000]	1997–99	10
Kilauea	basalt	flow in lava tube	*Garcés et al.* [2003]	2002	0.2
Klyuchevskoi	basalt	fissure and summit eruptions	*Firstov and Kravchenko* [1996]	1983, 87	25
Sakurajima	andesite	Vulcanian activity/vigorous explosions	*Garcés et al.* [1999]	1985–88	40
Sangay	andesite	discrete Strombolian explosions	*Johnson et al.* [2003]	1998	20
Santiaguito	dacite	pyroclastic eruptions from dome	*Johnson et al.* [2004]	2003	2
Shishaldin	basalt	vigorous Strombolian activity	*Caplan-Auerbach and McNutt* [2003]	1999	?
Stromboli	basalt	discrete explosions/persistent degassing	*Ripepe and Marchetti* [2002]; others	1999, 92	25
Suwanosejima	andesite	vigorous ash explosions	*Iguchi and Ishihara* [1990]	1989	?
Tokachi	andesite	phreato-magmatic eruptions	*Iguchi and Ishihara* [1990]	1988–89	?
Tolbachik	basalt	fissure eruption	*Firstov and Kravchenko* [1996]	1975–76	200
Tungurahua	andesite	Strombolian and Vulcanian activity	*Johnson et al.* [2003]	1999	?
Unzen	dacite	dome exhalations/pyroclastic flows	*Yamasato* [1997]	1992	2
Villarrica	basalt	persistent degassing from lava lake	this paper	2002	20

[a] Maximum peak excess pressures in the near-infrasound bandwidth as cited in reference. For comparative purposes these pressures have been reduced here to 1 km, assuming an inverse pressure decrease with radial distance from vent.

[b] Available at http://www.knmi.nl/~evers/infrasound/events/010729/etna.html.

simple. Erebus video reveals that intact bubbles with radii over 5 m emerge then burst from the surface of the lava lake, spewing volcanic bombs and ash, and releasing over-pressurized volatiles (primarily H_2O and CO_2) [*Aster et al.*, 2003]. Corresponding infrasound waveforms have an N-wave shaped appearance, characteristic of a weak shock wave that is generated during bursting of an overpressurized (bubble) volume [*Blackstone*, 2000]. Erebus N-wave amplitudes observed from 1999 to present have ranged from 2 to 100 Pa at 1 km [*Rowe et al.*, 2000], providing bubble gas mass estimates on the order of $\sim 10^3$ kg for gas pressurized at a few atmospheres (Figure 2) [*Aster et al.*, 2003, 2004]. Gas flux from these infrequent (<1 per day) events, indicates that only a small percentage of the estimated 10^6 kg degassing [*Andres and Kasgnoc*, 1998] is attributable to discrete explosions.

[6] Degassing during lava lake activity at Villarrica, Chile produces more continuous sustained infrasound than at Erebus (Figures 3a–3b). Like Erebus, Villarrica is also a fairly low-viscosity, open-vent system that at times hosts a lava lake at the tip of its conduit. However, following an N-wave onset similar to the Erebus bubble bursts, Villarrica infrasonic codas show continuing pressure oscillations lasting for 5–10 s with dominant energy ~ 0.5 Hz that hint at a sustained sequence of bursting bubble slugs. Although absolute mass flux is not recoverable from these more complex waveforms, the infrasound has time-integrated power that is four orders of magnitude greater than at Erebus, with more than 10^3 discrete degassing events occurring daily during December 2002. If these degassing events are responsible for the bulk of Villarrica's 10^5–10^6 kg/day SO_2 output [*Witter et al.*, 2004], a typical degassing event releases 10^2–10^3 kg of SO_2, with a correspondingly greater total volatile output (SO_2, H_2O, and CO_2).

[7] Basaltic Vulcanian activity at Fuego, Guatemala in January 2003 was considerably more explosive than the Strombolian behavior described at both Erebus and Villarrica. Here, infrasound from explosions also began impulsively, reflecting an abrupt outward acceleration of gases, but the vigorous degassing continued for several tens of s (manifested by a relatively low-amplitude, tremor-like infrasonic coda), which helped to fuel energetic (>1500 m) ash-rich convective plumes. The dominant mechanism of these eruptions is likely the continued explosive foam disruption of small ($\ll 10^{-3}$ m) pressurized vesicles, typical in more volatile-rich, explosive, silicic eruptions [*Sparks et al.*, 1994; *Mangan and Sisson*, 2000]. Although Fuego's explosivity may be attributed in part to the magma's gas-rich nature (>10^6 kg/day flux since 2001 (W. Rose, written communication, 2004)), the observed activity and corresponding infrasound suggest that either the mafic magma behaves viscously or that the vent/conduit geometry

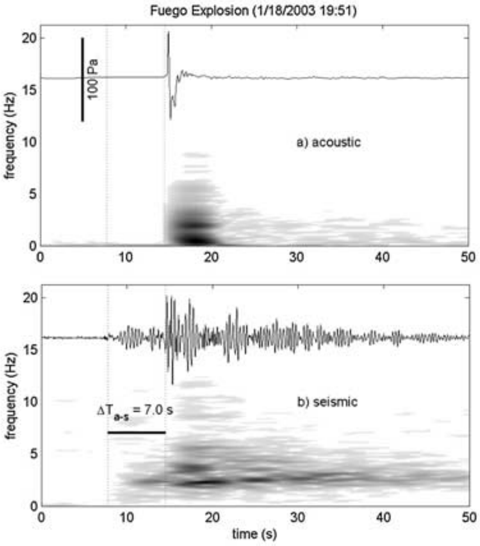

Figure 1. a) Infrasound and b) seismic traces with corresponding spectrograms from a characteristic pyroclastic eruption at Fuego, Guatemala. Ground-coupled airwave is evident on seismic trace and is caused by the primary, initial infrasonic pulse.

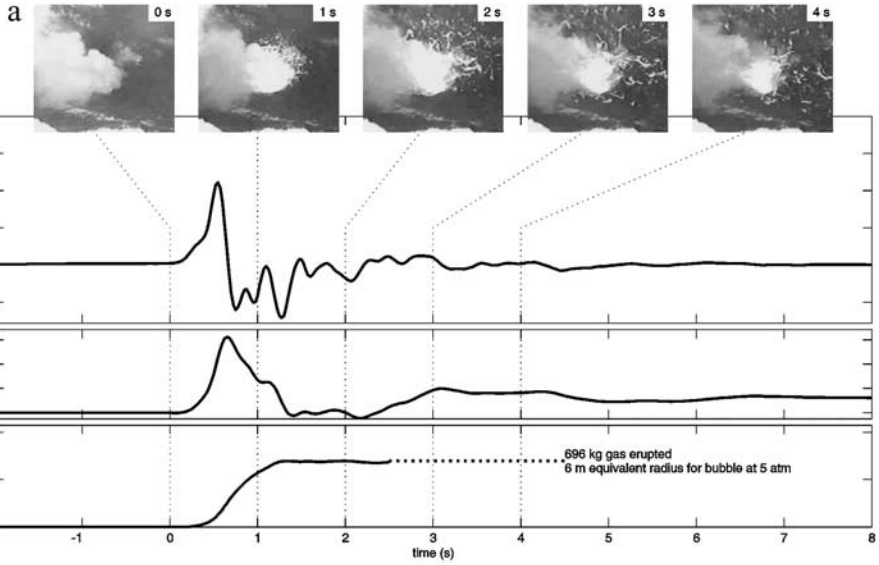

Figure 2. a) Video stills taken at 1-s intervals for a characteristically large (5-m-radius) bubble burst from the Erebus lava lake on Dec. 23, 2000. Infrasound explosion waveform is from a highly similar event occurring on Feb. 19, 2003 at 10:27:10. b) Gas flux and c) cumulative gas flux estimates are recovered through integration of excess pressure traces.

is narrow. Both situations likely inhibit the formation of large individual bubbles. Fuego infrasound (envelope and frequency content) is reminiscent of discrete eruptions at Karymsky and Sangay [*Johnson and Lees*, 2000] and Volcán de Colima (N. Varley, unpublished data, 2003), but differs from eruptive activity at more viscous volcanoes. Very low-amplitude or indiscernible infrasound typically produced by more silicic volcanic systems like Unzen [*Yamasato*, 1997], Pichincha [*Johnson et al.*, 2003], Monserrat (J. Neuberg, written communication, 2003), or Santiaguito [*Johnson et al.*, 2004] may be attributed to dispersed source regions and/or to non-impulsive vent degassing. Non-impulsive surface gas release is likely for vesiculation that occurs along conduit margins at depth.

3. Current State of Volcano Infrasound Studies

[8] Volcano infrasound observations have been made with both single sensors and arrays. To date, infrasonic deployments have included volcanoes ranging from low-viscosity basaltic or phonolitic systems, to basaltic-andesite and andesitic stratovolcanoes, to highly viscous, silicic systems (Table 1). Infrasound arrays and networks, deployed as tight antennas or distributed at various azimuths around a volcano, show tremendous potential for enhanced event detection and localization [*Yamasato*, 1997; *Ripepe and Marchetti*, 2002; *Garcés et al.*, 2003; *Johnson et al.*, 2003; *Johnson*, 2004]. The low velocity of sound (~343 m/s at STP) facilitates precise localization (<few m) of acoustic sources and allows for the tracking of evolving source locations with comparable resolution [*Yamasato*, 1997]. Cross-correlation techniques have been used at multi-vent systems such as Stromboli [*Ripepe and Marchetti*, 2002; *Johnson*, 2004] and Pu'u 'O'o, Kilauea [*Garcés et al.*, 2003] to monitor as many as 6 distinct vents. Integrating infrasound with other geophysical measurements, such as seismic, thermal, gas flux, and video, shows tremendous potential for improved understanding of fluid transport and conduit processes [*Aster et al.*, 2004; *Ripepe et al.*, 2001, 2002]. Comparison of radiated acoustic, seismic, and thermal power [*Johnson et al.*, 2004] promises new insights for eruption source dynamics such as melt properties [*Garcés et al.*,

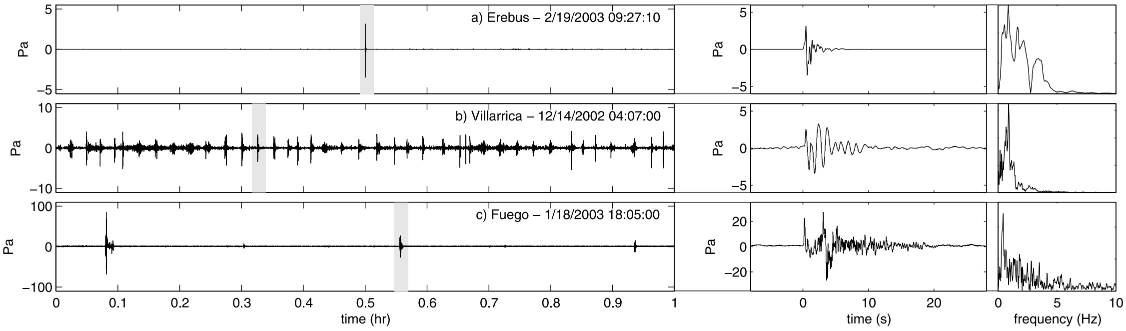

Figure 3. Infrasound traces for discrete eruptions at a) Erebus b) Villarrica, and c) Fuego provide information about the frequency, strength, and style of degassing activity. Excess pressure amplitudes are scaled to approximate reduced pressure equivalents 1 km from the source. Power spectra are normalized.

1998; *Hagerty et al.*, 2000], volatile fragmentation depth, and other source and near-source conditions (J. B. Johnson and R. C. Aster, Relative partitioning of acoustic and seismic energy during Strombolian eruptions, submitted to *Journal of Volcanology and Geothermal Research*, 2004).

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References

Andres, R. J., and A. D. Kasgnoc (1998), A time-averaged inventory of subaerial volcanic sulfur emissions, *J. Geophys. Res.*, *103*(D19), 25,251–25,261.

Aster, R. C., S. Mah, P. R. Kyle et al. (2003), Very long period oscillations of Mount Erebus Volcano, *J. Geophys. Res.*, *108*(B11), 2522, doi:10.1029/2002JB002101.

Aster, R., et al. (2004), New instrumentation delivers multidisciplinary real-time data from Mount Erebus, Antarctica, *Eos Trans. AGU*, *85*(10), 100–101.

Blackstone, D. T. (2000), *Fundamentals of Physical Acoustics*, 541 pp., John Wiley, Hoboken, N. J.

Buckingham, M. J., and M. A. Garcés (1996), Canonical model of volcano acoustics, *J. Geophys. Res.*, *101*(B4), 8129–8151.

Caplan-Auerbach, J., and S. R. McNutt (2003), New insights into the 1999 eruption of Shishaldin volcano, Alaska, based on acoustic data, *Bull. Volcanol.*, *65*(6), 405–417.

Chouet, B. A. (1996), Long-period volcano seismicity: Its source and use in eruption forecasting, *Nature*, *380*, 309–316.

Dibble, R. R. (1994), Velocity modeling in the erupting magma column of Mount Erebus, Antarctica, in *Volcanological and Environmental Studies of Mount Erebus, Antarctica*, *Anarct. Res. Ser.*, vol. 66, edited by P. R. Kyle, pp. 17–33, AGU, Washington, D. C.

Dowling, A. P. (1998), Steady-state radiation from sources, in *Handbook of Acoustics*, edited by M. Crocker, pp. 99–117, John Wiley, Hoboken, N. J.

Firstov, P. P., and N. M. Kravchenko (1996), Estimation of the amount of explosive gas released in volcanic eruptions using air waves, *Volcanol. Seismol.*, *17*, 547–560.

Gabrielson, T. B. (1998), Infrasound, in *Handbook of Acoustics*, edited by M. Crocker, pp. 331–336, John Wiley, Hoboken, N. J.

Garcés, M. A., and S. R. McNutt (1997), Theory of the airborne sound field generated in a resonant magma conduit, *J. Volcanol. Geotherm. Res.*, *78*(3–4), 155–178.

Garcés, M. A., M. T. Hagerty, and S. Y. Schwartz (1998), Magma acoustics and time-varying melt properties at Arenal Volcano, Costa Rica, *Geophys. Res. Lett.*, *25*(13), 2293–2296.

Garcés, M. A., M. Iguchi, K. Ishihara et al. (1999), Infrasonic precursors to a Vulcanian eruption at Sakurajima Volcano, Japan, *Geophys. Res. Lett.*, *26*(16), 2537–2540.

Garcés, M. A., A. Harris, C. Hetzer et al. (2003), Infrasonic tremor observed at Kuml;lauea Volcano, Hawai'i, *Geophys. Res. Lett.*, *30*(20), 2023, doi:10.1029/2003GL018038.

Hagerty, M. T., M. Protti, S. Y. Schwartz, and M. A. Garcés (2000), Analysis of seismic and acoustic observations at Arenal Volcano, Costa Rica, 1995–1997, *J. Volcanol. Geotherm. Res.*, *101*(1–2), 27–65.

Iguchi, M., and K. Ishihara (1990), Comparison of earthquakes and airshocks accompanied with explosive eruptions at Sakurajima and Sawunosejima volcanoes, *Ann. Disaster Prev. Res. Inst. Kyoto Univ.*, *33B-1*, 1–12.

Johnson, J. B. (2003), Generation and propagation of infrasonic airwaves from volcanic explosions, *J. Volcanol. Geotherm. Res.*, *121*(1–2), 1–14.

Johnson, J. B. (2004), Vent mapping and source location variability at Stromboli mapped with small-aperture infrasound array, *Bull. Volcanol.*, doi:10.1007/s00445-004-0356-8.

Johnson, J. B., and J. M. Lees (2000), Plugs and chugs—Seismic and acoustic observations of degassing explosions at Karymsky, Russia and Sangay, Ecuador, *J. Volcanol. Geotherm. Res.*, *101*(1–2), 67–82.

Johnson, J. B., R. C. Aster, M. C. Ruiz et al. (2003), Interpretation and utility of infrasonic records from erupting volcanoes, *J. Volcanol. Geotherm. Res.*, *121*(1–2), 15–63.

Johnson, J. B., A. J. L. Harris, S. T. M. Sahetapy-Engel et al. (2004), Explosion dynamics of pyroclastic eruptions at Santiaguito volcano, *Geophys. Res. Lett.*, *31*, L06610, doi:10.1029/2003GL019079.

Lighthill, M. J. (1978), *Waves in Fluids*, 504 pp., Cambridge Univ. Press, New York.

Mangan, M., and T. W. Sisson (2000), Delayed, disequilibrium degassing in rhyolite magma: Decompression experiments and implications for explosive volcanism, *Earth Planet. Sci. Lett.*, *183*, 441–455.

Reed, J. W. (1987), Air pressure waves from Mount St. Helens eruptions, *J. Geophys. Res.*, *92*(D10), 11,979–11,982.

Ripepe, M., and E. I. Gordeev (1999), Gas bubble dynamics model for shallow volcanic tremor at Stromboli, *J. Geophys. Res.*, *104*(B5), 10,639–10,654.

Ripepe, M., and E. Marchetti (2002), Array tracking of infrasonic sources at Stromboli volcano, *Geophys. Res. Lett.*, *29*(22), 2076, doi:10.1029/2002GL015452.

Ripepe, M., S. Ciliberto, and M. D. Schiava (2001), Time constraints for modeling source dynamics of volcanic explosions at Stromboli, *J. Geophys. Res.*, *106*(B5), 8713–8727.

Ripepe, M., A. J. L. Harris, and R. Carniel (2002), Thermal, seismic and infrasonic evidences of variable degassing rates at Stromboli volcano, *J. Volcanol. Geotherm. Res.*, *118*(3–4), 285–297.

Rowe, C. A., R. C. Aster, P. R. Kyle et al. (2000), Seismic and acoustic observations at Mount Erebus Volcano, Ross Island, Antarctica, *J. Volcanol. Geotherm. Res.*, *101*(1–2), 105–128.

Sparks, R. S. J., J. Barclay, C. Jaupart et al. (1994), Physical aspects of magmatic degassing I. Experimental and theoretical constraints on vesiculation, in *Volatiles in Magmas: Reviews in Mineralogy*, edited by M. R. Carroll and J. R. Holloway, pp. 413–446, Mineral. Soc. Am., Washington, D. C.

Vergniolle, S., and G. Brandeis (1994), Origin of the sound generated by Strombolian explosions, *Geophys. Res. Lett.*, *21*(18), 1959–1962.

Vergniolle, S., G. Brandeis, and J.-C. Mareschal (1996), Strombolian explosions: 2. Eruption dynamics determined from acoustic measurements, *J. Geophys. Res.*, *101*(B9), 20,449–20,466.

Witter, J. B., V. C. Kress, P. Delmelle, and J. Stix (2004), Volatile degassing, petrology, and magma dynamics of the Villarrica Lava Lake, southern Chile, *J. Volcanol. Geotherm. Res.*, *134*, 303–337.

Yamasato, H. (1997), Quantitative analysis of pyroclastic flows using infrasonic and seismic data at Unzen Volcano, Japan, *J. Phys. Earth*, *45*, 397–416.

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