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Explosion dynamics of pyroclastic eruptions at Santiaguito Volcano

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[1] In Jan. 2003 we monitored explosions at Santiaguito Volcano (Guatemala) with thermal, infrasonic, and seismic sensors. Thermal data from 2 infrared thermometers allowed computation of plume rise speeds, which ranged from 8 to 20 m/s. Rise rates correlated with cumulative thermal radiance, indicating that faster rising plumes correspond to explosions with greater thermal flux. The relationship between rise speeds and elastic energy is less clear. Seismic radiation may not scale well with thermal output and rise speed because some of the thermal component may be associated with passive degassing, which does not induce significant seismicity. But non-impulsive gas release is still able to produce a high thermal flux, which is the primary control on buoyant rise speed. INDEX TERMS: 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280); 8494 Volcanology: Instruments and techniques. Citation: Johnson, J. B., A. J. L. Harris, S. T. M. Sahetapy-Engel, R. Wolf, and W. I. Rose (2004), Explosion dynamics of pyroclastic eruptions at Santiaguito Volcano, Geophys. Res. Lett., 31, L06610, doi:10.1029/2003GL019079.

1. Introduction

[2] Since 1922 silicic lava flows and exogenous dome growth has occurred at Santiaguito, Guatemala, building a dacitic dome complex ~1200 m below and ~2500 SW the Santa Maria summit [Rose, 1987]. In the last 80 years, 4 vents with a lateral extent of ~1.5 km have contributed ~1.1 km3 to the construction of the ~500 m tall edifice [Rose, 1987; Harris et al., 2003]. Since 1986 activity has been focused at the easternmost Caliente Vent, which was the original locus of dome growth and is thought to most directly overlie the magma supply conduit [Rose, 1972; Rose, 1987].

[3] Explosive activity is a feature of nearly every observation period since the 1970s [Stoiber et al., 1983; Rose, 1987; BVGN, Santiaguito, Global Volcanism Network, 1990–2003]. These events, occurring at intervals ranging from 5 to 100 minutes, vary from short bursts producing 1–9600 m above the vent. The 15 FOV thermometer (OMEGA-TM OS554) and OS43. For a sensor-to-plume distance of ~1600 m, the two 1° FOV instruments each viewed areas of ~600 m2 separated by ~420 m, with the lower FOV instrument aimed ~100 m above the vent. The 15° FOV sensor integrated radiance over ~136,000 m2, incorporating the lower 1° FOV target area (Figure 1). It should be noted that recorded brightness temperature (as shown in Figure 2a) does not reflect actual plume temperature, but instead corresponds to a thermal radiance averaged over the FOV, which may

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including targets of variable temperature and emissivity. Thermal data were contingent upon cloud-free conditions, generally possible only at night.

2.2. Infrasound

Four microphones using Panasonic WM-034BY electret condenser elements were deployed as a small-aperture \((\sim 60 \text{ m})\) antenna. These instruments incorporated a band pass filter (0.1 to 10 Hz) and a high-pass filter associated with the sensors’ FET, inducing a low-frequency corner at \(0.5 \text{ Hz}\). Nevertheless, most of the Santiaguito infrasound appeared to lie in the flat portion of the microphones’ response. The multi-element array was used to discriminate volcanic degassing signal from non-volcanic noise through back-azimuth source determination. Wind noise was problematic in \(\sim 33\%\) of our data.

2.3. Seismic

A 1 Hz vertical-component Mark Products L4 seismometer was installed at the acquisition hub. The site response is likely significant because the sensor was buried in ash above porous talus.

3. Plume Rise Speed

We utilized delay times between correlated thermal pulses from the FOV sensors to estimate rise speeds \(V\) for vertically-directed plumes. The onsets of the thermal transients were characterized by rapid brightness temperature gains of 10 to 30°C, associated with the leading edge of the hot plume ascending through the FOV. Time delays between thermal onsets \((\Delta T_{\text{FOV1}} - T_{\text{FOV2}} = \sim 20 \text{ to } 80 \text{ s})\), divided by the separation distance of the sensors \((\sim 420 \text{ m})\), provided \(V\) of 5 to 20 m/s. These are consistent with the 9 to 24 m/s rise speed estimates obtained for 8 explosions recorded with digital video on Jan. 9, 2003.

It is also possible to estimate \(V\) using a brightness temperature waveform \(T_b(t)\) recorded by a single sensor.

Figure 1. Santiaguito dome viewed from Santa Maria. Active Caliente vent is at left (east) \(\sim 1600 \text{ m}\) from the inactive Brujo Dome, where sensors (inset map) were installed. Thermometer FOVs are shown as transparent cones.

Figure 2. (a) Five-hour thermal time series showing 18 distinct thermal events. (b–c) Thermal waveform stack and composite waveform from 8 consecutive explosions (events \#4–11) recorded with the lower (b) and upper sensors (c). Dotted line is a composite averaged signal (FOV #2) after time-migration of waveforms. (d) Plume rise velocities are calculated using both delay time between thermal transients (circular symbols) and equation (1) applied to the composite thermal waveforms.
This method (see appendix) uses brightness thermal rate of change \( \frac{dT_b}{dt} \) during the onset of an explosion as a proxy for \( \dot{V} \):

\[
\dot{V} \approx \frac{2\pi R}{T_h^4 - T_c^4} \left( \frac{dT_b}{dt} T_h^3 \right)_{\text{max}}
\]

where \( T_h \) and \( T_c \) are the maximum plume and background temperatures, respectively. Average velocities from equation (1) compare favorably with rise speeds determined from delay times (Figure 2d). This method further indicates that average velocity between FOV #1 (12 m/s) and FOV #2 (11 m/s) demonstrates insignificant deceleration. Because we would expect the plume to decelerate within a near-vent gas thrust zone and the plume to stagnate at an altitude of horizontal dispersion [Cioni et al., 2000; Carey and Bursik, 2000], we conclude that the plume is buoyantly driven 100 to 500 m above the dome.

4. Thermal-Seismo-Acoustic Energy Partitioning

A comparison of \( V \) with thermal flux and radiated elastic wave field provides additional constraints on eruption dynamics. We estimate the relative energy contributions for a suite of explosions occurring during periods of negligible cloud cover (high quality thermal records) and relatively windless conditions (good infrasonic records).

We assess the relative acoustic energy \( (E_A) \) and seismic energy \( (E_S) \) contributions because absolute estimates are beyond the capabilities of our data. Potential seismic source anisotropy, complex propagation filters, and uncertain site response preclude absolute estimates of seismic moment for explosion events. Similarly the time-integrated acoustic power may be precisely estimated only for an isotropic source that radiates into a homogeneous atmosphere. Because of these uncertainties we opt to compare normalized energy contributions, which enable inter-comparison of relative energy partitioning within a suite of explosions. Normalizing the elastic energy relationships presented in J. B. Johnson and R. C. Aster (Volcanic acoustic efficiency of Strombolian eruptions, submitted to Journal of Volcanology and Geothermal Research, 2004), we simplify the cumulative acoustic energy to be proportional to the time-integrated, squared pressure trace [Pierce, 1981].

\[
E_A \approx \int \Delta P(t)^2 dt \quad (2)
\]

\( \Delta P(t) \) is the excess pressure time history. Similarly, by assuming a predominance of body waves, we make simplifications to Boatwright [1980], so that cumulative seismic energy is proportional to the squared velocity trace \( U(t)^2 \), or time-integrated kinetic energy.

\[
E_S \approx \int U(t)^2 dt \quad (3)
\]

To obtain a comparative measure of thermal energy, we use the time-integrated thermal intensity, taken from the brightness temperature waveforms, as a proxy for relative heat flux. We are interested in comparing relative thermal contributions and thus use the Stefan Boltzmann Equation to recover thermal radiance. The cumulative thermal energy \( (E_T) \) is calculated for unity emissivity after removing thermal contributions associated with the background temperature:

\[
E_T \approx \int (T_h^4 - T_c^4) dt \quad (4)
\]

To facilitate comparison of events, the relative energy estimates are calculated from equations (2)–(4) for a 6-minute window and then scaled to the largest explosion within the comparison group (Figures 3 and 4).

Two individual events, medium explosion #15 and larger explosion #16 (Figure 3), illustrate the variability in energy partitioning. Despite possessing seismic traces with similar envelope and cumulative energy, #16 radiates nearly twice the acoustic energy and appears to output significantly more heat than #15. Sustained infrasound provides the primary contribution to the relatively high cumulative acoustic energy, whereas both increased thermal amplitude

\[\text{Figure 3.} \quad \text{(a) Calibrated seismic, calibrated stacked infrasound, and 1° FOV thermal brightness temperature traces for explosion #15 (left) and #16 (right). (b) Cumulative power is calculated from equations (2)–(4) and normalized to the larger explosion.}\]
and signal duration lead to the elevated cumulative thermal flux. The extended duration of the infrasound produced by #16 (≈70 s) compared to #15 (≈15 s), reflects continued perturbation of the atmosphere, that can be attributed to an extended-duration vigorous degassing source [Johnson et al., 2003]. Presumably the longer-duration source is also able to vent larger quantities of hot gas into the atmosphere. Because a voluminous hot plume is more efficient at retaining its heat than a small hot plume - less surface area per unit volume - it follows that #16 should exhibit elevated brightness temperatures. This hotter plume will maintain a lower average density and thus rise with a greater buoyant rise speed [Turner, 1973]. Indeed, inferred rise speeds prove to be nearly twice as fast for #16.

A clear relationship exists (R² = 0.91) between V and Eₚ (Figure 4), suggesting that the quantity Eₚ may be used as a proxy for relative thermal flux and/or explosion magnitude. There also appears to be reasonable correlation (R² = 0.76) between V and Eₛ using a quadratic fit, where the larger events are also effective at radiating louder, longer-duration infrasound.

The link between V and Eₛ is less clear and we do not feel confident to fit a curve to these data. We propose that seismic energy is not always an effective measure of eruption magnitude because much of the seismicity may be generated by internal brittle rock fracture, intermittent fluid flow, as suggested by Bluth et al. [2002], or rock falls on the dome. These sources may be completely independent from the net explosive gas output. We suggest that seismicity can also be underrepresented during low impulsivity explosions. Passive degassing would induce lower source stresses and hence be less efficient for producing high amplitude seismic waves.

5. Conclusion

We demonstrate that plume rise speeds at volcanoes can be reliably calculated using two infrared thermometers. At Santiaguito, constant rise speeds ranging from 8 to 20 m/s are inferred to be buoyantly driven ~100 to 500 m above the dome. Because rise speeds are correlated with the cumulative thermal flux, hotter, faster rising plumes likely indicate a more voluminous eruptive flux. Though larger magnitude eruptions tend to be associated with greater acoustic energy, they are not well correlated with seismic energy release.

Appendix

[17] We assume a FOF composed of a vertically rising isothermal plume (Tₜ) with fractional coverage fplume super-imposed upon a cold background (Tᵦ). Effective radiation brightness temperature (Tᵦ) is then (Tₑₚ + f(TplumeTₜ - Tᵦ))¹/₄ [Crisp and Baloga, 1990] and the rate of change (dTᵦ/dt) is ¹/₄(dfplume/df) (Tₑₚ - Tᵦ). Thus the change in fractional coverage (dfplume/df) is ⁴/₄ (dTᵦ/df) Tᵦ.

[18] We next assume that a plume with planar upper edge ascends at constant velocity (V) across a circular FOV of radius (R). The maximum fractional change occurs when fplume = 50% and (dfplume/df) = ½V/R. It follows that

V ≈ πR/2 (dp/df) max = 2πR/Tₚ - Tₚ (dTₚ/df) max

(A1)

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