Linking volcanic tremor, degassing, and eruption dynamics via \( \text{SO}_2 \) imaging

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Recently developed UV cameras offer improvement in remote sensing of volcanic \( \text{SO}_2 \), with temporal resolutions of \( \sim 1 \text{ Hz} \) and synoptic plume views. Integrated UV camera and seismic measurements recorded in January 2009 at Fuego volcano, Guatemala, provide new insight into the system’s shallow conduit processes. High temporal resolution \( \text{SO}_2 \) data reveal patterns of \( \text{SO}_2 \) emission rate relative to explosions and seismic tremor that indicate tremor and degassing share a common source process. Progressive decreases in emission rate appear to represent inhibition of gas loss from magma as a result of rheological stiffening in the upper conduit. Measurements of emission rate from two closely-spaced vents, made possible by the high spatial resolution of the camera (1024 \( \times \) 1024 pixels), help constrain this model. This inter-disciplinary approach illuminates eruptive processes at Fuego and holds promise for gaining similar understanding at other volcanic systems.


1. Introduction

Volatile play a crucial role in volcanism; their segregation from melts is fundamental in determining subsurface and eruptive processes. Bubbles affect generation of low-frequency seismicity and seismic tremor is typically attributed to interaction of multiphase magmatic or hydrothermal fluids and conduit walls [Chouet, 1996; Rippe and Gordeev, 1999], and eruptive style varies depending on gas-melt dynamics [Jaupart and Vergniolle, 1988; Parfitt and Wilson, 1995]. Though many models of volcanic phenomena depend on gas behavior, volcanic gas release has historically been difficult to quantify. Ground-based measurements of \( \text{SO}_2 \) emission rate made by ultraviolet (UV) spectrometers have been common since the 1970s, but generally lack temporal resolution sufficient for evaluation alongside continuous geophysical data. Previous studies have linked seismicity with \( \text{SO}_2 \) emission rates [Fischer et al., 1994; Palma et al., 2008; Williams-Jones et al., 2001], but over time-scales of months to years and based on sporadic \( \text{SO}_2 \) measurements. Integrated studies have thus been limited to interpretation of long-term degassing trends [Palma et al., 2008; Williams-Jones et al., 2001].

2. Methods

With images collected nearly every second, UV cameras [Bluth et al., 2007; Dalton et al., 2009; Mori and Burton, 2006] facilitate studies of volcanic degassing on unparalleled timescales. Accordingly, high-resolution \( \text{SO}_2 \) emission rate time-series can be used to corroborate models of tremor generation or eruption dynamics involving gas. In addition, two-dimensional images provide spatial context to observe variations within plumes and to identify multiple vents with distinct behaviors. As volatile segregation provides the driving force for volcanic eruptions, knowledge of how gas escape relates to other geophysical phenomena is essential for a comprehensive understanding of volcanic behavior.

We show that enhanced resolutions of UV camera data, both temporal and spatial, allow \( \text{SO}_2 \) data to be jointly interpreted with seismic and visual video records to give unprecedented insight into degassing and eruption dynamics. We present results from a January 2009 field campaign using seismometers, visual observations, and a UV camera to study Fuego volcano’s activity and relationships between degassing and seismic tremor. Fuego is a basaltic-andesite stratovolcano (~3800 m a.s.l.) in central Guatemala. Historical volcanism ranges from basaltic subplinian eruptions, most recently in 1974 [Rose et al., 1978, 2008], to persistent lower-level activity, the current phase of which began in 1999 and involves periodic lava flows, passive degassing, and explosions [Lyons et al., 2010].
emission rates range from 0.0014 kg/s to 6.5 kg/s with time L01304 \sim \sim \emission from a stationary site of tremor generation, or both. emissions cannot be quantified due to ash data being diluted or mixed with the dominant tremor frequencies. highlight variation on the order of minutes and to bracket heights reached a maximum of \sim 500 m above the summit. Explosion onsets ranged from emergence of a single pulse of ash from the summit area driven solely by buoyancy to momentum-driven jets with sustained pulsing for up to \sim 2 minutes.

vent. We restricted our analysis to a band-limited (1–5 Hz) 10 second average seismic amplitude (RSAM) [Endo and Murray, 1991] time-series from the closest station (a 30 second Güralp CMG-40T with a Reftek 130 digitizer) to highlight variation on the order of minutes and to bracket the dominant tremor frequencies.

3. Results

[7] Continuous but varying passive gas emissions were interrupted roughly twice per hour by ash-rich explosions (Figures 1, 2a, 2b, and S2). Owing to poor weather (e.g., high winds, clouds), UV image acquisition was restricted to 12, 14, and 21 January 2009, with 169, 3447, and 5277 images in 0.25, \sim 8, and \sim 8.5 hours, respectively. Measured SO_2 emission rates range from 0.0014 kg/s to 6.5 kg/s with daily means of 0.86, 1.5, and 0.59 kg/s and an overall mean of 0.94 kg/s (81 t/d), comparable to 1.9 kg/s (160 t/d) and 3.9 kg/s (340 t/d) reported for Fuego in previous years [Andres and Kasgnoc, 1998; Rodriguez et al., 2004]. While explosive SO_2 emissions cannot be quantified due to ash interference, many explosions were followed by increased gas emissions (Figures 2a, 2b, and S2). Though atmospheric effects (e.g., ponding of gas in the crater before buoyant rise) may cause variations in measurements, they are likely negligible given the small crater size.

[8] Under favorable conditions, two vents with distinct eruptive and degassing behaviors (Figures 1a and 2b) could be distinguished: one at the summit and one \sim 100 m west on the flanks. Passive emissions were variable and included periods of high correlation between the vents’ emission patterns (Figure 2b). While explosions originated only from the summit vent (Figure 1a, left) and summit vent emissions usually dominated, we also observed a short time (\sim 5 min prior to explosion 11) during which summit emissions decreased such that flank emissions equaled or exceeded summit emissions. For the short time distinct plumes were visible, flank vent degassing appeared mostly unaffected by pre-explosive summit activity.

[9] Explosion signals and continuous \sim 1–5 Hz tremor of variable amplitude dominated seismicity. Tremor was occasionally harmonic with >10 overtones and particle motions were consistent with surface waves, suggesting a relatively shallow source. We also find that seismic tremor and SO_2 emission rate correlate on a scale of minutes (Figure 2c). Though correlation is not always present, it appears repeatedly over the course of the measurements and persists over time scales ranging from \sim 10 minutes to \sim 2 hours. This correlation occurs during both harmonic (HT) and non-harmonic tremor (NHT), though is more commonly associated with NHT. The datasets are most similar when the magnitude of each is relatively high; this may be a consequence of smaller puffs (i.e., small emission rate changes relative to low background) in SO_2 data being diluted or mixed with ambient air to the extent that their integrity is lost prior to rising above the crater rim to the point of measurement by the UV camera. During periods of uniformly high RSAM, correlation is less obvious. In such instances, SO_2 emission rate varies while RSAM remains high, possibly indicating another source of seismicity overprinting the gas-sourced signature.

[10] We quantified the similarity between the RSAM and SO_2 time-series, calculated time lags, and evaluated possible implications. One instance of data similarity occurred over \sim 30 minutes between explosions 1 and 2; cross-correlation of data from this interval yielded a maximum correlation of 0.6 with SO_2 lagging 32 s behind seismicity. Other periods had lags between 5 and 83 s. Application of smaller moving windows (3–9 min) to the \sim 30 minute dataset revealed increasing lags, from a few to \sim 60 s (Figure 2d). The progressive increase implies increasing distance between the tremor generation depth and the vent, decreasing rise speed of SO_2 from a stationary site of tremor generation, or both.

4. Discussion and Conclusions

[11] We observe correlation between RSAM and SO_2 emission rates that links degassing and seismogenic tremor processes. Fluid flow [Julian, 1994, 2000], bubble coalescence [Ripepe and Gordeev, 1999], oscillation of bubbles or bubble clouds [Chouet, 1996], and conduit resonance [Chouet, 1992] have previously been invoked to explain HT and NHT signals. Tremor has also been linked to outgassing activity [Métaxian et al., 1997; Palma et al., 2008]. A resonant crack containing bubbly fluid can possess a sufficiently large impedance contrast to sustain tremor [Kumagai and Chouet,
In most such tremor models, higher bubble concentrations or more rapid flow of bubbles and bubble-rich fluid generate stronger tremor. It follows that more numerous or larger volumes of bubbles producing larger amplitude tremor signals would, after rising through the conduit, result in a greater SO$_2$ emission rate (Figure 2c). These processes are non-destructive and may be continuous, in agreement with the persistence of tremor both prior to and immediately following explosions at Fuego.

In addition to correlation with tremor, both long- and short-term decreases in SO$_2$ emissions were observed prior to explosions (Figures 2a and S2): from 6.4 kg/s to 0.31 kg/s over $\sim$1.5 hrs (explosion 14), and from 2.6 to 0.36 kg/s in $\sim$4 min (explosion 16). One way to explain this is by variable gas supply, which could result from variable magma and/or bubble ascent rates, variable spatial distribution of gas in the conduit, or both. Non-uniform distribution of gas in magma is not unreasonable; bubbles in basaltic melts may concentrate into layers or clusters with instabilities causing further variability in bubble distribution [Manga, 1996]. If bubble layers collapse into large gas slugs, the slugs could burst through crater backfill, causing ash-rich explosions [Patrick et al., 2007]. However, when time-series from separate vents are examined, similarity between degassing patterns at the two vents, which indicates some degree of coupling, disappears prior to explosion 11 (Figure 2b); the only anticorrelation between emissions from the vents occurred immediately prior to explosion 11 ($r = -0.51$ for 179 samples over $\sim$8 minutes), when flank vent emissions were relatively high. In contrast, the highest correlation occurred immediately following explosion 12 ($r = 0.76$ for 100 samples over $\sim$6 minutes). If short-term variations in SO$_2$ emission rate are the surface expression of variable bubble concentrations within the magma column, instances when highly correlated SO$_2$ emission rates dominate may be indicative of uninhibited gas release from both vents, while periods of dissimilar SO$_2$ time-series may represent inhibition of gas release from the summit.

Based on our observations of Fuego’s activity, we have developed a model for small, ash-rich explosions (Figure 3). We consider background activity to be free degassing from both vents (Figure 3a). Given the absence of effusive activity, we assume magma supply was low during our field campaign, and such conditions may lead to enhanced cooling, degassing, crystallizing, or ‘stiffening’ of magma in the conduit. These rheological changes would
hinder bubble ascent, partially sealing the main conduit as bubbles accumulate under a rheological boundary below the summit vent (Figure 3b). Increased viscosity in the upper conduit may slow magma convection, thereby further decreasing the supply of gas to the summit. Small variations in SO$_2$ emission overprinting longer-term (≈30 min) trends would represent heterogeneous distribution of gas in the conduit, minor variations in gas-rich magma ascent rates, or both. Once sufficient pressurized gas collected beneath the stiffened layer to overcome the confining pressure of the viscous magma, an explosion would occur, ejecting ash and bombs comprising mostly-solidified magma from the upper conduit and previously ejected crater infill. Gas emissions would peak initially, reflecting release of gas collected beneath the stiffened layer, and then drop to levels associated with gas release from the free magma surface (Figure 3c).

[14] The general increase in lag between tremor and SO$_2$ time series that accompanies decreasing SO$_2$ emission is consistent with our model of progressive rheological stiffening. The increased lag suggests that the tremor source deepens or the velocity of escaping gas decreases following large explosions. Progressive cooling and/or crystallization would propagate downward through time from the top of the magma column, gradually inhibiting upward migration of gas and possibly increasing the depth of the tremor source. Variable inter-explosion times may be due to arrivals of varying amounts of pressurized gas beneath scaling layers with different degrees of stiffening and confining pressures, and instances of sustained jetting may reflect a relatively large build-up of bubbles such that their extended release is akin to the collapsing foam of Jaupart and Vergniolle [1988]. Flank degassing may be a result of persistent degassing through a crack network in magma solidified following a lava flow in mid-2008 (Figure 3b), which would not be subject to stiffening and would be largely unaffected by summit activity.

[15] Similar magma stiffening or solidification in the upper conduit and subsequent pressurization has been inferred to be the source of ash–rich explosions in eruption sequences at Mt. Etna (Italy) [Taddeucci et al., 2004]. Ash–rich explosions and associated SO$_2$ emissions at Karymsky volcano (Russia) have been attributed to the repeated presence of viscous, capping plugs [Fischer et al., 2002], while gas pistoning at Kilauea volcano (Hawaii) is also theorized to be caused by a build-up of gas beneath a rheological boundary [Johnson et al., 2005] despite magma of a relatively low viscosity; similar stiffening of magma and ensuing inhibition of gas release is thus also conceivable at Fuego.

[16] Work conducted at Fuego volcano highlights the impact of integrating UV cameras into volcanological field campaigns. By supplementing seismic and visual observations with high-resolution SO$_2$ emission rates, we identified the presence of linked source processes for tremor and degassing; isolated vents with distinct behaviors; and detected gas emission decreases prior to explosions that likely result from rheological stiffening within the upper conduit. This interdisciplinary approach involving UV cameras may yield similar results at other volcanoes, thereby providing new information about eruption mechanism and aiding model validation.

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References

Figure 3. Schematic model of gas release and explosion generation for small ash–rich explosions at Fuego volcano, with theoretical SO$_2$ release over time. (a) Both vents degas freely. (b) Rheological stiffening in upper conduit inhibits gas release from summit; flank degassing is unaffected. (c) Pressure beneath stiffened magma overcomes confining pressure, resulting in ash–rich explosion and release of accumulated gas before a return to free degassing.


