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Highlights

- Eruptive dynamics characterized by seismicity, SO$_2$ degassing and ash componentry.
- Conduit conditions explored through multiparametric time series.
- Violent Strombolian vs. Vulcanian eruptive dynamics at Tungurahua volcano.
- Presence of a two magma waxing-waning cycles during a single eruptive phase.
Autopsy of an eruptive phase of Tungurahua volcano (Ecuador) through coupling of seismo-acoustic and SO$_2$ recordings with ash characteristics

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Abstract

Eruption style and dynamics are controlled by various parameters including magma supply rate, magma viscosity, volatile content, and the permeability of the conduit. Rapid changes of these parameters can significantly modify the hazards associated to the eruption processes and understanding their relationship with multiparametric geophysical monitoring data can greatly
improve our forecasting capacities. From 2008 to 2016, volcanic activity at Tungurahua was characterized by eruptive phases separated by episodes of quiescence. These phases displayed great variability of eruptive patterns including Vulcanian and Strombolian explosions, low pyroclastic fountaining, continuous or sporadic ash emissions and passive degassing. We use the comparison between geophysical data (seismic, acoustic and SO$_2$ emission), recorded by permanent monitoring networks, and the characteristics of the emitted ash to track changes in eruption dynamics during an eruptive phase that lasted from late December 2009 to March 2010. We show that the correlation between the analyzed parameters allows imaging and interpretation of the conditions at the vent. At Tungurahua, these conditions can rapidly change at the time scale of a single eruptive phase, corresponding to various degrees of opening, plugging and permeability of the conduit. Two magma intrusions could be identified during a single eruptive phase showing transitions between violent Strombolian and Vulcanian activity. Changes in the componentry of the analyzed ash samples, together with the geophysical data, nicely highlight these evolutions. Studying these parameters simultaneously provides a unique insight into the physical processes controlling superficial volcanic activity and offers a potential tool for better understanding volcanoes and detecting changes in their activity. The joint interpretation of multiparametric data which we propose is potentially applicable to multiple andesitic volcanoes.

1. Introduction

Stratovolcanoes with long-lasting eruptive cycles, such as Tungurahua (Ecuador), Sakurajima (Japan), Semeru (Indonesia), Soufrière Hills (West Indies, United Kingdom) or Popocatepetl (Mexico), among others, pose a significant threat to local populations for three main reasons.
1) They constantly expose local populations to variable amounts of ash that can create chronic health diseases (Baxter et al., 2014) and have long-term impacts on livelihoods (Few et al., 2017). 2) Continuous accumulation of pyroclastic material on the flanks of the volcanic edifice promotes the formation of rain-triggered lahars (Jones et al., 2015). 3) Local authorities and populations are used to the more frequent low activity of the volcano and might underestimate or overrule the potential impacts of the less frequent larger eruptions (Mothes et al., 2015). A recent example is the June 2018 eruption of Fuego volcano (Guatemala) that caused the death of at least 198 people (INACIF, 2019). During long-lasting eruptions, the eruptive dynamics can rapidly shift from low explosive activity to high explosive activity that translates into a substantial increase of the volcanic threat (Hidalgo et al., 2015). These variations in surface activity are typically controlled by the characteristics of the magma, such as composition, viscosity, permeability, bubble and crystal contents (Cashman and McConnell, 2005; Melnik et al., 2005; Heap et al., 2015), the conditions at the vent (i.e. open or closed) (Diller et al., 2006), the geometry of the conduit (Vitturi et al., 2008) and the magma discharge rate (Cassidy et al., 2015; Bonadonna et al., 2016). Some of these parameters can be quantitatively determined afterwards by conducting a precise analysis of volcanic products like pyroclasts and/or lava (Wright et al., 2012; Gurioli et al., 2015). However, the combined analysis of continuous geophysical signals permanently recorded by multiparametric monitoring networks can give, in near real-time, at least qualitative insights into the volcano behavior and help to forecast eruptive events (Ripepe et al., 2002, 2005). Accurately imaging the evolution of eruptive dynamics through geophysical observations ideally requires multiparametric monitoring systems including seismic, acoustic, geodetic, thermal, geochemical, IR measurements, and visual observations.
Tungurahua (5023 m a.s.l.) is an andesitic stratovolcano located in Central Ecuador. It has an eruptive recurrence interval of 80-90 years (Le Pennec et al., 2008). The most recent eruptive cycle started in September 1999 and lasted until March 2016, with a major VEI3 paroxysm in August 2006 (Eyenchene et al., 2012). Tungurahua, as many other andesitic volcanoes, displays various types of eruption styles: continuous to sporadic gas and ash emissions, individual explosions with ejecta of blocks, low pyroclastic fountaining, violent explosions producing pyroclastic density currents, and lava flows (Arellano et al., 2008; Samaniego et al., 2011; Eyenchene et al., 2012; Hall et al., 2015; Hidalgo et al., 2015). Pyroclastic fountaining (e.g. Branney and Kokelaar, 2002) is different from spattering or lava fountaining given that the pyroclasts are already solid in the gas jet. This term is more appropriate to describe the activity at Tungurahua, as pointed out by Bernard (2018). There is an extensive literature on Tungurahua’s recent eruptive cycle focused on seismo-acoustic activity (Johnson et al., 2005; Kumagai et al., 2010; Kim et al., 2014; Bell et al., 2017), degassing (Arellano et al., 2008; Hidalgo et al., 2015), ground deformation (Champenois et al., 2014; Neuberg et al., 2018), and eruption products (Samaniego et al., 2011; Wright et al., 2012; Eyenchene et al., 2012; Douillet et al., 2013; Eyenchene et al., 2013; Hall et al., 2015; Bernard et al., 2016). However, none of this research uses more than two methods to characterize the activity. Furthermore, this literature is mostly focused on large events, such as the 2006 eruption, or long periods of activity. Smaller events (VEI ≤2) are mostly neglected. This last comment can also apply in general to most of literature in volcanology.

For this study, we use seismic, acoustic, and SO₂ emission data to characterize the eruption mechanisms during a phase of eruptive activity, which occurred from December 2009 to March 2010. During this phase, Tungurahua exhibited a wide range of eruptive processes
including passive degassing, continuous ash venting and transient volcanic Strombolian and Vulcanian explosions. We compare geophysical parameters with visual observations of the surface activity reported by the Instituto Geofísico of Escuela Politécnica Nacional (IG-EPN) and with diverse characteristics (geochemistry, mineralogy, componentry and grain-size distribution) of ash samples collected throughout this eruptive phase. We use these comparisons to propose a model of the temporal evolution of the eruption and determine the vent conditions. The correlations highlighted in this paper can be used to follow and forecast rapid changes in eruptive dynamics at andesitic volcanoes that show transitions between emissive and explosive behaviors.

2. Quantification of geophysical parameters and ash characterization

2.1 Seismic, acoustic and SO$_2$ emission quantification

Tungurahua is monitored by the IG-EPN whose monitoring network includes five short-period and five broadband seismic stations coupled with acoustic sensors (Kumagai et al., 2010), and three permanent scanning-DOAS instruments (Novac-I, Galle et al., 2010). The location of these instruments is shown in Figure 1. We examined the seismic, acoustic and SO$_2$ data recorded during the eruptive sequence, which started on December 30, 2009 and lasted until March 4, 2010. The seismicity of Tungurahua includes a great variety of signals related to eruptive activity including explosion quakes generated by individual explosions but also various types of tremors and chugging signals related to longer-duration venting (Figure 2). To quantify both short- and long-term variations we proceeded in two ways.

We first quantified the acoustic and seismic energies of large individual explosions. For this purpose, we used data from the broadband and acoustic sensors. For each explosion with an
acoustic peak-to-peak amplitude greater than 45 Pa at reference station BMAS located 5.5 km from the summit (equivalent to 100 Pa at 1 km from the vent as mentioned by Hidalgo et al., 2015), we calculated the seismic and acoustic energies at each station using the formulas proposed by Johnson and Aster (2005), namely:

\[ E_{\text{acoustic}} = \frac{2\pi r^2}{\rho_{\text{atmos}} c_{\text{atmos}}} \int \Delta P(t)^2 dt \]  

(1)

where \( E_{\text{acoustic}} \) is the acoustic energy (J), \( r \) is the distance from the station to the vent (between 4695 and 6341 m depending on station), \( \rho_{\text{atmos}} \) is the atmospheric density (between 0.7278 and 0.7878 kg/m\(^3\)), \( c_{\text{atmos}} \) is the typical infrasound wave velocity at the average elevation of the stations (339.2 m/s), \( \Delta P(t) \) is the excess acoustic pressure measured by the instrument. And:

\[ E_{\text{seismic}} = 2\pi r^2 \rho_{\text{earth}} c_{\text{earth}} \frac{1}{A} \int S^2 U(t)^2 dt \]  

(2)

where \( E_{\text{seismic}} \) is the seismic energy (J), \( \rho_{\text{earth}} \) is the volcano density (2380 kg/m\(^3\)), \( c_{\text{earth}} \) is the P-wave velocity (3500 m/s), \( A \) is the attenuation factor (between 0.7963 and 0.8305), \( S \) is the site response (1 for all stations), \( U(t) \) is the particle velocity (m/s) measured by the seismometer.

For each event, average seismic and acoustic energies were estimated by taking the mean value of respective energies calculated at the four less noisy stations (BMAS, BPAT, BRUN...
and BBIL, see Figure 1), assuming a fixed location at the vent surface for all explosion sources. Energies were then summed up on a daily basis to obtain cumulative seismic (SEE) and acoustic (AEE) explosion energies. Calculations show that AEE is generally about 100 times higher than SEE and therefore, for comparison, we refer to a reference value of 100 for the AEE/SEE ratio. A total of 521 explosions were identified based on these criteria. The presence of these high-energy explosions allowed the distinction among High Explosive Activity (HEA) and Low Explosive Activity (LEA) periods (Hidalgo et al., 2015).

To estimate the amplitude of longer-term processes such as tremor, we calculated median seismic amplitudes (MSA) over 10-minute sliding windows for the full short-period frequency range (0.5-25 Hz). To obtain the median value of each window, we filter the seismic signal with a 4-pole Butterworth filter, calculate the absolute value of the seismic amplitudes and determine the median value of the amplitude distribution. For this, we used the short-period station RETU (Figure 1), because it is the closest (3900 m asl) to the summit and better reflects surface activity compared to more distant stations. However, when the station was either saturated or experiencing technical problems, the time-series was completed by using data from station BMAS, after scaling its MSA by an empirical factor estimated to guarantee the continuity of the recordings. This empirical factor was calculated by matching the amplitudes at RETU and BMAS when both stations were working properly. In figure 3, we present MSA as values integrated over one-day windows. Finally, to specifically quantify monochromatic or harmonic tremor we used the IG-EPN catalog, which characterizes this type of activity by estimating the duration and mean amplitude of each burst identified by frequency analysis. We calculated for each burst the product of these two parameters and summed them on a daily basis. Because of differences in the calculation mode, results from
the quantification of monochromatic/harmonic tremor cannot directly be compared with the
daily cumulative MSA.

Scanning-DOAS instruments provide SO₂ emission rate measurements only during typically
ten hours of daylight at the volcano location and under good weather conditions, leading to
sometimes sparse time-series. To quantify the daily SO₂ emission with data from a dense
DOAS monitoring network, Hidalgo et al. (2015) proposed integrating the highest validated
SO₂ emission rate measurements among all stations to obtain a daily observed mass of SO₂,
rather than extrapolating the highest of the averages calculated for each station over the
available measurements obtained during the day. The daily-observed mass is originally
expressed in tons per 10 hours (the constant daily measurement duration), but can easily be
expressed in tons per day (t/d) by multiplying by a factor 2.4. This approach better takes into
account the daily-validated measurement duration (DVMD), i.e. the time of effective
detection of gas, which is usually high during eruptive phases and low during quiescence.
This method significantly improves long-term (i.e. yearly) correlation between SO₂ emission
and eruptive activity, as demonstrated by Hidalgo et al. (2015).

2.2 Ash characterization

The geophysical datasets were completed with direct observations on the eruptive dynamics
compiled by the Tungurahua Volcano Observatory (OVT for the Spanish acronym). We also
derived different characteristics from a total of eight samples of ash deposits collected by
volunteers on solar panels located at 6 to 8 km distance from the vent, on the WSW flank of
the volcano (under the most common wind direction) during the studied eruptive period.
These characteristics are: 1) bulk ash chemistry of major elements, 2) semi-quantitative mineralogy, 3) componentry, and 4) grain-size distribution.

Bulk ash chemistry and semi-quantitative mineralogy were obtained at the Departamento de Metalurgía Extractiva of the Escuela Politécnica Nacional (DEMEX-EPN). For the chemical analysis we used an S8 TIGER High-end wavelength-dispersive X-ray fluorescence (WDXRF) spectrometer with Spectra plus software. Analytical errors are around 1%. Semi-quantitative mineralogy was obtained through X-ray diffraction (D8 Advance and Diffrac plus software). Manual sieving and componentry were performed at the IG-EPN. The componentry analysis followed the methodology described by Eychenne et al. (2012, 2013). Over 300 grains were classified through optical microscopy and Secondary Electron Microscopy (SEM) from at least four grain-size classes for each sample. Grain-size distribution was obtained combining manual sieving for coarse fractions (−2 to 4 φ or D between 16 and 0.063 mm, with φ=−log₂D where D is the particle diameter in mm) and laser diffraction (Horiba LA-9520V2) for the fine fractions (>4 φ or D<0.063 mm).

Bulk ash samples showed a homogenous andesitic composition throughout the two months of eruption (SiO₂ = 57.81 ± 0.22%, K₂O = 1.73 ± 0.04%; 6 samples). Mineralogical assemblage was characterized by plagioclase, clinopyroxene, orthopyroxene, olivine, and magnetite. This assemblage was also constant for the 6 analyzed samples (Plagioclase = 61.0 ± 0.9%; Clinopyroxene = 32.7 ± 1.9%; Orthopyroxene = 4.8 ± 1%; Olivine = 1.3 ± 0.5%; Magnetite = 0.2 ± 0.4%). These results are in agreement with previous analyses reported by Samaniego et al. (2011).
Componentry analysis allowed the identification of eight classes (Figure 4). Four classes were formed by juvenile material, two classes displayed accidental components, one comprised only free crystals and the last class showed both juvenile and accidental features. Juvenile components were identified as material exhibiting fresh vitreous shiny surface. They were then divided according to their color (dark or honey) and vesicularity (dense or scoriaceous). Accidental components were identified as material exhibiting more matte or opaque surfaces. There were two accidental classes: 1) accidental oxidized fragments that showed a homogeneous and penetrating reddish color, and 2) grey lithics that were generally dense and slightly altered. Free crystals without attached groundmass were counted apart as it was impossible to determine their origin with optical microscopy. Finally, an important class was the vitreous oxidized fragments that exhibited both juvenile and accidental features. They presented a very thin layer of rust on top of a shiny surface. This material was interpreted as recycling of slightly altered, mostly fresh, material from the active crater (Acuña, 2017). Significant variations were observed in the componentry (eight samples) throughout this phase, with the beginning being characterized by honey color of mostly vesicular juvenile material evolving through time to dark color of mostly dense juveniles. The detailed evolution will be described in the next section together with the observed seismic and degassing changes.

Grain-size distribution (six samples) was characterized by very fine to extremely fine ash (Mz = 3.38-4.52 φ; σ = 1.75-2.43 φ; with Mz = mean ((φ_{16} + φ_{50} + φ_{84})/3) and σ = standard deviation ((φ_{84}-φ_{16})/4+(φ_{95}-φ_{5})/6) as defined in Folk and Ward, 1957) and showed some changes during this eruptive phase. All the samples showed bimodal distributions, with a
coarse mode between 1.8 and 2.9 φ (medium to fine ash), and a fine mode between 5.9 and
6.4 φ (extremely fine ash). In general, we observed coarsening of the coarse mode while the
fine mode remained rather constant throughout the eruption.

The ash data set does not mimic exactly the geophysical data because the ash samples were
both discontinuous and accumulated over inconsistent periods of time (few days to about a
week). This sampling creates an artificial smoothing of the changes in eruptive dynamics.
This is why in general geophysical data allow to better identify the different episodes but we
argue that petrological monitoring adds significant information to the conventional
geophysical monitoring and allows to better constrain the conduit processes (Gaunt et al.,
2016).

3. Chronology of the eruptive phase

The eruptive phase from December 2009 to March 2010 followed a period of almost six
months of quiescence. During this quiescent period, no surface activity was visually observed.
To describe eruptive activity at Tungurahua, Hidalgo et al. (2015) distinguished between LEA
(yellow background color in Figure 3) and HEA periods (orange in Figure 3). These last
periods are characterized by discrete, high-amplitude explosions, for which we have
calculated explosion energies (SEE and AEE), as described above. The eruptive phase
discussed here includes two periods of LEA separated by one period of HEA. We divide the
eruptive phase into six episodes whose beginning and end were defined according to changes
in the temporal evolutions of the geophysical parameters described above (Figure 3). The
evolution of componentry and grain-size of the ash is shown in Figure 4 and detailed for each
episode.
(a) 30 December 2009 – 3 January 2010: seismically silent magma ascent and degassing. The first signs of eruptive activity were observed late on 30 December 2009 with the occurrence of a long period (LP) event followed by the emission of a small gas plume that reached a height of ~300 m above the crater. A steady SO$_2$ emission rate ($967 \pm 221$ t/d) was measured during the following three days, with very small ash emission up to 1.5 km above the summit (not seen by satellite instruments), accompanied by weak roaring sounds. This episode was characterized by the almost complete absence of seismicity, even at station RETU, the closest to the summit (2 km), except for a few small amplitude LP events. Despite this quiet onset, visual observations inside the crater on 2 January indicated the presence of an incandescent lava accumulation in the actively degassing crater. This feature was absent in November 2009. This activity did not produce a significant amount of ash, leading only to very thin fallouts restricted to the crater area. This prevented any ash sampling for this episode. The activity began to change on 3 January with SO$_2$ emission increasing up to 3400 t/d.

(b) 3 - 10 January 2010: appearance of tremor. After four days of degassing and weak ash emissions, seismic signals related to venting processes appeared simultaneously with semi-continuous ash plumes reaching up to 4.1 km above the crater (as reported by the Washington VAAC) and weak pyroclastic fountaining. Few discrete explosions were recorded during this episode. A progressive buildup of the MSA accompanied an irregular increase and stabilization of SO$_2$ emissions, which averaged $3073 \pm 1140$ t/d during the episode. SO$_2$ individual measurements showed an increase in daily variability, indicating a more discontinuous gas discharge, which is in agreement with the appearance of tremor pulses that occasionally had large amplitudes (MSA peak on 7 January). Episodes of harmonic tremor
started on 7 January. This activity was associated with low-to-moderate intensity roaring sound. During this episode the ash grain-size distribution was bimodal and fine-grained, as for most of the eruption. Ash componentry was dominated (>85 %) by honey-color juvenile fragments (mostly scoria), with some free crystals and a very small amount of accidental material (grey lithics or oxidized fragments) and dark-color juvenile (two samples 06/01 in Figure 4).

(c) 11 - 15 January 2010: appearance of larger explosions. On 11 January, a major change was observed in eruptive activity with the appearance of larger explosions with typical cannon-like shot sounds, sometimes followed by high amplitude tremor. This transition was not accompanied by any marked increase in the flux of SO₂, which remained stable around 2760 ± 1516 t/d. This highly explosive activity, which lasted for five days, showed strong seismic energy partitioning (AEE/SEE<<100). The superficial activity was characterized by explosions ejecting ballistics, followed by low pyroclastic fountaining. This activity was associated with sustained ash plumes (typically 3 km-high, and up to 5 km-high) and moderate-to-high intensity roaring sound. Harmonic tremor was recorded throughout the episode and almost vanished afterwards (Figure 3). Moderate to strong ash fallouts occurred during this episode. The change of eruptive activity was directly recorded in the componentry of the ash sample while the grain-size distribution remained unchanged and fine-grained (sample 12/01). The amount of honey-color juvenile material dropped to ~37% while the amount of dark-color and vitreous oxidized particles rose to 34 and 20% respectively. Free crystals and grey lithics remained very scarce (Figure 4).
(d) 16 - 23 January 2010: drop of explosive activity. A drop in explosive activity (SEE and AEE) was observed on 16 January coinciding with a decrease and stabilization of tremor amplitude as seen in the MSA. A few less energetic explosions remained with a ratio AEE/SEE > 100. This drop in seismicity was, however, only accompanied by a very small reduction of SO$_2$ emissions (2495 ± 887 t/d). Pyroclastic fountaining and quasi-continuous gas and ash emissions reaching up to 3 km above the summit were observed, associated with moderate intensity roaring sounds and small-to-moderate intensity ash fallouts, whose juvenile fraction was dominated by dark-color and scoriaceous material (sample 20/01).

(e) 24 January - 24 February 2010: increase in larger explosions. Large explosions resumed progressively from 24 January with an energy increasing irregularly until 11 February before decaying towards the end of the episode. This change was correlated with an intensification of roaring and canon-shot-like sounds, an increase of column height (typically 2 km and up to 4 km above the summit) and ash content of the emissions. Compared to episode (c), the daily number of large explosions was similar but the SEE was significantly lower and the AEE higher, resulting in a ratio AEE/SEE > 100 during most of the episode, similarly to episode (d). A decrease of this ratio (<100) was observed during the end of the episode, simultaneously with the drop of both energies. Accompanying this activity, the MSA decreased smoothly except for a short increase peaking around 5 February. These signals corresponded to a progressive decrease of background tremor, which was replaced by occasional LPs or explosions. Grain-size distribution showed a significant increase in the fine mode fraction compared to previous episodes (Sample 6/02). During this episode, the SO$_2$ emission displayed significant fluctuations with a globally decaying trend (1729 ± 1272 t/d), except for a short-duration increase roughly synchronous with the one observed for the MSA and the
change in grain-size distribution (Sample 6/02). Small pyroclastic flows due to collapses of
the material accumulated near the vent occurred at the end of this episode. This was followed
by a slight coarsening of the ash grain-size. The ash componentry became clearly dominated
(>85 %) by dark-color juvenile fragments (samples 17 and 24/02). Also, interestingly, we
observed an increase of dense material compared to scoria.

(f) 25 February to 4 March 2010: dying out of the activity. By 25 February, sporadic ash
emissions (less than 3 km-high) were observed with only minor seismic activity: a few
transient events including mostly LPs and no significant tremor. SO2 was almost at
background levels observed during quiescence periods (78 ± 41 t/d). The small ash fallouts
during this episode showed a slight decrease of the amount of dark-color juvenile material
even though it still remained as the main component (>80%). The ash grain-size distribution
was also slightly finer-grained compared to the episode (e) mostly associated to a higher
amount of the fine sub-population mode (sample 07/03).

The average emission rate of SO2 during the entire eruptive phase was 1807 ± 1394 t/d, which
is equivalent to a total gas release of about 120 kt of SO2 to the atmosphere during the 65 days
of activity. We found average emissions of 2020 ± 1302 during HEA (45 days) and 1430 ±
1591 t/d during LEA (20 days). It could be argued that this difference reflects a real change in
gas emissions. A t’Student test of the difference between the averages of the two samples
(HEA and LEA daily measurements) resulted in a p-value of 0.08, meaning an 8% probability
of having observed a false difference by chance. However, we note that the size of our
samples is not large enough to derive a robust conclusion in a statistically significant sense.
The typical uncertainty of individual measurements is estimated at about 30% (see Galle et al., 2010; Hidalgo et al., 2015).

4. Discussion

The comparison of the different geophysical time series with visual observations of superficial activity and ash characteristics provides unique information about the eruptive dynamics and processes occurring in the conduit. We discuss and interpret the parameters for each episode to recompose the temporal evolution of the eruptive phase. The sketches shown in Figure 5 illustrate this evolution.

(a) **Open conduit, silent magmatic ascent with free magma degassing**

The progressive and seismically silent appearance of gas during episode (a) can be interpreted as a new batch of magma reaching the surface through an open conduit, with SO$_2$ easily and rapidly exsolving through a permeable ascending magmatic column. This corresponds to the seemingly seismically silent emplacement of the lava observed in the crater on 2 January. This lack of seismicity is rather uncommon, especially for magmas with a high viscosity. For basaltic magmas, seismically silent lava outpouring from a shallow pocket has been reported at Etna (Bonaccorso et al., 2006), and Eibl et al. (2017) reported silent magma transport at Bardarbunga after dyke opening. At Tungurahua, the high temperature (~1000°C) of andesites (58-59 wt.% SiO$_2$) and their high water content (5-6 wt.% H$_2$O) may result in a relatively low viscosity magma (Samaniego et al., 2011; Andújar et al., 2017). Therefore, the slow emplacement of a small volume of lava in the crater, originating from a shallow source, as well as the fact that the closest station is located at about 2 km from the crater, could explain the absence of recorded seismicity. The low ash content in the emissions was likely due to
passive reworking of ash driven by high gas pressure (Figure 5a). Our observations suggest that when the conduit is open to magma transport, a seismically silent propagation of magma is possible but not without generating SO2 emission.

(b) Removal of the blocky lava surface and deepening of the fragmentation surface

The sustained degassing and low explosive activity may have resulted in the removal of part of the blocky lava emplaced at the top of the conduit toward the end of episode (a). Such a process may have lowered the pressure in the conduit, leading to an increase in the amount of exsolved SO2 as observed since 3 January. This type of depressurization-induced degassing has been modeled by Girona et al. (2014). Higher gas exsolution could have led in turn to magmatic fragmentation, which would have progressively depleted the upper part of the magma column. This process would result in an increase in viscosity and density of the remaining magma, ultimately generating a denser, less fluid and permeable zone in the magma column. This is in agreement with the model proposed by Diller et al. (2006) based on the 1997 Vulcanian activity of Soufrière Hills volcano, Montserrat. The progressive appearance of tremor during episode (b) is in good agreement with the formation of a rheological barrier or partial plug. Tremor or tremor bursts may be caused by resonances induced in this barrier by the continuous or intermittent transit of gas through this denser zone, based on similar mechanisms to those proposed by Ferrick et al. (1982) or Julian et al. (1994) for the generation of tremor, for example. Preliminary locations obtained for eruptive phases in 2014 with a dense seismic network (Battaglia et al., 2015), suggest that a large part of volcanic sources (tremors, LPs, explosion quakes) may be located about 1 km below the summit. This depth is in agreement with results found by Kumagai et al. (2010) and Kim et al. (2014) for explosion sources at Tungurahua recorded respectively in May 2009 and May
2010. Since the source location appears to be relatively constant through time, we may speculate that the barrier at the origin of tremors and explosions during our eruptive phase was formed at about 1 km below the summit (800 m below the crater floor). The increase of tremor amplitude may be related to the progressive narrowing of the resonating conduit or an increase in gas flux and ash emissions. The occurrence of harmonic tremor during this episode may be explained by specific geometries of the conduit during the formation of the dense barrier, leading to specific dominant frequencies in a similar way to the clarinet model proposed by Lesage et al. (2006) for Arenal volcano. The shallow activity (violent Strombolian explosions, low pyroclastic fountaining and small ash plumes) might be explained by the migration of volatiles through the low-viscosity magma in the upper part of the conduit, leading to magmatic fragmentation and enhancing the growth of the plug. The mostly vesiculated honey-color juvenile material would be the evidence of this shallow magmatic fragmentation and rapid ascent of magma thought the conduit. Similar vesicular material has been observed at Villarrica volcano and reported as golden pumice by Gurioli et al. (2008).

(c) Explosive activity during conduit cleaning, muffling effect and stiffening of the rheological barrier

The appearance of large explosions during episode (c), without any large increase in the rate of SO₂ degassing, suggests a transition in the way in which gas escapes rather than an increase in the amount of exsolved gas. The barrier formed during episode (b) acts like a plug or valve system during episode (c), leading to the accumulation and cyclic release of highly over-pressured gases that trigger Vulcanian explosions. A similar mechanism is proposed by Campion et al. (2018) for E2-type explosions at Popocatépetl volcano. Nevertheless, in this last case the gas is unable to escape due to a rapid gravitational compaction of dome, while
we propose a densification of the magma due to the exsolution and loss of gas following the model of Heap et al. (2015). Magma densification by gas loss and conduit plug formation have also been modeled by Diller et al. (2006) and used to explain Vulcanian activity at Soufrière Hills. These authors showed that a dense zone, a plug, could be produced at 750 m depth, a depth similar to the one assumed in present work (800 m below the crater level). During episode (c), the plug sits below already fragmented juvenile and old material, which results in a muffling of acoustic waves and a ratio AEE/SEE<<100. Recycling of this material in the ash column is evidenced by the drastic increase of vitreous oxidized material in the ash componentry. Large explosions eject parts of this material as well as new magmatic foam and gases released through the plug. Dark juvenile material shows a sharp increase at this time. Similar dark dense material has also been reported in direct relation to Vulcanian explosions at Colima volcano (Cassidy et al., 2015). Harmonic tremor is still generated, sometimes following the occurrence of large explosions, and might be associated to the production of honey-color juvenile material. These internal processes coincide with the strongest superficial activity interpreted as a mixed dynamism between violent Strombolian, mainly characterized by the dominance of honey-color juvenile components, and Vulcanian eruptive styles, dominated by dark juveniles.

(d) Open conduit and triggering of a second magmatic pulse

After the partial or complete destruction of the plug, the conduit is partially open again during episode (d). The pressure drop produced by the partial emptying of the conduit might have triggered a new magmatic injection through a depressurization mechanism similar to that proposed by Girona et al. (2014). The absence of chemical or mineralogical changes in the subsequent eruptive products suggests that the source of this new injection is the same as the
one that occurred during episode (a). According to Samaniego et al. (2011), the magmatic reservoir that fed the shallow system between 1999 and 2006 was located between 7.5 and 9.5 km below the summit. This arrival of new magma explains the sustained SO$_2$ degassing and ash venting observed despite the clear decrease of superficial activity at the end of episode (c). Mostly continuous tremor is recorded accompanying these SO$_2$ and ash emissions. Starting with this episode, the smoothed SO$_2$ time-series roughly follows the MSA, suggesting a common source process. Only a few significant explosions are observed which may relate to the occasional formation of an impermeable zone near the free surface, as supported by the AEE/SEE ratio (>100). Dark-color and honey-color juvenile material are fairly equivalent during this episode.

(e) Explosive events after conduit cleaning, followed by progressive stiffening of the plug inside the conduit

Episode (e) shows a new increase in the number of significant explosions, except that a high AEE/SEE ratio (>100) is recorded during most of the episode, suggesting that the upper conduit is less clogged in comparison to episodes b and c. In terms of magma supply, it can be interpreted as composed of two sub-episodes, from 24 January to 4 February (e.i), and from 5 to 24 February (e.ii), repeating a waxing-waning sequence similar to the one which occurred during episodes (b), (c) and (d). Therefore, (e.i) is interpreted as the increase of activity caused by the arrival of new gas-rich magma. However, compared to (b), the presence of a more efficient rheological barrier (plug) or a deeper level of fragmentation may explain the occurrence of Vulcanian explosions in between of the dominating violent Strombolian activity (Bernard, 2018). In contrast, (e.ii) would rather correspond to waning of the episode with more “pure” Vulcanian activity, as shown by the seismo-acoustic ratios of explosions and the
clear increase in dense black juvenile components in the ash and the coarsening of the grain-size dominant mode. The decrease in SO$_2$ emissions, explosion energies and MSA during (e.ii) indicates a decreasing magma supply rate. This would lead to the progressive plugging and obstruction of the conduit. Its progressive burial may then explain the decrease of the AEE/SEE ratio (<100) observed toward the end of the episode.

(f) Sealing of the system

Finally, episode (f) corresponds to the final closing and sealing of the conduit with only residual ash and gas being emitted. The characteristics of the ash are similar to those from episode (e) with a small increase of oxidized material, recycled from the vent. The plug emplaced at the end of the eruption was later broken at the beginning of the following eruptive phase which started in May 2010 with Vulcanian explosions and moderate-size pyroclastic flows (Kim et al., 2014; Hidalgo et al., 2015; Bernard, 2018).

The eruptive phase that we studied, displayed a wide spectrum of eruptive dynamics. We interpret this diversity as being the result of variable conditions of opening or constriction of a rheological barrier or plug in the conduit, additionally to variations in the magma supply rate. Despite the morphological differences, Soufrière Hills volcano displayed similar dynamics during its eruptive activity from 2005 to 2010, showing also ash venting and Vulcanian explosions. At Soufrière Hills, Cole et al. (2014) explained the ash venting by short term increases in the extrusion rate related to shear-induced fragmentation at the conduit margin. Seismic tremor and ash componentry were similar to what we observed in episode (b). The origin of Vulcanian explosions at Popocatepetl or Montserrat is ascribed respectively to the self-collapse of the dome (Campion et al., 2018) and the sealing of the dome cracks, allowing
degassing, by precipitation of hydrothermal minerals (Edmonds et al., 2003). At Tungurahua, the activity does not include the formation of domes and its Vulcanian explosions are more similar to those observed at Sakurajima volcano (Watt et al., 2007). Hence, we argue that a high-viscosity, high-density barrier inside the conduit is responsible for the occurrence of Vulcanian explosions, following the experimental models proposed by Heap et al. (2015), while the violent Strombolian activity is probably associated to a hotter less degassed magma.

5. Conclusions

The comparison of seismic, acoustic and SO₂ gas emission time series recorded during the December 2009 - March 2010 eruptive phase of Tungurahua volcano outlines diverse patterns and correlations between the parameters. Based on this diversity, we identified 6 episodes with different characteristics, which we interpret in terms of conduit conditions and magma supply rate. During these episodes, degassing could freely occur without generating any seismicity if the conduit was open. Tremor could be observed, including monochromatic tremor if the conduit was (properly) constricted and larger Vulcanian explosions could occur if it was occasionally or partially plugged. At some point, dynamics changed from continuous degassing during ash venting and violent Strombolian activity to a degassing dominated by Vulcanian explosions without any significant change in the amount of SO₂ emitted from the vent.

We associate this variability to changes in the conduit and more specifically to the evolution of a rheological barrier or plug which we assume to be about 1 km below the summit based on locations of seismic sources. Vent conditions and fragmentation processes are also clearly
reflected in the ash componentry and to a lower degree in the grain-size distribution. Our results suggest that the correlation of multiparametric data can highlight transitions in the nature of superficial activity that can be confirmed through petrological monitoring. They also outline geophysical patterns that allow to identify two waxing-waning cycles within the eruptive phase produced by a second magmatic injection. The geophysical and petrological signature of the two cycles was different as the conduit conditions evolved.

Comparing and correlating the different parameters allow making better interpretations of the eruption evolution which is of major importance to improve hazard assessment. Our interpretation patterns may be applied to most andesitic volcanoes independently of the presence of plugs or domes which may act as shallow rheological barriers.

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**WEB REFERENCES**


**Figure 1**: Map of Tungurahua volcano showing the location of the three scanning-DOAS stations, five broadband seismic/infrasound stations and one short-period seismic station RETU whose data was used for this study.
Figure 2: Seismic -vertical component- (black) and acoustic (red) signals recorded at station BMAS. Plots (A), (B) and (C) show 40-min seismic and acoustic waveforms illustrating three different types of eruptive activity starting at the times specified in the lower left corners. On these 3 plots, seismic and acoustic traces have respectively common vertical scales and the amplitude of acoustic traces have been divided by a factor 100. (A) Tremor bursts, mostly harmonic, recorded during Strombolian activity in episode (b), (B) harmonic and non-harmonic tremor bursts during episode (c) and (C) strong Vulcanian explosions and low background tremor during episode (e). Plots (D) and (E) detail two 24-s windows showing respectively examples of seismic recordings for non-harmonic and harmonic tremor. Plot (F) shows a 60-s time frame for a seismic explosion quake with its corresponding acoustic signal.
All three time frames are extracted from the signals shown in plots (B) and (C) at the corresponding locations shown within blue rectangles.
Figure 3: Comparison of geophysical time-series. Onset and ending times of the six episodes (a) to (f), described in the text, are delimited by vertical red dashed lines. HEA and LEA periods are displayed in yellow and orange background colors, respectively. “Daily Cumulated Seismic Amplitude” shows the daily cumulative values of the Median Seismic Amplitude (MSA) for the full short-period range at station RETU (black), completed with scaled data from BMAS (blue) when station RETU was down or saturated. “Explosions Energies” shows daily cumulative values of the seismic (black) and acoustic (red) energies for
the significant explosions. The vertical scale for acoustic energy is exactly 100 times that of seismic so that the reader can directly compare the energies with respect to the threshold value of 100 mentioned in the text. “N. Explo.” displays the daily number of significant explosions. “SO₂” shows the daily Observed Mass of SO₂ with the averaged values calculated over 5-d sliding windows shown in turquoise. “DVMD” shows the Daily Valid Measurement Duration, i.e. the number of minutes of valid SO₂ measurements. All three scanning-DOAS stations were functioning properly during the study period. Figure 5 shows sketches presenting a model of conduit dynamics corresponding to the six episodes.
Figure 4: A) Barplots of the componentry and B) histograms of the grain-size distribution of ash samples collected during the December 2009-March 2010 eruption. Description of the components is given in the text. $\phi = -\log_2 D$ where $D$ is the particle diameter in millimeters. b, c, d, e, f correspond to the eruptive episodes described in the text.
**Figure 5:** Sketches showing a model of conduit dynamics for the six episodes of activity defined in the text. Annotations along the sketches describe the characteristics of each activity from bottom to top. (a1) New magma input, (a2) gas easily exsolved, (a3) high gas pressure at the base of the lava accumulation in the crater, (a4) gas and ash venting. (b1) Steady arrival of magma, (b2) generation of a dense, gas depleted zone, (b3) destruction of the lava accumulation in the crater, (b4) gas and ash venting with Strombolian activity, emissions dominated by honey-color juvenile material. (c1) Gas accumulation below the dense zone, (c2) cyclical breaking of the dense zone, explosive release of gas, (c3) gas transport of juvenile material and cleaning of the conduit, (c4) gas and ash venting, Strombolian and Vulcanian activity. (d1) New magma injection with the same composition, (d2) mixed fragmentation process, (d3) steady ash column. (e1) same as (c2), (e2) gas transport of juvenile material with decreasing recycling, (e3) transition toward a more purely Vulcanian eruptive process. (f1) No more gas arrival, (f2) the dense zone cools down and forms a plug, (f3) remnant gas leaving the conduit, (f4) low gas and ash emission.