EXPLOSIVE ACTIVITY AT TUNGURAHUA VOLCANO: ANALYSIS OF SEISMIC AND INFRASONIC DATA IN 2010

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Introduction

Tungurahua (1.45°S, 78.43°W, 5032 m) is a steep-sided, andesitic stratovolcano, located in the Real Cordillera of central Ecuador. Notable for its high relief (3200m) and steep flanks, Tungurahua forms one of the most active volcanic centers within the Ecuadorian Andes (Hall *et al.*, 1999). Significant eruptions (VEI ≥ 3) were recorded in AD 1640-41, 1773, 1886 and 1916-1918, and were typically accompanied by strong explosions, lava and pyroclastic flows, lahars and fallout tephra (Hall *et al.*, 1999; Le Pennec et al., 2008). In the past, these volcanic products affected small villages around the volcano's base, as well as the populated town of Baños, which lies just 8 km from the summit.

After 80 years of quiescence, a renewed and important phase of activity was initiated in November-December 1999 that ultimately triggered the evacuation of 26,000 people. Since 1999, Tungurahua has experienced a series of eruptive cycles, with periods of considerable activity taking place in August 2001, July-August 2006, February 2008, January-March 2010, May-July 2010, November-December 2010, April-May 2011, November-December 2011, and February-May 2012.

The Instituto Geofisico monitors the activity of Tungurahua through a network of six broadband and five short period seismic stations, and five infrasonic sensors that are all located at distances between 5-8 km from the vent. A collocated seismic-acoustic array is also present, located at a distance of 37 km. Information is digitally recorded, before transmission through a series of repeater stations back to the IG centralized office in Quito, providing a continual stream of real-time data (Kumagai *et al.*, 2010). Through this continuous monitoring, a catalogue of explosion events at Tungurahua has been created, dated from July 2006 to the present. The catalogue records the seismic and infrasonic energies (and reduced amplitudes), from four of the stations around the volcano (Bmas, Bpat, Brun & Bbil), for each discrete explosion.

Applying statistical techniques to the 2010 explosion data

Explosive activity at Tungurahua was observed during three phases of unrest across the year of 2010: 05 January-19 March, 26 May-28 July, 22 November-25 December (Fig. 1). A series of statistical techniques were then applied to the explosion dataset, to understand temporal variations in event rate (number of explosions within a given time) as well as the energies of seismic and acoustic partitioning.

After explosion initiation, energy is propagated both through the earth (seismic waves) and through the atmosphere (acoustic shocks and waves). Seismic and acoustic energies were calculated for each discrete explosion at Tungurahua, across 2010. The relationship between seismic and acoustic partitioning VASR (Volcano Acoustic-Seismic Ratio), highlights temporal variations in explosion initiation, volcanic conditions and eruption mechanisms, between discrete events or across periods of unrest (Johnson & Aster, 2005). For example, high values of VASR are formed when larger proportions of acoustic energy are propagated and thus typically where explosions are initiated at shallow depths within the vent. In contrast, deeper explosions within the conduit propagate higher seismic energy and in turn, a lower value in the VASR.

To understand the relationship between the number of explosions with their magnitudes, a Frequency-Amplitude Distribution (FAD) was constructed for each period of activity. The reduced displacement of explosion seismic waves was used to calculate the FAD's and a proxy *b*-slope value was devised to determine the nature of fracturing taking place within the shallow volcanic system during explosion initiation.

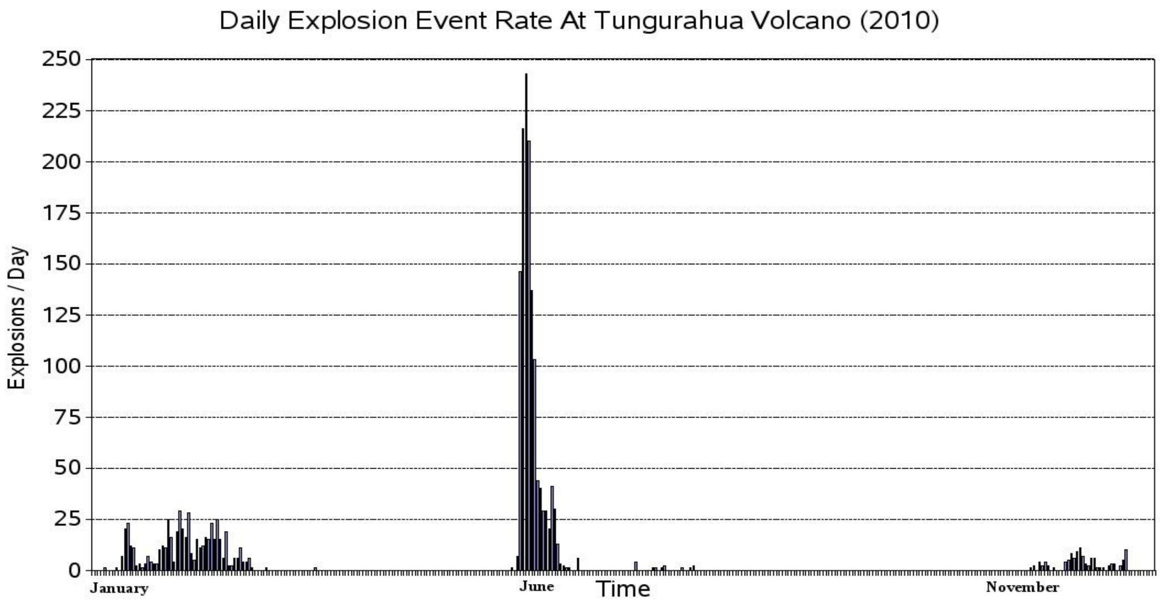

Fig. 1 Number of daily explosions at Tungurahua Volcano (2010). Note three clear periods of activity in January-March, May-July and November-December 2010.

To understand temporal variations in explosion event rate, the coefficient of variation (*Cv*) was calculated, which identifies the degree of clustering between events, and was used to determine if there was a statistical significance between explosions within the event rate data. The *Cv* is given by the equation:

$$Cv = \sigma / \mu$$

where σ is the standard deviation and μ is the mean time between explosion events. If the $Cv = 1$, then the controlling process is Poissonian and events can be treated as randomly distributed through time, whereas if the Cv is > 1, then the controlling process is typically clustered.

These statistical techniques were applied across each phase of unrest throughout 2010 at Tungurahua in order to obtain a comprehensive understanding of the temporal variation in explosive activity.

Episode 1: 05 January 2010 – 19 March 2010
After some months of repose, a renewal in explosive activity was recorded on the 05 January 2010. A rate increase in the number of daily explosions was then observed before reaching a peaking on the 31 January, with 29 events. After this date, explosion numbers steadily declined until activity had all but finished by the 02 March. Across the two-month episode, a Gaussian distribution in event rate was observed with a typical bell-shaped curve. Along with an increase in event rate, seismo-acoustic energy also began to rise. Values in seismic energy had already peaked during the early part of January, whilst acoustic pressure values continued to increase. Cumulative daily acoustic energy reached a maximum on the 11 February (energy ~ 650 x 10^{12} Joules), before explosion seismo-acoustic energy and event rate began to rapidly decline, ending the explosive cycle.

The calculated FAD provided a proxy *b*-slope value of ~ 3.03 (Fig. 2). Values in the Volcano Acoustic-Seismic Ratio across the episode generally ranged between 1-1000, with such a large degree in VASR scattering often being observed at andesitic stratovolcanoes (Varley *et al*., 2006). A few explosions produced anomalously large values in the VASR during the first 10 days in February, with one event calculated at over >4000. This correlates with the accelerating acoustic energy that was recorded during this time.

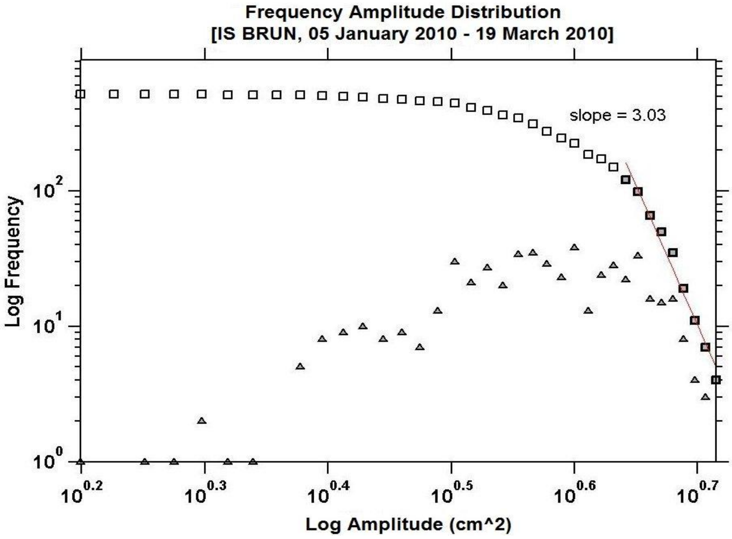

Fig. 2 Frequency-Amplitude Distribution (FAD) for determining the relationship between the number of explosions with their proxy magnitudes. 05 January - 19 March, 2010. Proxy *b*-slope value ~ 3.03.

Episode 2: 26 May 2010 – 28 July 2010

On the 26 May 2010, one high energy explosion was recorded at Tungurahua, with a seismic energy value of ~ 573 x 10^6 J. Such a large value in seismic propagation, compared to acoustic partitioning, suggests that this explosion was initiated at a far deeper source within the conduit, compared with all other events previously monitored throughout 2010. Activity resumed on the 28 May, with strong eruptive activity. Between the 29 May-03 June, hundreds of explosions were being produced each day, with event rate peaking just 6 days into the new cycle (31 May) with 242 events. After the 03 June, daily explosion numbers decreased sharply. Unlike the Gaussian distribution observed in January-March, here a sharp rise and peak in event rate was seen, before an exponential decay in daily numbers.

A proxy *b*-slope value from the calculated FAD across the period produced a value of ~ 2.94, and a slight decrease from the previous episode. This implies that after the repose following the explosive cycle in January-March, the system had become more considerably sealed. As well, the coefficient of variation was found to be anomalously high (*Cv* ~ 13.71) compared with all other periods of unrest dating back to 2006, where *Cv* values generally ranged between ~ 2-5. Whilst all periods of activity show a strong clustering of events with time, such an anomalous value during May-July (2010) suggest a change in eruption mechanism (and an alteration in volcanic conditions) during this phase of activity. During the early stages of this eruptive phase, explosions were initiating lower VASR values, as highlighted by the 26 May event which displayed very high seismic partitioning, suggesting that explosions were being initiated from deeper sources within the conduit and under a more plugged vent system, as typical of vulcanian explosions. A few days later, values in the VASR began to rise, suggesting that continued explosive degassing had eventually cleared the plug. This allowed gas bubbles to travel unimpeded towards the free surface and initiate explosions with higher VASR`s, as is typical in strombolian type activity. This sequence of low to high VASR across an active cycle is common at many volcanoes (Caplan-Auerbach & McNutt, 2003).

Episode 3: 22 November 2010 – 25 December 2010

High energy explosions began on November 22nd, but activity only lasted for one month in total. Daily event rate was low throughout the episode, with just a few explosions being initiated each day. Event rate reached a peak on the 09 December 2010 with just 11 events, before a steady decline in explosion numbers was observed. Whilst mean acoustic and seismic daily energy remained relatively consistent across the period, cumulative daily energy increased to a peak around the 10 December, owing to an increase in the number of events during this time. VASR values remained consistent, ranging between 1-1000 (Fig. 3), whilst the *Cv* was calculated at ~ 1.72, a value more reminiscent of explosion clustering in periods of activity prior to May-July 2010.

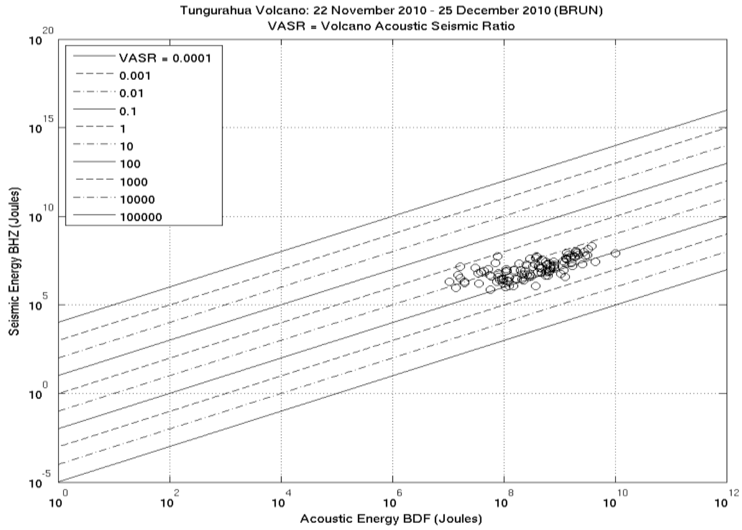

Fig. 3 Volcano Acoustic-Seismic Ratio (VASR) at Tungurahua Volcano (22 November 2010 – 25 December 2010). Values in the VASR for this period typically ranged between ~ 1-1000.

Conclusion

A number of statistical techniques were applied to explosion data from Tungurahua volcano, which ultimately highlighted temporal variations in explosive activity across three phases of unrest throughout the 2010 year. Data of explosion event rate and seismo-acoustic energy appeared consistent between activity in January-March and November-December, and as well with periods of unrest dating back to 2006. During May-July however, explosion numbers and cumulative seismo-acoustic energy, appeared anomalously high. Results within statistical tests as highlighted by the coefficient of variation and some particularly low values in the VASR during the early phase of this episode confirm an inconsistency within the data when compared with other periods of activity and suggest a change in volcanic conditions (and eruption mechanism) during this time. Results suggest that during the early part of the May-July 2010 episode, the system was strongly plugged, initiating deeper sourced explosions. Continued degassing eventually cleared the plug allowing explosion initiation at shallower levels within the vent, as similar to other periods of activity at this volcano. This study ultimately revealed hidden structure in patterns of explosive behavior, implying that andesitic stratovolcanoes like that of Tungurahua are prone to temporal variations in volcanic conditions and eruption mechanisms, as the volcano evolves with time.

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