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Drumbeat LP 'aftershocks' to a failed explosive eruption at Tungurahua Volcano, Ecuador

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Key Points:

- An episode of accelerating and decelerating long-period (LP) drumbeat earthquakes is identified at Tungurahua volcano, Ecuador
- Bayesian gamma point process analysis constrains mirrored sequences of Omori Law accelerating and decelerating seismicity
- Waveforms examined by cross correlation and Q factor reveal a gas driven, repeating, single source, which failed to culminate in an eruption

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Abstract

Highly periodic, repetitive long-period (LP) earthquakes, known as 'drumbeats', have been observed at a range of volcanoes, typically during the ascent of degassed magma. Accelerating rates of drumbeats have been reported before explosions, and potentially offer forecasts of future activity. However, the broader phenomenology of drumbeats is poorly understood. Here we describe an episode of over 900 LP earthquakes recorded in November 2015 at Tungurahua Volcano, Ecuador, that we believe are associated with a failed explosion. Rates of LP drumbeats accelerated for 10 hours, consistent with an Inverse Omori's Law. Before any explosion occurred, seismicity decreased following Omori's Law, over a further six days. Despite earthquake rates decelerating, amplitudes, spectral peaks, Q values and periodicity remain constant, suggesting there is little change in the source process with time. We argue that the decelerating seismicity is a result of progressive reduction of gas flux, unable to provide sufficient overpressure for explosion.

Plain Language Summary

When a volcano is erupting, small earthquakes from the volcano can be used to infer what internal processes may be occurring. Earthquakes that are very similar to one another and repeat at consistent intervals are known as drumbeat earthquakes. These are of interest in volcanic systems as it implies the earthquakes are generated by a single, repeating source. Previous studies of drumbeat earthquakes at Tungurahua Volcano, Ecuador, have described these earthquakes occurring closer together in time and accelerating up to an explosion. In this case, we identify a sequence of drumbeats where the rate accelerates, and without any explosion, decelerates again. We suggest these earthquakes are generated by gas flux which is slowing down. This gas originates beneath a plug at the top of the conduit. We use statistical models to estimate when the volcano may have exploded if the earthquakes had continued to accelerate, and quantify the subsequent deceleration in earthquake rate.

1 Introduction

Active arc volcanoes of andesitic-dacitic composition are often sources of rich seismic data. Signals at these volcanoes are often dominated by long-period earthquakes (LPs), commonly associated with processes occurring in and around the magma column. Understanding these signals could be key to improving our ability to forecast volcanic activity. LPs are characterised by frequencies between 0.5 and 5.0Hz, emergent onsets, and missing clear S wave arrivals (Chouet et al., 1994). They often begin with a mixed frequency onset, followed by low frequency coda that decays in amplitude with time. This characteristic shape has been modelled as a two part process with an initial excitation trigger and subsequent resonance (Chouet, 1996). These are some of the features that have been used to distinguish different categories of volcano seismic events, attributed to different source processes (Chouet & Matoza, 2013)(fig S1). Swarms of periodic, highly similar, repeating LPs occur in a phenomenon known as drumbeats. Drumbeat seismicity is commonly associated with degassed magma ascent, however, the broader phenomenology of drumbeats is still poorly established. Locating LPs is generally a very difficult process, however, with one or two stations, careful analysis of the waveforms and their frequency content can tell us about an evolving source mechanism.

Drumbeat earthquakes are best known from the dacite spine extrusion episode at Mount St. Helens between 2004 and 2005. Iverson (2008) approximated long term steady-state behaviour and slowly changing drumbeat rates and amplitudes with frictional stick-slip at the conduit margins. However, drumbeat seismicity is known to display a variety of characteristics from many arc volcanoes. Drumbeat seismicity at Soufrière Hills Volcano appeared in pulses lasting several hours (Green & Neuberg, 2006). These pulses were associated with brittle failure of ascending magma at conduit margins (Neuberg et al., 2006). The behaviour of drumbeats observed at Tungurahua alone is varied. One study examined a six-day episode of steady-state, repeating LPs in 2001 where the Q factors of individual earthquakes were changing through time (Molina et al., 2004). This shift was modelled with repetitive injections of increasingly ash-laden gas. Repeated low frequency (1-3Hz) pulses are recorded in both the seismic and infrasonic record for episodes in 2004 (Ruiz et al., 2006). In July 2013, accelerating drumbeats merged into tremor before a large explosions (Bell et al., 2018). A further study identified the incremental breakdown of an episode of drumbeat LP seismicity during April 2015 (Bell et al., 2017). Building on previous models at Soufrière Hills, a more developed plug model argued that LPs were triggered by gas escape and shear failure in the conduit margins with magma ascent.

Accelerating seismicity, has been related to material failure in the Failure Forecast Method (FFM) (Main, 1999; Voight, 1988). New statistical methods allow analysis of point process data, revealing properties of precursory sequences. Improved methods help to quantify data, identify changes and understand underlying processes. We can examine seismicity rates with relationships such as the Modified and Inverse Omori's Laws. By contrasting accelerating and decelerating seismicity with models and examining this 'mirrored' effect we can investigate the significance of failed explosions, better understand the physics of the process and develop forecasting statistics.

Here we describe a six day sequence of accelerating and decelerating drumbeat LP earthquakes at Tungurahua during November 2015, associated with a 'failed' explosive eruption. We use a Bayesian gamma point process model (Bell et al., 2017) to examine the acceleration of seismicity rate, and the subsequent decelerating rate of seismicity. We find that the drumbeats both accelerate and decelerate according to a power law with an exponent value, $p = 0{:}96 \quad 0{:}51$ and $p = 0{:}97 \quad 0{:}12$ respectively. Despite prolonged decaying temporal rates of seismicity, the earthquakes show strong similarity with families persisting across the six day sequence and amplitudes unchanging. This suggests a slowing rather than a breakdown of the driving source mechanism following a failed eruption.

First we introduce the activity and data recorded at Tungurahua during November 2015. We then present the seismic data, along with the statistical methods for analysis. We model the data using a Bayesian point process methodology, testing different rate models and estimating parameter posterior distributions. We analyse earthquake properties including waveform similarity, families and Q factor values. We finally present a model for accelerating and decelerating drumbeats, and discuss the implications this has for magma ascent dynamics at Tungurahua.

2 Data & Methods

2.1 Tungurahua

Tungurahua is a 5,032m high andesitic stratovolcano in the Central Cordillera of the Ecuadorian Andes (Hall et al., 1999). The most recent phase of activity occurred between 1999 and 2016 with notable sub-Plinian activity in 2006 (Mothes et al., 2015). Unrest at Tungurahua was typically associated with high rates of LP seismicity. Between the major explosive episodes of 2014 and 2016, heightened seismicity accompanied deformation and repeating tilt cycles (Bell et al., 2017; Neuberg et al., 2018; Marsden et al., 2019). This study focuses on an episode of drumbeats during one such cycle in November 2015. The drumbeats persist for six days and did not culminate in any explosion. There was then a repose period of 3 months before the final explosions in February 2016. Drumbeat seismicity in persisted for several weeks in April 2015 and was accompanied by small explosions and ash emissions (Bell et al., 2017). Whilst in October and early

November 2015, small pulses of drumbeat seismicity emerged and ceased over just a few hours or days and are as yet unstudied (fig 1).

2.2 Monitoring data

The Instituto Geofísico de la Escuela Politécnica Nacional (IGEPN) maintain a volcano monitoring network on Tungurahua. The network includes short period and broadband seismometers, DOAS gas flux stations, infrasound stations, tiltmeters, GPS, cameras and acoustic flow monitors. From a seismic network of 11 stations, IGEPN maintain a catalogue of detected, classified, and where possible, located events. Over 90% of events were recorded at RETU, a short period seismometer at elevation over 4000m, approximately 2000m from the crater rim. This proximity means the signal to noise ratio (SNR) is high and many small, shallow events are recorded. We manually picked 932 events from 25 - 30 November 2015 for this study, representing all detectable events at RETU. These events were only visible at the one station and with emergent onsets and no clear S-phases, locating the events was not possible. As the seismicity is only recorded at this uppermost station, we believe these LPs are associated with shallow processes in the top 2000m of the conduit (Bell et al., 2018). The similarity of the waveforms indicates that they are all closely co-located within a small depth range. Given this co-location, we use the maximum amplitudes of individual events as a relative comparison for magnitude. 615 of the manually picked events appear in the IGEPN catalogue. However, there are only 20 events which are located and have estimated magnitudes, all of which are less than magnitude 1.5, and carry large uncertainties. The seismicity on 25 November is the first clearly identifiable sequence of LP events as in the preceding days, the signal at RETU is dominated by emission tremor.

Details of surface observations and ash column heights are extracted from daily reports produced by the Observatorio del Volcán Tungurahua (OVT) (`https://www.igepn.edu.ec/`), and used in conjunction with the seismic data for temporal analysis. Explosion counts and radial tilt measurements at station RETU are also collected from IGEPN catalogues.

2.3 Methods

The seismic data is initially processed using the ObsPy toolkit (Krischer et al., 2015). 30 second duration waveforms are sliced and bandpass filtered between 1 and 40Hz. The maximum amplitude of each event is extracted. Fast Fourier Transform (FFT) of each signal is calculated to generate a periodogram. We find the power spectral density (PSD) for frequencies sampled at an interval of 0.01Hz and extract the maximum value as the fundamental peak frequency.

The Q factor for each event is calculated using an auto-regressive moving average (ARMA) technique, adapted from *Seismo-Volcanalysis* software (Lesage, 2007). The Q factor is a non-dimensional number that describes how quickly or slowly wave energy dissipates and is often strongly linked to the fundamental peak frequency. Auto-regressive methods have been successfully used to analyse changing LP frequency contents (Kumagai & Chouet, 1999; Lokmer et al., 2008). The approach is similar to the commonly used Sompi method (Hori et al., 1989). A signal is composed of a number of individual harmonic decaying oscillations. Each component can be represented in complex frequency space and quantified by a peak frequency (f, Hz) and growth rate (g, s^{-1}). (Kumazawa et al., 1990). We generated cumulative f-g diagrams for all filters between 2 and 30 and points that cluster around a pole at the spectral peak are used to calculate Q (Eq 1) (Cusano et al., 2008). In this automated adaptation of the ARMA method, a hierarchical clustering method is used to automatically select points in the complex frequency space (Eads, 2008).

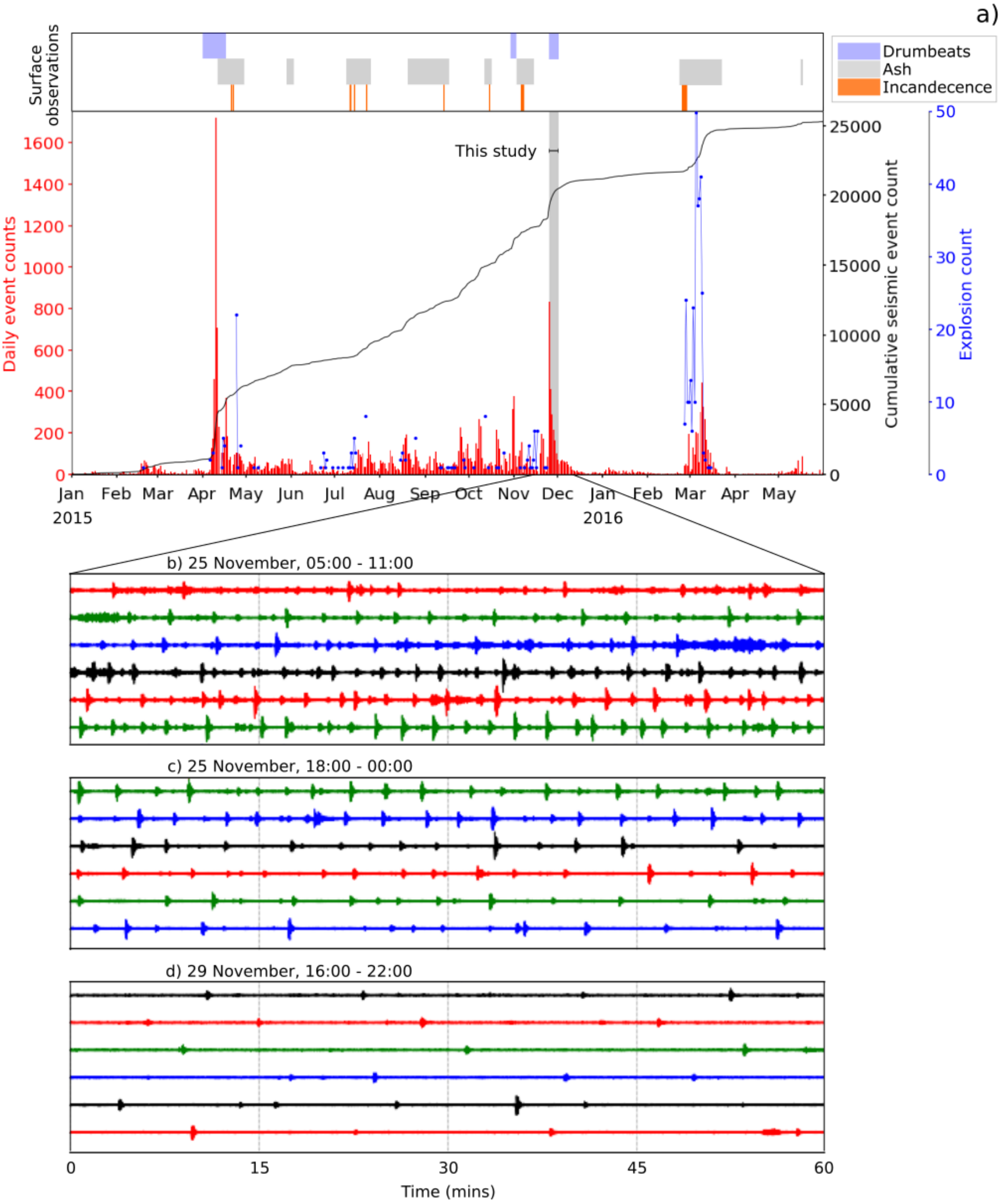

Figure 1. *a)* Seismicity at Tungurahua 2015-2016. Red bars show daily event counts, blue dots mark daily explosions, black line shows cumulative seismicity, grey shading marks period of interest for this study. Top panel marks surface observations - blue shows known episodes of drumbeats, grey shows ash ejection and orange are sightings of incandescent glow in crater. **b)** Accelerating drumbeats, 25 November. *c)* Decelerating drumbeats, 25 November. *d)* Penultimate day of drumbeats, 29 November. All 6hr extracts from RETU.

$$Q = \frac{f}{2g} \tag{1}$$

We determine the maximum cross correlation coefficient between 0 and 1, for all pairs of events in our catalogue and use a threshold value to group events into families (Waite et al., 2008; Yukutake et al., 2017; Park et al., 2019). Following previous studies, including that of LP drumbeat seismicity in April 2015 at Tungurahua, the threshold is set at 0.7 (Petersen, 2007; Thelen et al., 2011; Bell et al., 2017).

We also calculate earthquake inter-event times (IETs) and their periodicity to highlight times of pronounced drumbeat activity. (Bell et al., 2017) defines periodicity as the ratio between the mean, , and standard deviation, , of IETs. Events randomly distributed in time, with an average rate, , will have a probability density function such that − = 1. Clustered events have periodicities less than 1, whereas periodic events have periodicities greater than 1.

Finally we considered models for the accelerating and decelerating components the drumbeat episode. Previous studies of accelerating seismicity have modelled rates using power, exponential and hyperbolic relationships (Ignatieva et al., 2018; Bell et al., 2018). In accelerating and decelerating components we opted to model the event rates using an exponential relation (Eq 2) and a power law. For the decelerating event rates this is the Modified Omori's Law (Eq 3) and for the accelerating rates, an Inverse Omori's Law (Eq 4).

$$n(t) = ke^{\quad t} \tag{2}$$

$$n(t) = k_1(t \quad t_f)^{\quad p_1} \tag{3}$$

$$n(t) = k_2(t_f \quad t)^{\quad p_2} \tag{4}$$

We model the drumbeat sequence as an inhomogeneous Gamma process (Bell et al., 2018). We define the point of maximum seismicity as, t_0, separating the accelerating and decelerating components. We use a Bayesian approach with PyMC3 implementation (Salvatier et al., 2016). We use Markov Chain Monte Carlo (MCMC) to sample the posterior distributions of model parameters. We run 5000 iterations. We provide initial estimates for parameters p, t_f, k and . The prior distribution and rate parameters used are detailed in table S1.

3 Results

Across the six day period from 25-30 November we see an initial increase in the rate of seismicity before a rapid deceleration (fig 3). The peak in event rate occurs at 10:00 on 25 November (fig 2). During the drumbeat episode the radial tilt increases and decreases in a range of 10 rad.

3.1 Drumbeat Onset

The first 10 hours of the drumbeat sequence is markedly different from the activity observed thereafter. In the first 10 hours, the event rate increases, the individual event amplitudes increase slightly and the seismicity becomes increasingly periodic (fig 2). The point process modelling shows the accelerating rates of seismicity can be defined by a power law (fig 3a). The best fitting exponent, $p = 0{:}96 \quad 0{:}51$. The best fit value for