Forecasting Volcanic Eruptions: the Narrow Margin between Eruption and Intrusion at Cotopaxi, Ecuador

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Helping the vulnerable protect themselves

Alexander L. Steele[1], Christopher R. J. Kilburn[1], Richard J. Wall[1], Danielle Charlton[1]

[1]UCL Hazard Centre, Department of Earth Sciences, University College London, Gower Street, London, WC1E 6BT, UK

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Summary

Volcano-tectonic (VT) seismicity provides a natural proxy for gauging the stability of a pressurizing body of magma. Here we use monitoring data from the 2015 unrest at Cotopaxi volcano, in Ecuador, to show how VT time series can be quantified in terms of general elastic-brittle deformation. The results show an evolution from an exponential to a hyperbolic increase in VT event rate with time, coinciding with the rupture of a magma chamber and the opening of a new pathway to the surface. The emplaced dyke eventually stalled, allowing a small lateral intrusion to form.

1. Cotopaxi Volcano - Eruptive History and Recent Unrest

Cotopaxi is an andesitic stratovolcano 60 km southeast of Quito (Fig. 1). At least 55 eruptive episodes have been recorded since 1698. During the last major eruption in 1877, pyroclastic flows melted the summit glaciers, triggering lahars that travelled to the Western Amazon Basin and more than 300 km to the Pacific coast [1]. The mudflows devastated the populated districts of Latacunga 35 km to the south and the Los Chillos valley 40 km to the north of the volcano. Today, more than 300,000 people live within direct range of its eruptive activity.

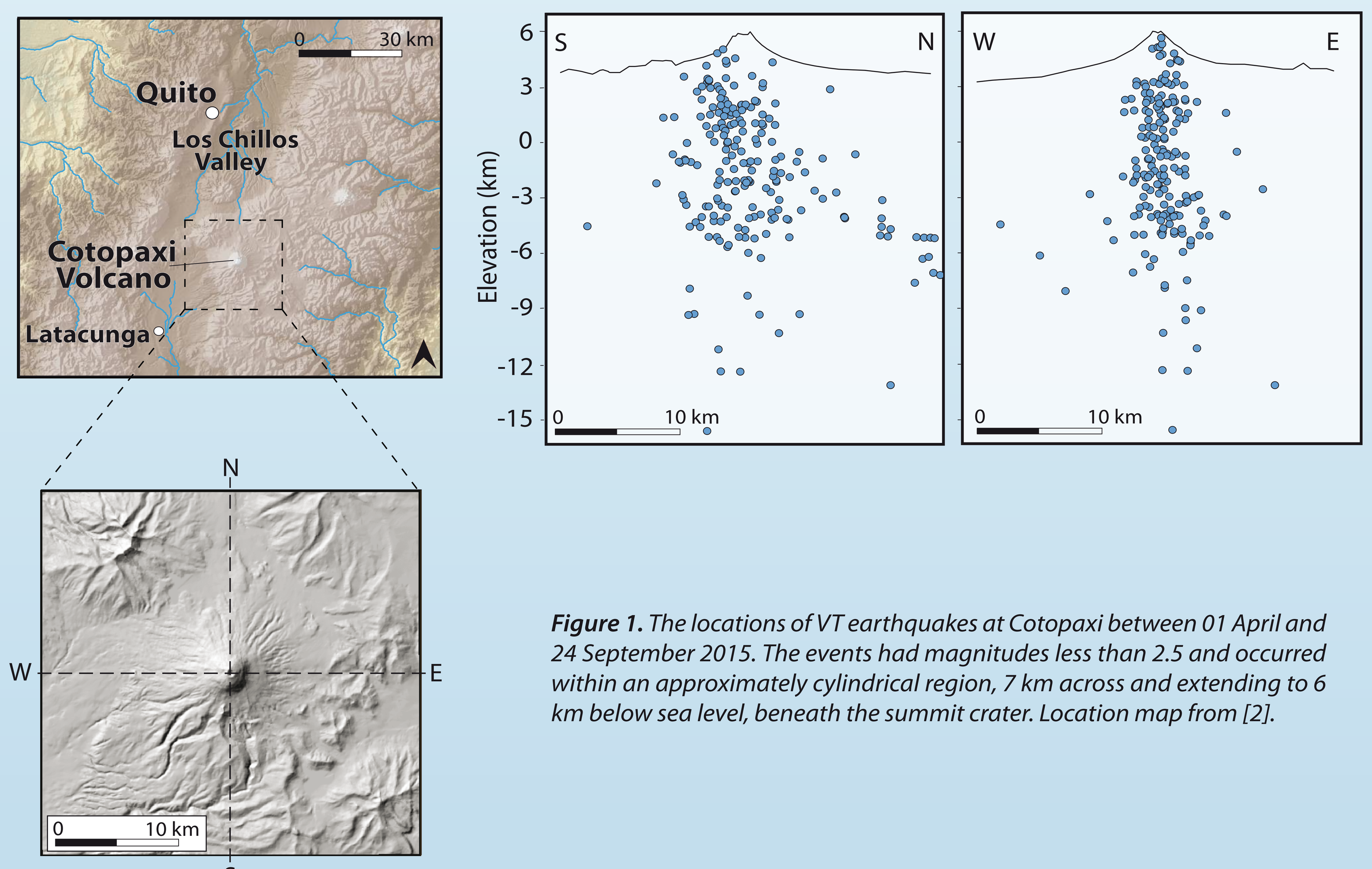

Figure 1. The locations of VT earthquakes at Cotopaxi between 01 April and 24 September 2015. The events had magnitudes less than 2.5 and occurred within an approximately cylindrical region, 7 km across and extending to 6 km below sea level, beneath the summit crater. Location map from [2].

Cotopaxi entered a new phase of unrest in April 2015, after at least 73 years of repose. Unrest was characterised by the appearance of volcano-tectonic (VT) earthquakes, long-period seismicity and tremor. VT numbers accelerated during the unrest, peaking in September (Fig. 2). The earthquakes occurred between the summit region and 6 km below sea level, within 3.5 km of the central axis of the volcano and without a significant migration in preferred location with time (Fig. 1). Vigorous gas release from the summit began in mid-August. This was accompanied by phreatic explosions (Fig. 2) and, subsequently, by emissions of small quantities of juvenile ash.

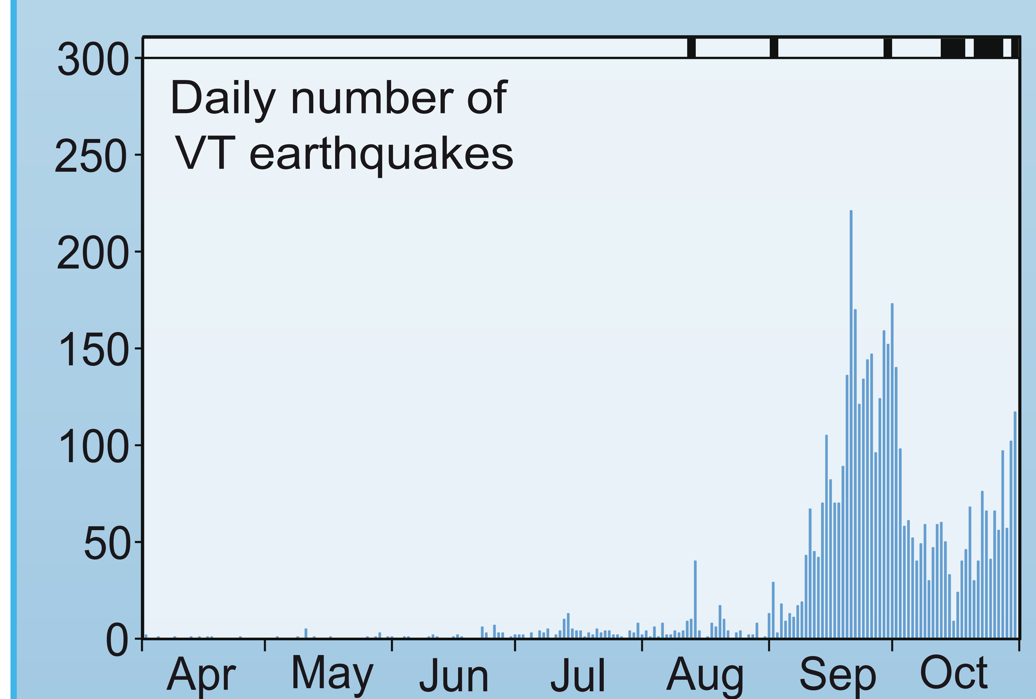

Figure 2. Variation in rates of seismicity at Cotopaxi between April and November 2015. Phreatic explosions were first recorded in August (black bars). Later explosions also ejected small quantities of juvenile ash [3].

2. Relating Accelerations in VT Event Rate to the Structural Evolution of the Shallow Magmatic System at Cotopaxi

Pressurization triggers faulting in the crust as well as rupture of the magma body. It thus connects VT event rate to stress conditions that may end up with magma escaping along a new fracture from the parent body. Cotopaxi's recent unrest shows an acceleration in VT event rate that evolved from an exponential to a hyperbolic trend on 09-10 September (Fig. 3).

For pressurized bodies, conditions for rupture yield values for the ratio S_F/σ_T (rupture stress, S_F, to the crust's tensile strength, σ_T) of 1 for planar failure, and 2 and 3 for the rupture of, respectively, cylindrical and spherical portions of the margins of a magma body.

Rupture of a magma chamber is expected at the end of the exponential increase, for which the Cotopaxi data yield $S_F/\sigma_T \approx 3$ - consistent with the rupture of a spherical portion of a magma chamber (Fig. 3). The hyperbolic trend describes subsequent faulting under a constant stress. Field data give $\gamma^* = 1.4 \times 10^{-3}$ and hence $S_F/\sigma_T \approx$ 1.3-2 - consistent with the rupture of a planar or cylindrical portion of a magma body (Fig. 3). The data also give 15 days for the duration of the hyperbolic trend, corresponding to a singularity on 25 September. A change was observed on 21-22 September, after the rate had reached 221 events per day. Instead of accelerating to eruption, the rate decreased by a third to a quasi-constant value of 140±20 events per day until 02 October, after which it decayed to 10 events per day on 16 October (Fig. 2).

Photo: Degassing from the summit crater at Cotopaxi volcano on 21 September. The volcano poses a direct threat to more than 300,000 people. Photo by B. Bernard.

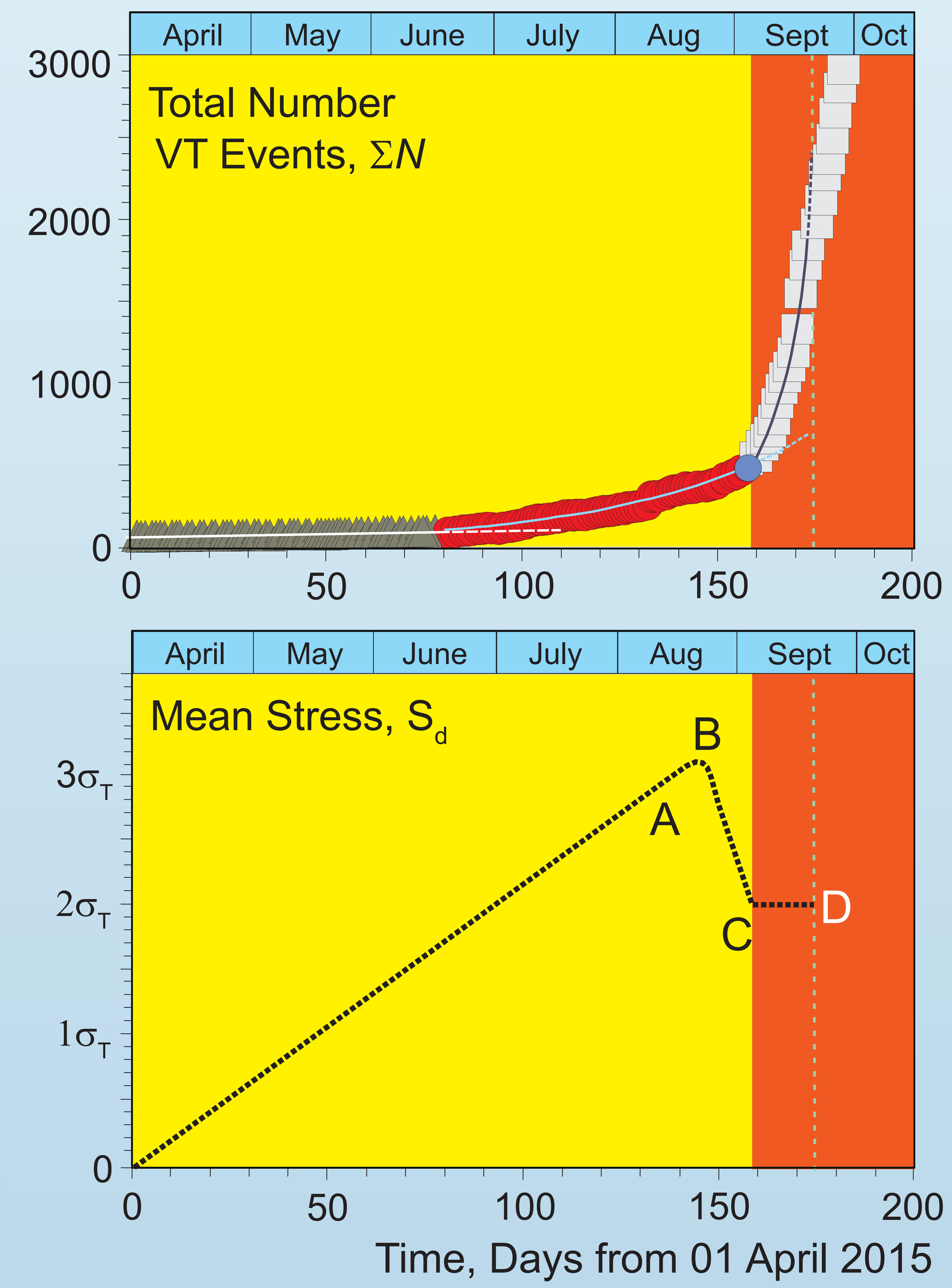

Figure 3. (Top) The total number of VT events measures inelastic deformation. The mean trend in VT rates evolved with time from approximately constant (01 April - 21 June), through exponential (22 June - 09 September) to hyperbolic (10 September - 22 September). Quasi-elastic and inelastic deformation is shown in yellow and red.

(Bottom) The VT trends are consistent with a mean stress field around the magmatic system that increases at an approximately constant rate to c. $3\sigma_T$ between times A and B, when the magma chamber ruptures, followed by a decrease to c. $2\sigma_T$, as energy is lost during magma transport and the dyke increases the volume of the system (B-C). The stress remains at $2\sigma_T$ until a lateral intrusion occurs (D). See also Fig. 4.

Box 1: Theory

The mean applied differential stress, S_d, increases with pressurization of a magma body but decreases with fault movement. As S_d increases from lithostatic conditions, the crust's response changes from quasi-elastic to inelastic, when it is held constant by a balance between pressurization and faulting [4; 5]. For a constant rate of increase in magma pressure, the quasi-elastic and inelastic VT event rates (dN/dt) are [4; 5; 6]:

$$dN/dt = (dN/dt)_{e,0} \exp[(t-t_{e,0})/t_{ch}] \quad (1)$$

$$dN/dt = [(dN/dt)_{h,0}^{-1} - \gamma^*(t-t_{h,0})]^{-1} \quad (2)$$

where; t is time, t_{ch} and γ^* are characteristic scales, and the subscripts e,0 and h,0 denote values at the start of the exponential and hyperbolic trends. At the end of the exponential trend, $S_F/\sigma_T = T/t_{ch}$ where T is the duration of increasing stress from the start of unrest. The hyperbolic trend has a maximum duration $T_h = [\gamma^* (dN/dt)_{h,0}]^{-1}$, at which time the VT event rate approaches an infinite value. This singularity indicates an abrupt change in the physical state of the magmatic system.

The field data are well described by Eq. (1) for 22 June to 09 September with $(dN/dt)_{e,0} = 2$ events per day and $t_{ch} = 47.8$ days and, from 10 September, by Eq. (2) with $(dN/dt)_{h,0} = 48$ events per day and $\gamma^* = 1.4 \times 10^{-3}$ (Fig. 3). The hyperbolic scale $\gamma^* = B(S_F/\sigma_T)^2(\sigma_T/Y)$, where Y is Young's modulus and the geometic factor B lies between $(4/\pi)$ and π for penny-shaped and straight-edged fractures. For common siliceous crustal rocks, $\sigma_T/Y \sim 2.5 \times 10^{-4}$.

3. Interpretation

The VT trends suggest an evolution in the shape and size of the magmatic system during unrest (Figs 3 & 4):

a. 01 April - Mid-August. Pressurization and rupture of a magma chamber c. 6-9 km below sea level. Rupture occurs from a spherical boundary of the chamber.

b. Mid-August - 09 September. Propagation of a dyke into the volcanic edifice. This triggers phreatic explosions and the emission of ash. The small volumes suggest disruption of a poorly vesicular magma, as would be expected from a solidifying, degassed cap of ascending magma. The dyke increases the total volume of the magmatic system and so favours a decrease in the mean stress applied to the crust.

c. 09 – 22 September. Pressurization of the stalled magma and eventual rupture near the surface, where the margins of the magma body follow a geometry between planar and cylindrical. Rupture leads to an intrusion, instead of an eruption.

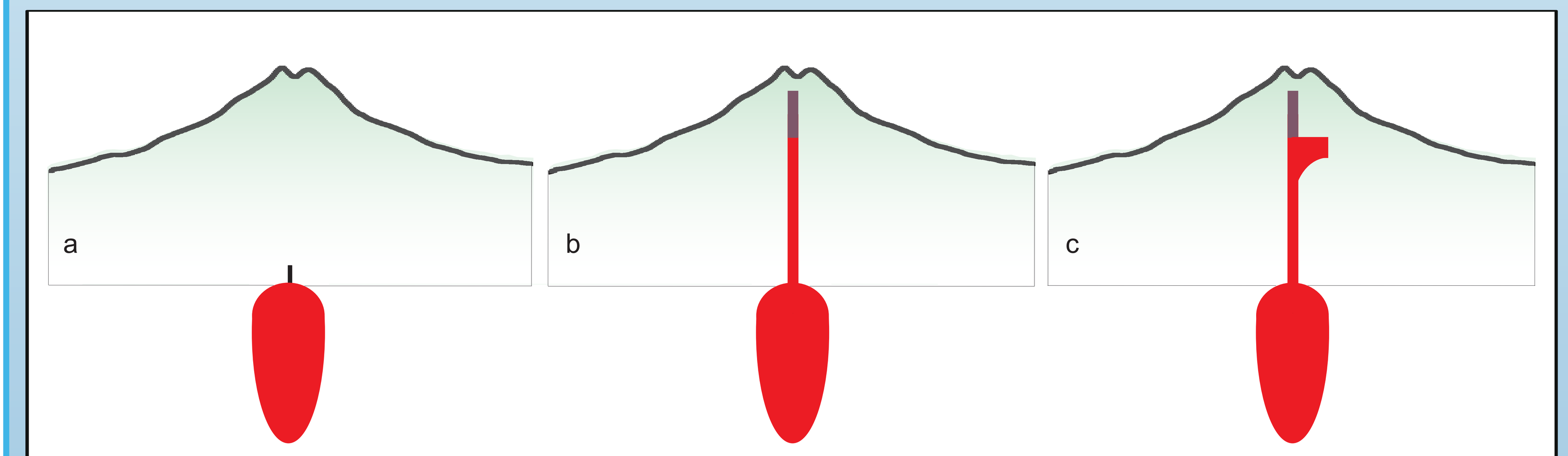

Figure 4. The VT trends in Fig. 3 suggest that Cotopaxi's 2015 unrest was initiated by pressurization of a magma chamber with a top at about 6 km b.s.l. (a) Rupture of chamber and formation of an incipient dyke (at A-B in Fig. 3). (b) Propagation of dyke and formation of a solidifying cap (B-C in Fig. 3). (c) Lateral intrusion of magma away from the base of the solidifying cap. Not to scale.

4. Conclusions

- The trend for mean VT event rate evolves with time. For a constant rate of increasing stress, the trend changes from exponential to hyperbolic.
- Unrest at Cotopaxi was characterised by (1) the pressurization and rupture of a magma chamber, (2) propagation of a dyke into the volcanic edifice, and (3) failure of the stalled dyke to form a lateral intrusion.
- Sensitivity to the relative resistance of a solidifiying magmatic cap and of the surrounding crust emphasizes the uncertainty inherent in eruption forecasts, even when magma has arrived close to the surface.

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Contact

For more information please contact:

Alexander L. Steele
(alexander.steele.14@ucl.ac.uk)