

The rupture of magma chambers before eruptions

Aon Benfield UCL
Hazard Centre

Richard Wall and Christopher Kilburn

Aon Benfield UCL Hazard Centre, Dept of Earth Sciences, University College London, UK



Summary. Volcano-tectonic event rates commonly evolve before eruptions from exponential to faster-than-exponential trends. Here we propose that the transition coincides with the rupture of a magma chamber and infer that, close to the chamber, pore-fluid pressures in the crust approach lithostatic values.

1. Introduction

Volcanic eruptions are commonly preceded by increases in the rate of volcano-tectonic (VT) seismicity. When the accompanying rate of stress increase is constant, the change in VT event rate evolves from an exponential to a faster-than-exponential (FTE) increase with time [7]. At strato-volcanoes, the final FTE trend normally continues for ~1-10 days and accounts for 10% or less of the total precursory sequence [6].

Analyses of VT precursors have focused on using the FTE trend to forecast eruptions. Here we examine the exponential trends, in order to identify (1) conditions in the magmatic system that favour a transition from exponential to FTE trend and, as a result, (2) new criteria that may extend the forecasting potential of precursors to times *before* the start of an FTE trend.



2. Observations

Exponential VT trends have been recorded at volcanoes in subduction-zone and extensional tectonic settings (Fig. 1). The data cover durations of ~10-1,000 days, magma compositions from basalt to andesite-dacite, and effusive and explosive styles of eruption.

For the cumulative number of detected VT events, ΣN , the exponential behaviour is given by $\Sigma N = K \exp(t/t^*)$, where the constant K describes the volume of crust being deformed, t is time and t^* is a characteristic timescale that determines the specific shape of the trend.

The ratio T/t^* at all volcanoes lies between 3 and 5.5 (Fig. 2). Such a restricted range suggests that the duration of exponential trends is constrained by a general feature of volcanoes that does not depend on tectonic setting, magma composition or style of eruption.

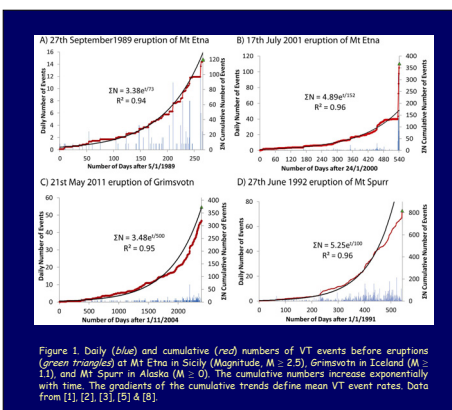


Figure 1. Daily (blue) and cumulative (red) numbers of VT events before eruptions (green triangles) at Mt Etna in Sicily (Augustine, M = 2.5), Grimsvotn in Iceland (M = 3), and Mt Spurr in Alaska (M = 0). The cumulative numbers increase exponentially with time. The gradients of the cumulative trends define mean VT event rates. Data from [1], [2], [3], [5] & [8].

3. Theory

The number of VT events measures the crust's inelastic response to an applied stress. Inelastic deformation increases exponentially with the applied differential stress, S [7]. In terms of VT events, the relation yields $\Sigma N = A \exp(S/S^*)$, where A is a scaling constant and the characteristic stress S^* describes the energy per unit volume stored in atoms at absolute temperatures and confining pressures greater than zero [7].

For a constant rate of stress increase, $T/t^* = S_f/S^*$, where S_f is the stress applied at the end of the exponential VT sequence. We can therefore relate T/t^* to a critical state of stress in the crust.

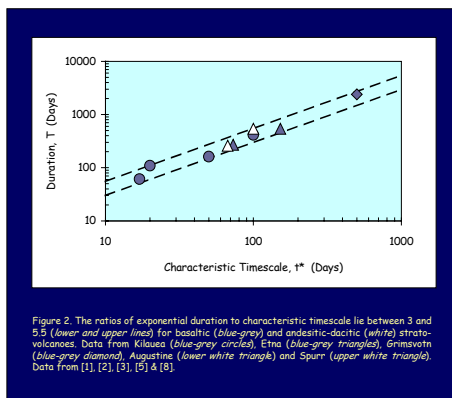


Figure 2. The ratios of exponential duration to characteristic timescale lie between 3 and 5.5 (lower and upper lines) for basaltic (blue-grey circles) and andesitic-dacitic (white triangles) strato-volcanoes. Data from Kilauea (blue-grey circles), Etna (blue-grey triangles), Grimsvotn (blue-grey diamonds), Augustine (lower white triangle) and Spurr (upper white triangle). Data from [1], [2], [3], [5] & [8].

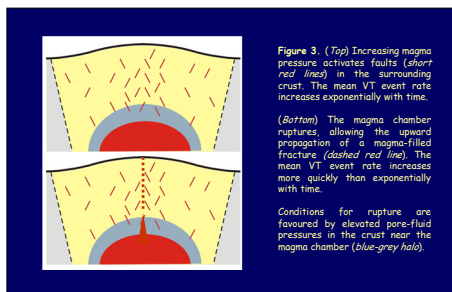


Figure 3. (Top) Increasing magma pressure activates faults (short red lines) in the surrounding crust. The mean VT event rate increases exponentially with time.

(Bottom) The magma chamber ruptures, allowing the upward propagation of a magma-filled fracture (dashed red line). The mean VT event rate increases more quickly than exponentially with time. Conditions for rupture are favoured by elevated pore-fluid pressures in the crust near the magma chamber (blue-grey halo).

4. Critical conditions

Assuming that unrest is triggered by the pressurization of a magma chamber, a natural critical stress coincides with the rupture of the chamber walls. In this case, the exponential trend can be related to the pressurization of the chamber and the FTE trend to the escape of magma once the chamber has been broken (Fig. 3).

For a spherical magma chamber, the Mohr-Coulomb-Griffith model for rock failure indicates that rupture occurs when, in crust close to the chamber wall, the ratio of S_f to tensile strength, S_f/σ_T is 3-4 for tensile failure and 4-5.6 for failure in combined tension and shear [9]. The total range coincides with the observed values for T/t^* (Fig. 2) and strongly supports the proposed interpretation.

5. Structure of the magmatic system

Linking the timescale ratio to chamber rupture implicitly assumes that $T/t^* = S_f/\sigma_T$. It thus implicitly assumes also that $S^* = \sigma_T$.

To a first approximation, $S^* = \sigma_T + (1/3)(P_c - P_p)$, where P_c and P_p denote the confining and pore-fluid pressures. Hence, for $S^* = \sigma_T$, the local pore pressure must balance the confining pressure (for which $P_c - P_p = 0$). Such conditions have been recorded in the crust at depths of 4-6 km or more [4]. They would be favoured also by local heating of fluids and their entrapment beneath impermeable horizons. Both conditions are reasonable in the vicinity of magma chambers.

5. Conclusions

- Volcano-tectonic event rates increase along different trends before and after the rupture of a magma chamber.
- From the start of an exponential increase in mean VT event rate, the condition for rupture commonly occurs after an interval 3-5.5 times the characteristic timescale, t^* .
- The probability of eruption increases significantly after an exponential sequence has continued for a time of $3t^*$.
- Pore-fluid pressures in the crust close to a magma chamber may approach lithostatic values.

References

1. Alaska Volcano Observatory (undated) www.avo.alaska.edu
2. Alparone, S., Brancato, S., Ursino, A. (2011). Pers. Comm.
3. Bell, A.F., Kilburn C.R.J. (2011) Bull Volcanol 74, 325-339.
4. Hillis, R.R. (2003) Geol Soc London Spec Pub 236, 359-368.
5. Huggett, P. (2012) Seismic precursors to eruptions at Alaskan volcanoes, University College London, Master's Thesis.
6. Kilburn, C.R.J. (2003) J Volcanol Geotherm Res 125, 271-289.
7. Kilburn, C.R.J. (2012) J Geophys Res. 117, doi:10.1029/2011JB008703.
8. Roberts, M., Þorbjarnardóttir, B.S. (2012) Pers. Comm.
9. Shaw, H.R. (1980) In, Hargraves, R.B. (ed.) Physics of magmatic processes, 201-264, Princeton University Press.



Eruption of Mt Spurr, Alaska, on 18 August 1992. Photo: Alaska Volcano Observatory.

Acknowledgements. We thank the following for providing VT data for this study: Matthew Roberts and Bergþóra S. Þorbjarnardóttir (data from the Icelandic Meteorological Office), Andrea Ursino and Salvatore Alparone (data from the INGV's Etna catalogue) and Alfonso Brancato (data from the University of Catania's Etna catalogue).