Volcano-tectonic seismicity before flank eruptions at Mt Etna

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1. Introduction

Volcanic eruptions are commonly preceded by increases in volcano-tectonic (VT) earthquakes, representing brittle failure of the crust. Numbers of earthquakes can increase at different rates, but commonly sequences accelerate before eruptions[1]. These accelerating trends evolve from an exponential to a faster-than-exponential (FTE) increase with time, which at strato-volcanoes normally occurs 1 to 10 days before an eruption[5]. Accelerations are not recorded in every case and, therefore, it is necessary to compare variations in the temporal evolution of VT seismicity to determine if they can be used to forecast eruptions. Earthquake locations can also be used to interpret the underlying processes that facilitate the ascent of magma to the surface.

2. Precursory VT seismicity

To investigate and compare sequences at the same volcano we have examined seismicity before ten flank eruptions at Mt Etna, between 1981 and 2008. The changes in VT event rate within these sequences are described below:

1) In 70 % of pre-eruptive sequences seismicity initially accelerates or increases at a quasi-linear rate, on timescales of 30 to 540 days. Locations are distributed across the edifice, with more events occurring on the western flank of the volcano, above 30 km b.s.l.

2) 80 % of sequences are terminated by a jump in seismicity 1 to 4 days before the eruption, which consists of between 14 and 96 events in one day. Locations of events during these jumps commonly cluster in the summit region and at shallow levels, above 5 km b.s.l. Before more recent eruptions (2001, 2002 and 2008) earthquakes migrate and concentrate on the eruptive fissure.

Accelerations in the cumulative number of events (ΣN) can be modelled by an exponential trend given by, $\Sigma N = K \exp (t/\tau)$ (Figure 1A and B), where K is a constant, t is time and τ is the characteristic timescale that determines the shape of the trend. Constant increases are modelled by a linear trend, $\Sigma N = m(t) + c$ (Figure 1C and D), where m is the gradient of the line. Both types of long-term trend contain similar numbers of the earthquakes, commonly between 80 and 120.
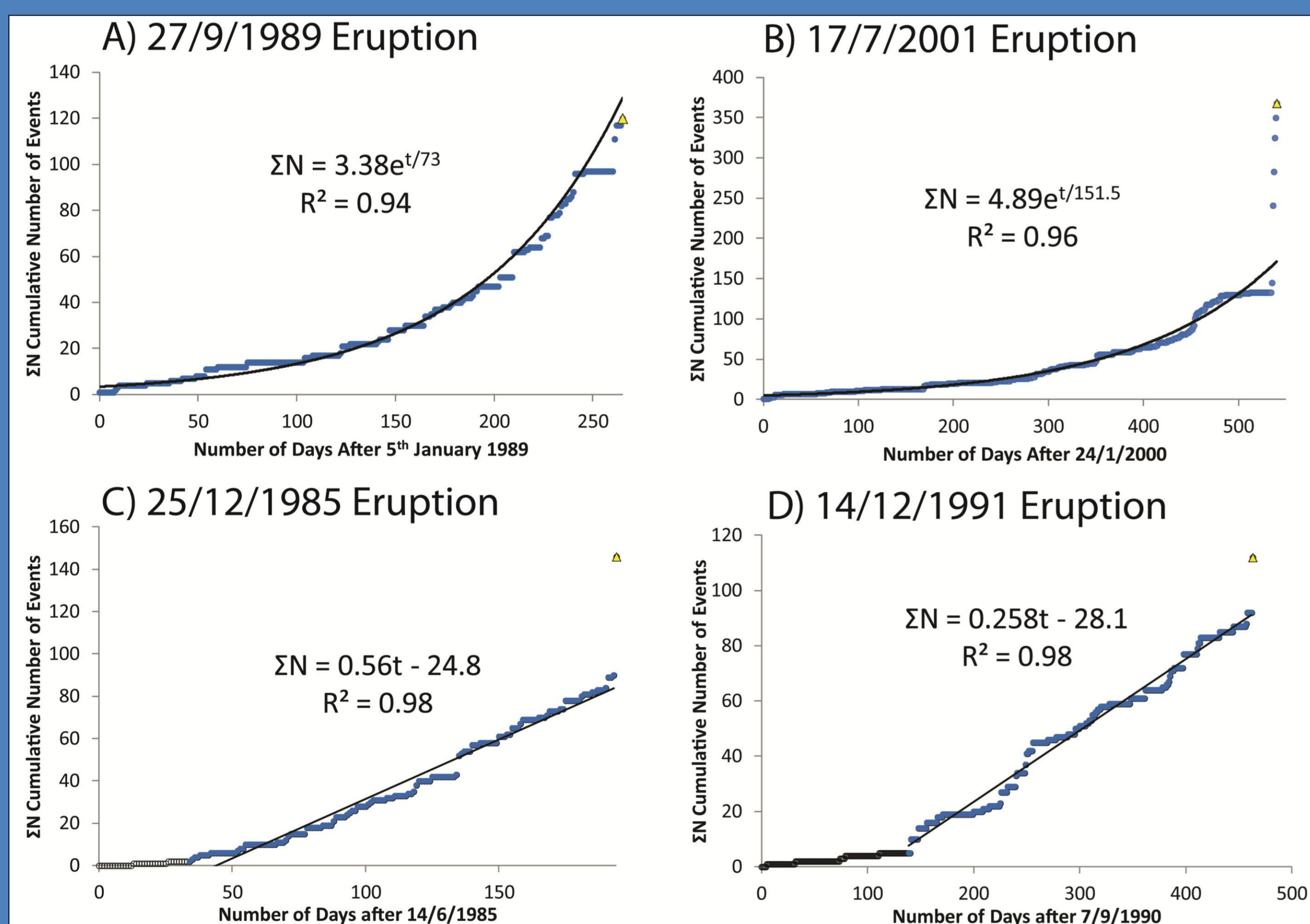

Figure 1. Cumulative numbers of VT earthquakes before flank eruptions at Mt Etna. Seismicity accelerates before eruptions in A and B and increases at a quasi-linear rate in C and D. In all cases a jump in seismicity occurs between 1 and 4 days before the eruption itself. The magnitude cut-off (M_c) is 2.5 for eruptions A,B and D and 2.6 for C.

3. Mechanisms causing unrest

From the changes in locations of earthquakes between both long- and short-term trends, we have interpreted the underlying processes that result in the different VT event rates (Figure 2).
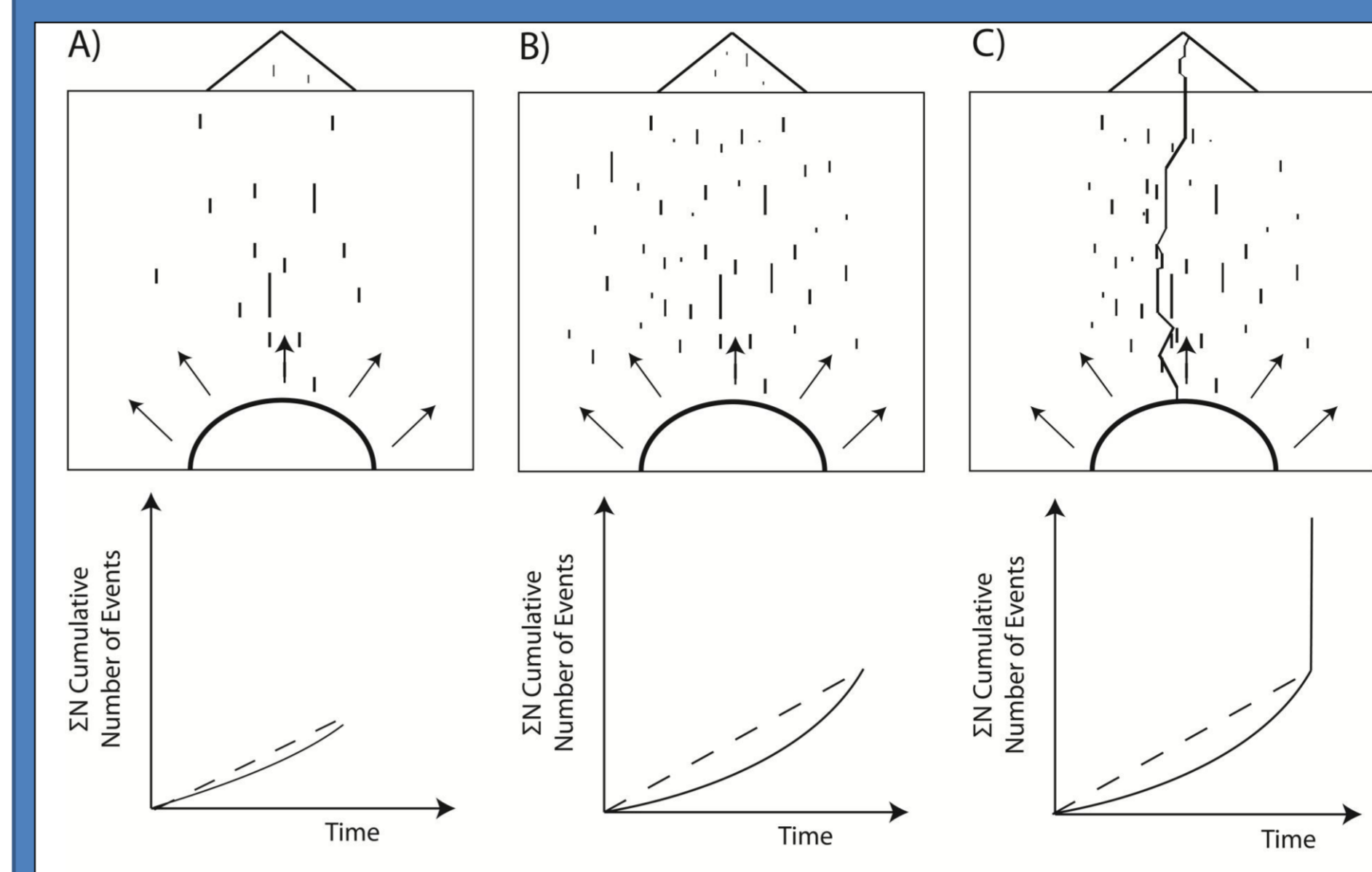

Figure 2. A) Pressurisation, caused by the intrusion of magma into a chamber, activates faults in the surrounding crust. This primarily occurs beneath the western flank of Etna[2]. B) With increasing pressure greater numbers of faults are activated. C) The magma chamber ruptures allowing a dyke to propagate to the surface, which is recorded as a jump in seismicity. Locations and migrations in seismicity can indicate the future eruption site.

4. Conditions for eruptions

Short-term increases do not provide sufficient time to issue warnings of an impending eruption, however, long-term trends may extend the forecasting potential of VT precursors. Assuming that initial unrest is caused by the pressurisation of a magma chamber, the end of the sequence must represent the rupture of this chamber. For this to occur the increase in pressure must exceed the tensile strength of the surrounding rock (σ_t), described by the equation, $p_l + p_m = \sigma_3 + \sigma_t$, where p_l and p_m are lithostatic and magmatic pressure, respectively and σ_3 is the minimum compressive stress[3].

Numbers of earthquakes increase exponentially when rock is deformed at a constant strain rate[5], in a volcanic environment this requires a steady supply of magma into the chamber. Using this interpretation a linear increase in numbers of VT events requires strain to increase at a decaying rate. A potential mechanism for this is a pulse of magma into the chamber.
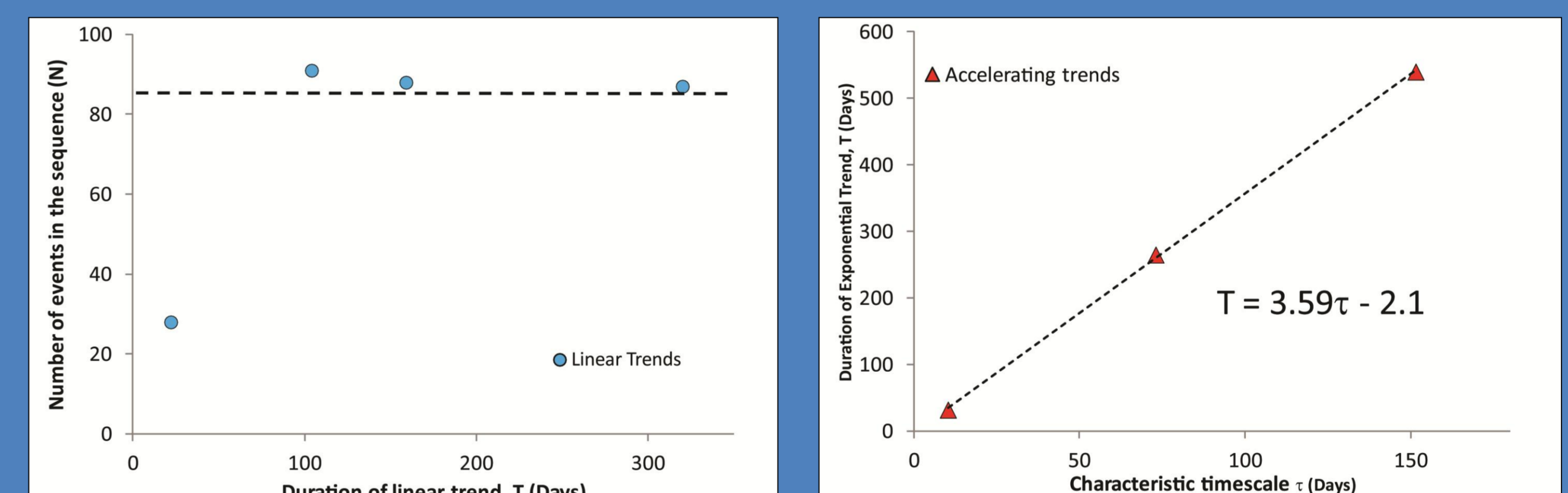

Figure 3. A) The relationship between numbers of events (N) and duration of linear sequences (T). B) The ratio of duration (T) and characteristic timescale (τ) for accelerating trends.

The similar numbers of events in linear longer-term sequences suggests that a specific number of fractures are required before a dyke can propagate to the surface. At Etna, a warning can be issued as the number of events in the sequence tends towards 80 (Figure 3A). For all accelerations the ratio of T/τ is restricted to between 3 and 4 (Figure 3B), suggesting the duration of the exponential trend is also related to the amount of fracturing required to allow the propagation of a dyke. If accelerations are identified then a warning can be issued as T tends to 3τ.

5. Conclusions

- On short- and long-term timescales numbers of VT events increase at different rates before eruptions, associated with pressurisation of a magma chamber and dyke propagation, respectively.

- Similar numbers of earthquakes in the longer-term trends suggest that a common amount of fracturing is required before an eruption can occur, which can be used as a forecasting tool. Further work could examine if this same threshold applies at other volcanoes.

- It is important to improve forecasts using VT seismicity because numbers of events can be monitored using very simple equipment. Future work could also focus on differentiating eruptive and non-eruptive precursor trends to improve forecasts.

References. 1. Bell, A.F., Kilburn, C.R.J. (2011) Bull Volcanol 74, 325-339. 2. Bonforte, A. et al. (2008) J Geophys Res 113, doi:10.1029/2007JB005334. 3. Gudmundsson, A. (1990) Tectonophys 176, 257-275. 4. Kilburn, C.R.J. (2003) J Volcanol Geotherm Res 125, 271-289. 5. Kilburn, C.R.J. (2012) J Geophys Res 117, doi:10.1029/2011JB008703.

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