Seismic Precursors to Eruptions at Volcanoes in Extensional Stress Fields

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1. Introduction

Volcano-tectonic (VT) earthquakes are one of the first precursors to be detected before volcanic eruptions. Their rate of occurrence tends to accelerate with time, evolving from an exponential to a faster-than-exponential (FTE) trend[1], in a manner consistent with the Voight relation[2]. In compressional background stress fields, the exponential trend commonly develops over months, whereas the FTE trend emerges ~1-10 days before eruption[3] (Fig 1). Different patterns in VT precursors for volcanoes in extension have shown similar durations of exponential increases, but much shorter timescales for their final FTE trends[4]. Precursory trends may therefore be related to the nature of the background stress field. Using data from Mt Etna, in Sicily, we continue to investigate the temporal evolution of VT events before eruptions and seismic crises in extensional stress fields.

Figure 1
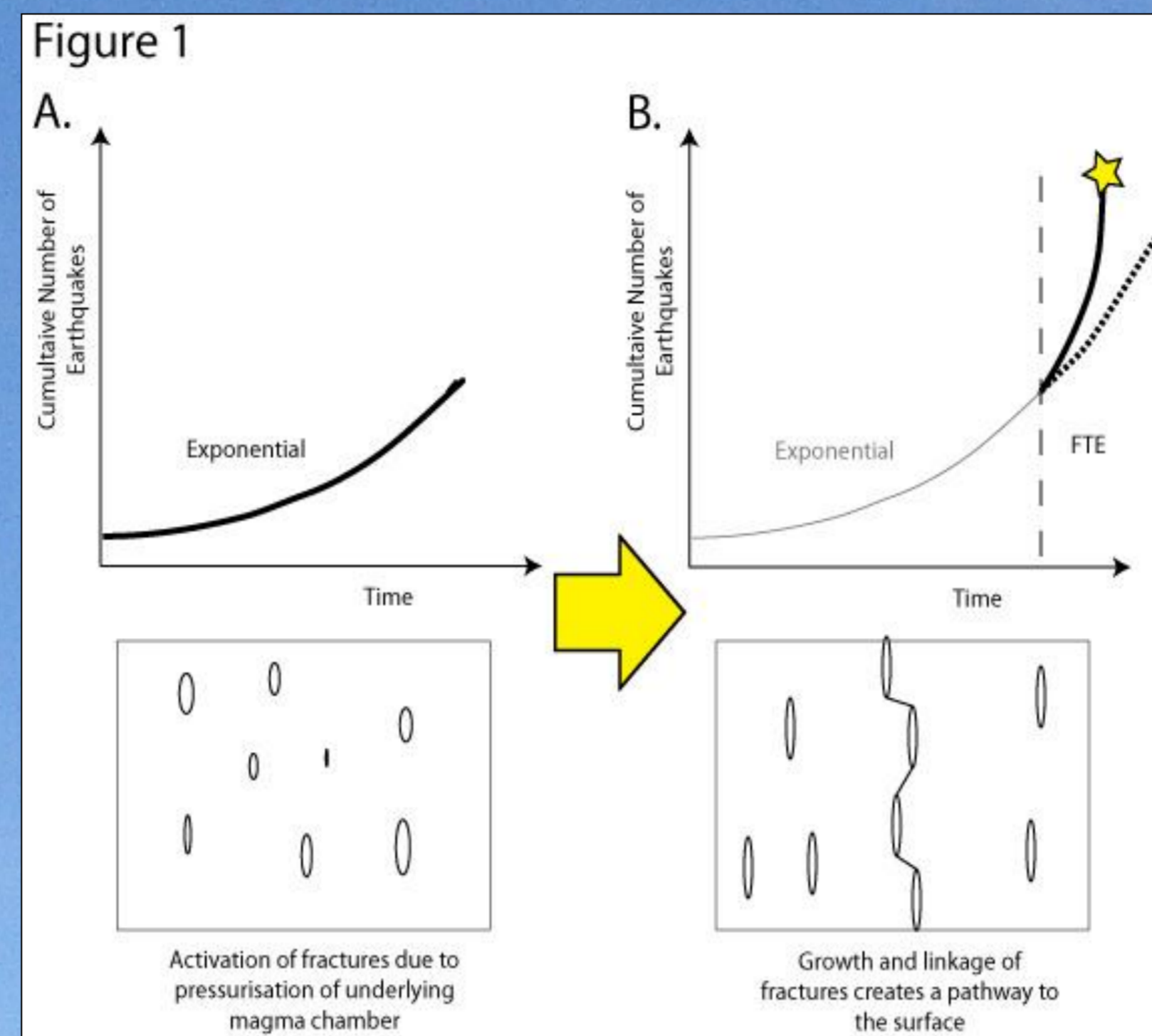
2. Method

Mt Etna lies in an extensional stress field, created by a regional E-W tectonic extension and local gravitational forces acting on its flanks[5]. Historically, the volcano has had flank eruptions and seismic crises at intervals of ~1-10 years, most of which have been preceded by accelerating sequences of VT events. Using data obtained between 1977 and 2008 from seismic networks operated by the University of Catania and the INGV, selected VT sequences have been analysed to identify repeating behaviour in precursory trends (Figs 2 & 3).

Figure 1. Precursory trends observed before eruptions. A) represents an exponential trend when fracturing is dominated by the activation of new cracks. In B) the FTE trend is attributed to the linking of fractures.

3. Sequences of VT Precursors

Figure 2 (right) shows examples of the daily and cumulative rate of VT events from three eruptions (1989, 2001 and 2008) and from a seismic crisis in 1983. In each sequence, Day 0 represents the time of eruption or of the culmination of a seismic crisis. The events have typical magnitudes of 2.5-4.3 (M_d) suggesting movements ~cm along faults ~0.1 km across. Their locations are shown in Fig. 3 (below).

The VT sequences evolve over intervals of 1-18 months (34-540 days). The greater part of each sequence can be described by an exponential increase with time in the cumulative number of VT events (ΣN), which, independent of duration, involves a total of about 100-150 events as measured from the same seismic network. Assuming that ΣN is proportional to the total amount of fracturing, therefore, it appears that the exponential trends maybe associated with similar amounts of increasing damage in the edifice. The duration of a sequence may thus mainly depend on the rate at which the edifice is loaded by increases in magma pressure.

The sequences are terminated by FTE increases in VT number over ~0.1-1 day. They involve ~10-100 events and, because of their short durations, they appear as jumps in Fig. 2. Their rapid onset and short duration suggest that the FTE trends are linked to the propagation of a fracture through the edifice.

The values of final ΣN and duration for the non-eruptive sequence (leading to a seismic crisis) lie within the ranges observed for the pre-eruptive trends. Hence, there appears to be no immediate difference between the precursors to eruptions and seismic crises. The precursors suggest that there is a similar mechanism in both cases and that the seismic crisis can be also attributed to inflation of the crust. However in the case of non eruptive sequences, stress was not sufficient to allow magma to link between a source and the surface.
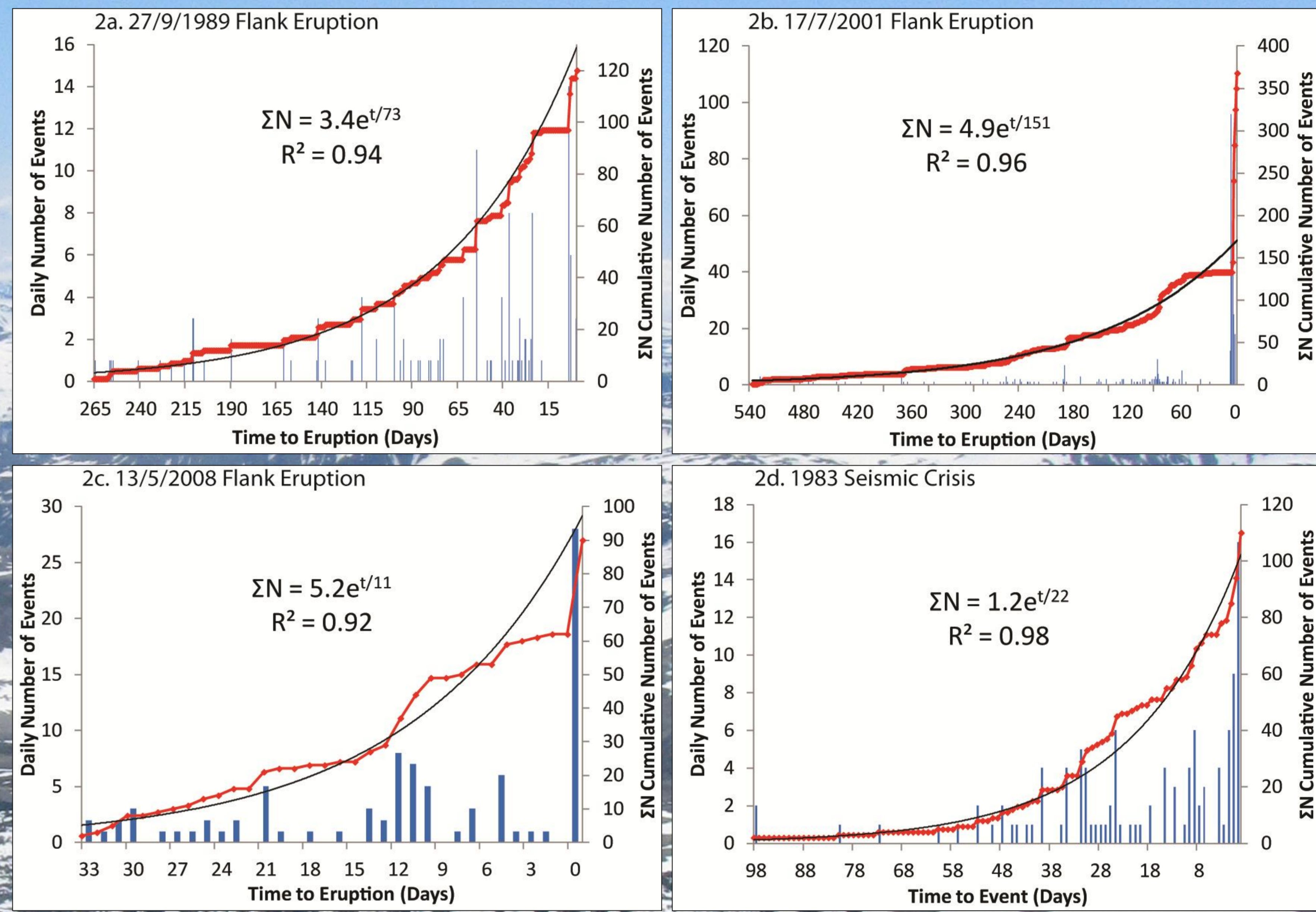

Figure 2. Precursory seismicity before eruptions (A-C) and seismic crisis (D) at Mt Etna. In each case an exponential trend has been used to model the change in cumulative seismicity before the eruption or maximum daily number of events. A,B and D have cut-off magnitudes (M_c) = 2.5 and for C, M_c = 1.2.
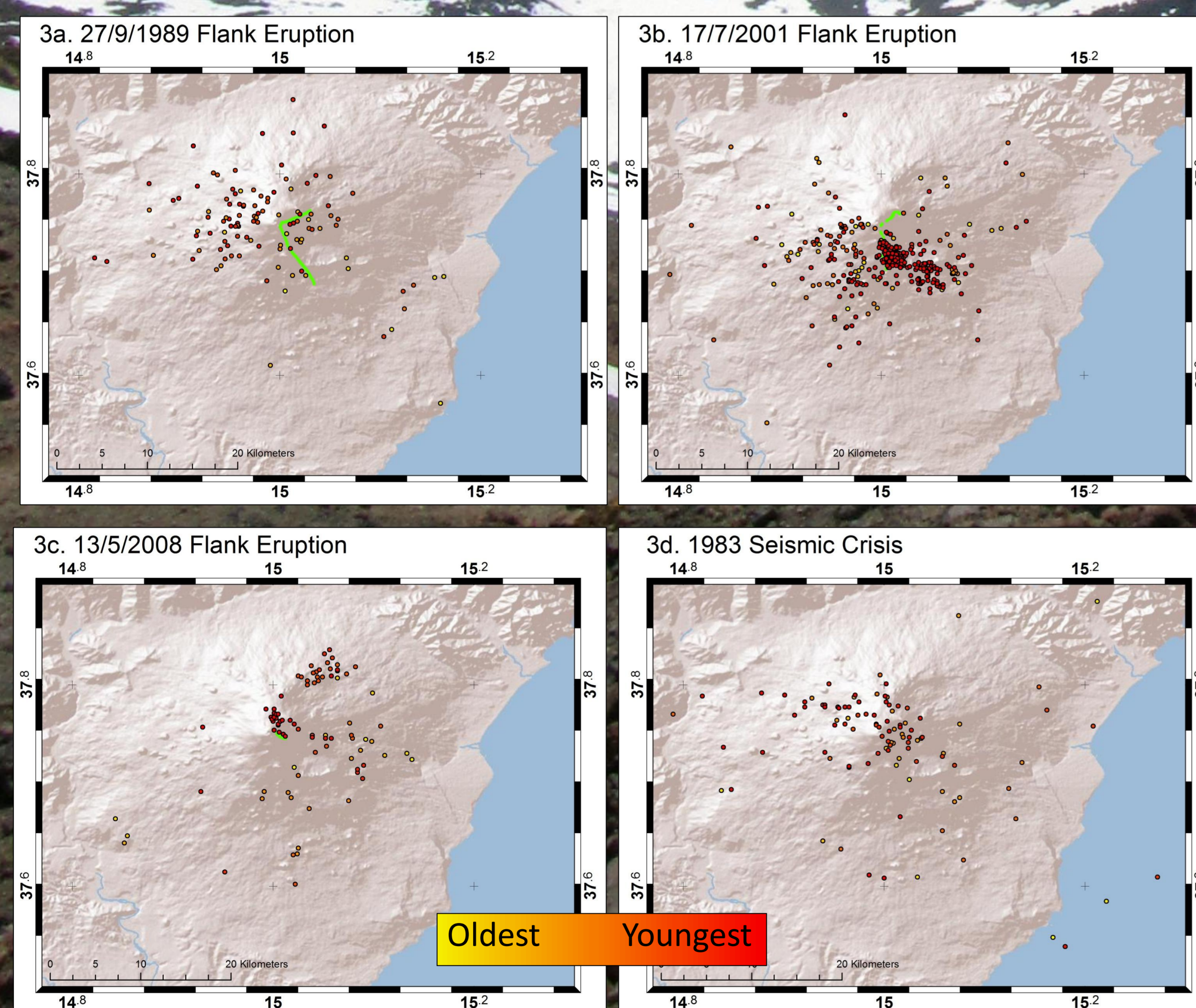

Figure 3. The locations of earthquakes during precursory periods (Fig 2). Before 2001 and 2008 eruptions, earthquakes cluster on the eruptive fissure (green lines). In other event such as in 1983 and 1989, earthquakes do not appear to have such clear spatial patterns and are randomly distributed across the volcanic edifice.

4. Exponential behaviour of VT precursors

The exponential increase in number of VT events is described by $\Sigma N = K e^{t/t^*}$, where K is a constant and t is the number of days before the eruption. The time t^* represents the minimum interval required for observations to identify the development of an exponential trend; it is also a characteristic timescale of the process limiting deformation and fracturing of the edifice. The ratio of a sequence's duration (T) to t^* thus measures the difficulty of overcoming the resistance of the edifice.

Data from Etna yield values of T/t^* of 3-4 and 3-5 for pre-eruptive and non-eruptive VT sequences. These compare with corresponding values of 3-5 and 1-3 at Kilauea, Hawaii[4]. The two volcanoes share overlapping values of T/t^*, suggesting that their precursory trends are controlled by similar physical processes. In addition, T/t^* on Etna is similar for eruptive and non-eruptive events, supporting the conclusion that, on their own, accelerations in the numbers of VT events cannot be used to distinguish between an imminent eruption or seismic crisis.

5. Conclusions

1. The edifice of Mt Etna may undergo a similar increase in damage before a through-going fracture can be propagated. The increase in damage is recorded by an exponential increase in the number of VT events with time, whereas fracture propagation is characterized by a FTE increase in VT events.

2. On Mt Etna, changes in the number of VT events with time cannot be used to forecast whether a precursory sequence will end in an eruption.

3. Similar physical processes control precursory sequences at Etna and Kilauea.

4. FTE sequences that develop over ~0.1-1 day may be diagnostic of precursory VT trends at volcanoes in extensional stress fields.

References

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