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Forecasting eruptions after long repose intervals from accelerating rates of rock fracture: The June 1991 eruption of Mount Pinatubo, Philippines

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abstract

as widening of the conduit and friction between the magma and country rock during magma ascent.

1. Introduction

Increasing rates of rock fracture, recorded as volcano-tectonic (VT) seismic events, are a common precursor to volcanic eruptions, especially after long repose intervals when there is no existing open conduit (Kilburn, 2003). Models of precursory fracturing rates, developed with the aim of forecasting eruptions at these systems, propose that VT seismic event rates will exhibit a hyperbolic acceleration with a linear decrease in inverse rates in the final one to two weeks before they erupt (Kilburn and Voight, 1998; Kilburn, 2003; Kilburn and Sammonds, 2005). This arises from the growth and coalescence of fractures forming a new pathway between the magma source and the surface (McGuire and Kilburn, 1997; Kilburn, 2003; Kilburn and Sammonds, 2005). Extrapolation of the linear inverse trend to 0, where the rate approaches infinity, gives the expected ‘system failure’ or eruption time (Voight, 1988; McGuire and Kilburn, 1997; Kilburn and Voight, 1998; Kilburn, 2003; Kilburn and Sammonds, 2005). This trend is likely to give warning times (the time between the recognition of a clear trend and the eruption) of three to five days (Kilburn and Sammonds, 2005). These models also propose that there should be no migration of the ‘•

Mount Pinatubo, Philippines, erupted in June 1991 after 500 years of repose and two months of detected unrest, which included earthquake swarms and phreatic activity (Wolfe and Hoblitt, 1996; Newhall et al., 1996). Before these two months, little unrest was noted and there was no scientific monitoring of the volcano (Punongbayan et al., 1996). The eruption began on 7th June with the emergence of a dacite spine. It then evolved into a more explosive eruption, with the first large vertical eruption on 12th June, and the climactic VEI 6 explosion on 15th June (Harlow et al., 1996). Here we analyse precursors to the first emergence of fresh magma on 7th June, when a dacite spine was extruded. It has been proposed that a full connection between the magma reservoir and the surface did not exist until the climactic phase of the eruption (Scandone et al., 2007). However, we believe that the 7th June eruption would have required a fully established fracture connection between the magma reservoir and the

2th the development into more explosive activity, which

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would have been preceded by accelerating rates of rock fracture as the connection between the reservoir and the surface was established.

Accelerating VT event rates, whose minimum inverse rates had a linear gradient approaching 0 within hours of the time the eruption began, were seen in the final five days before the emergence of the dacite spine (Kilburn, 2003; Kilburn and Sammonds, 2005). Re-analysis of this sequence of VT events for this study indicates that the precision and time of the forecast is highly dependent upon the way that the VT event rate data are grouped. Grouping the data into fixed VT number intervals rather than fixed time intervals gives more precise forecasts, but indicates that the ‘failure’ occurred 24 hours before the eruption began. This is interpreted as the ‘failure’ being the formation of a new magma conduit, whilst the additional fracturing that continued in the final day before the magma reached the surface is interpreted as widening of the conduit and friction between the magma and country rock during magma ascent.

1.1. Precursory seismicity at Mount Pinatubo

After unrest was first noted at Pinatubo in late March 1991, new seismometers were installed during April and early May (Harlow et al., 1996; Punongbayan et al., 1996). From 10th May until the first magmatic eruption on 7th June, there were 7 operational telemetered seismometers in the positions shown in Fig. 1 (Lockhart et al., 1996). During this time there were two distinct seismic source regions, shown in Fig. 2; one near the summit of the volcano with depter wT*(2Pu)17(no)1a10(nal)-3usn(ti)9.18; 14oepA; lem-30314585T*(2Pu31422(me)-o)-3t314

Richter relation (Rydelek and Sacks, 1989). This catalogue contains 409 earthquakes in the summit region from 10th May until 7th June 1991 with magnitudes between 0 and 2. They do not exhibit the Gutenburg–Richter frequency–magnitude relation and there are insufficient data to test whether more earthquakes are recorded at different times of day. However, these are the typical data available during volcanic crises at this type of volcano, where the seismic network is often newly installed in response to volcanic unrest and earthquake magnitudes rarely exceed 3 or 4. To discard records on the grounds of completeness would leave no data on which to base forecasts and develop forecasting methods. The data collection was, however, self consistent. That is, during the time considered (mid May to 7th June 1991) the local seismic network used to detect and locate earthquakes was not changed, nor were the detection thresholds. There were also no reported issues with increased noise levels, overlapping events, or damaged seismometers affecting the ability to locate earthquakes until after 7th June (Harlow et al., 1996).

2. Forecasting methods

Rock fracture and material failure models have been used in studies analysing seismicity and ground deformation to forecast eruptions both after a long repose interval (e.g. Cornelius and Voight, 1996; Kilburn and Voight, 1998; Kilburn, 2003), and during extended periods of intermittent lava dome growth (e.g. Voight, 1988; De la Cruz-Reyna and Reyes-Davila, 2001; Smith et al., 2007). Voight's (1988; 1989) failure forecasting method, FFM, is the most widely applied empirical model for forecasting volcanic eruptions from fracturing rates. The rate and acceleration of fracturing, observed through VT seismicity, are related in this empirical law as:

$$\ddot{\ } = A\dot{\ } \qquad (1)$$

where $\dot{\ }$ and $\ddot{\ }$ are the rate and acceleration of VT seismicity, and A and α are empirically determined constants with α usually lying between 1 and 2. As $\dot{\ }$ approaches infinity, this equation becomes mathematically unstable. Such a condition is associated with a major change in a physical system; in this case with wholesale failure of rock under stress, which creates a pathway for magma ascent. In the limit where $\alpha = 1$, there is an exponential increase in seismicity with time and $\dot{\ }$ never approaches infinity. In the special case where $\alpha = 2$ there is a hyperbolic increase in seismicity with time and $\dot{\ }^{-1}$ decreases linearly with time with gradient A. When $\alpha > 2$, the inverse trend is convex, when $1 < \alpha < 2$, the inverse trend is concave, and when $\alpha \leq 1$ the inverse trend never approaches 0.

When the FFM is used to forecast eruptions, the simplest criterion to use is that the eruption is expected when $\dot{\ }$ approaches infinity or $\dot{\ }^{-1} = 0$. The failure time (t_f) is then forecast by integrating Eq. (1) to obtain (Voight, 1989):

$$t_f - t_* = \frac{\dot{\ }^{1-}_{*}}{A(\ \ -1)} \qquad (2)$$

where t_* is an arbitrary time and $\dot{\ }_*$ is the seismicity rate at that time. The empirical constants A and α must be determined before using Eq. (2). The only non-iterative way to find these values is to plot the logarithm of $\ddot{\ }$ against the logarithm of $\dot{\ }$ with the gradient giving α and the intercept giving A (

different start dates for the data analysis to see how this influences forecast precision and accuracy: 27th May, which is after the swarm of activity to the North-West of the volcano had ceased and a few days before the clear acceleration began, and 3rd June, the date used in Kilburn (2003), which is when the clear acceleration began. Earthquake data are analysed for the summit region only, using the record from Hoblitt et al. (1996), because only earthquakes in this region accelerated before the eruption (Fig. 3). There were 350 recorded earthquakes in this region from 27th May until the eruption began.

3.2. Method 2: The FFM linear inverse rate mean trend

When α is fi

later analysed using the FFM consistently gave an eruption forecast within a few hours of the time the forecast was made (Figs 5 and 6). The forecast

The forecasts from the N-binned data from all three forecasting methods indicate that fracturing rates were accelerating towards a potential failure on the 6th of June. Rates then stabilised, before a final acceleration on 7th June, when the eruption began. The preferred forecast date of 6th June may indicate that the new conduit had formed by that day, with an additional day taken for the magma to migrate towards the surface. During that day, the event rates were approximately constant until they increased as the magma emerged at the surface (Fig. 4). Stick–slip earthquakes arising from friction between the magma body and the conduit, in addition to fracturing of the surrounding rocks as the conduit widened to accommodate the ascending magma, could have caused the additional earthquakes after the conduit was formed. It has been shown that these earthquakes at the conduit margins may be seismogenic (Neuberg et al., 2006; Tuffen et al., 2008). This model of precursory fracturing at Mount Pinatubo in 1991 is shown schematically in Fig. 9. Stick–slip earthquakes typically occur in bursts, but when the shear strain rate and the normal stress acting on the sliding fracture surface are constant and the rate is considered over a timescale long enough to smooth out these bursts, the rate of stick–slip events is constant (Sammonds and Ohnaka, 1998). Therefore, if the pressure driving the ascent of the magma and the normal force acting on the surface between the ascending magma and the country rock are near constant, there will be a near constant rate of stick–slip earthquakes at the magma conduit margins and near constant deformation and cracking of the surrounding rocks as the conduit widens. This could explain the nearly constant earthquake rate in the final 24 hours before a final spike in event rates at the time of the eruption.

5. Conclusions

Forecasts of t15(c(e)15(ca)25(st)19(s)-395(o)144(7t)224h*[(coJu))-2ir-81

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