Bull Volcanol (2013) 75:677
DOI 10.1007/s00445-012-0677-y

RESEARCH ARTICLE

Trends in the aggregated rate of pre-eruptive volcano-tectonic seismicity at Kilauea volcano, Hawaii

Andrew F. Bell · Christopher R. J. Kilburn

Received: 2 December 2011 / Accepted: 18 December 2012 / Published online: 10 January 2013

Abstract Accelerating rates of volcano-tectonic (VT) earthquakes are commonly observed during volcanic unrest. Understanding the repeatability of their behaviour is essential to evaluating their potential to forecast eruptions. Quantitative eruption forecasts have focused on changes in precursors over intervals of weeks or less. Previous studies at basaltic volcanoes in frequent eruption, such as Kilauea in Hawaii and Piton de La Fournaise on Réunion, suggest that VT earthquake rates tend to follow a power-law acceleration with time about 2 weeks before eruption, but that this trend is often obscured by random fluctuations (or noise) in VT earthquake rate. These previous studies used a stacking procedure, in which precursory sequences for several eruptions are combined to enhance the signal from an underlying acceleration in VT earthquake rate. Such analyses assume a common precursory trend for all eruptions. This assumption is tested here for the 57 eruptions and intrusions recorded at Kilauea between 1959 and 1984. Applying rigorous criteria for selecting data (e.g. maximum depth; restricting magnitudes to be greater than the completeness magnitude, 2.1), we find a much less pronounced increase in the aggregate rate of earthquakes than previously reported. The stacked trend is also strongly controlled by the behaviour of one particular pre-eruptive sequence. In contrast, a robust signal emerges among stacked VT earthquake rates for a subset of the eruptions and intrusions. The results are consistent with two different precursory styles at Kilauea: (1) a small proportion of eruptions and intrusions that are preceded by accelerating rates of VT earthquakes over intervals of weeks to months and (2) a much larger number of eruptions that show no consistent increase until a few hours beforehand. The results also confirm the importance of testing precursory trends against data that have been filtered according to simple constraints on the spatial distribution and completeness magnitude of the VT earthquakes.

Keywords Volcano-tectonic earthquakes · Eruption forecasting · Basaltic volcanism · Dyke intrusion · Volcano flank instability · Completeness magnitude

Introduction

Volcanic eruptions are often associated with elevated rates of volcano-tectonic (VT) seismicity. Characterization of these VT earthquake signals is important to understanding the processes that precede eruptions and shallow intrusions of magma and, in particular, may allow more reliable and quantitative forecasts of eruptions in the future. An outstanding problem in volcanology is the degree to which pre-eruptive increases in the rate of VT earthquakes can be the basis for deterministic forecasts of eruption time. Several different theoretical models have been proposed to explain the temporal evolution of rates of VT earthquakes (Voight 1988, 1989; Main 1999; Kilburn 2003; Lengliné et al. 2008), based on concepts of material failure and damage accumulation. These models predict either a power-law or exponential increase in the mean rate of VT earthquakes with time and have the potential to be applied in deterministic forecasting scenarios. The case for these models has been predominantly supported by retrospective fitting (i.e. after the eruption has occurred) to individual sequences of earthquakes preceding a few example eruptions, typically from andesitic and dacitic volcanoes. Several studies examine the performance of forecasts based on such models, and

Editorial responsibility: T. Ohminato

A. F. Bell (✉)
School of GeoSciences, Grant Institute, The University of Edinburgh, The King's Buildings, West Mains Road, Edinburgh EH9 3JW, UK
e-mail: a.bell@ed.ac.uk

C. R. J. Kilburn
Aon Benfield UCL Hazard Centre, Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK

evacuations have been made on the basis of their results (De la Cruz-Reyna and Reyes-Davila 2001; Zobin et al. 2002). However, the predictive power of these models has yet to be formally evaluated, and there are examples of volcanic eruptions beginning with only short-lived or little precursory VT seismicity (e.g. Soosalu et al. 2005). The latter examples are more commonly observed at basaltic volcanoes, suggesting that different types of volcano or eruption may have fundamentally different patterns of VT earthquake precursors. Two studies of VT seismicity at the basaltic Kilauea volcano, Hawaii (Chastin and Main 2003), and Piton de la Fournaise volcano, Réunion (Collombet et al. 2003), have argued that accelerating rates of VT earthquakes cannot always be identified before individual eruptions and can only be resolved when aggregated over many eruptions. These studies concluded that the physical conditions at basaltic volcanoes produce high-amplitude stochastic variations in earthquake rate that mask the underlying accelerating trend in individual sequences. As a result, they have questioned the feasibility of using VT seismicity to develop deterministic eruption forecasts at basaltic volcanoes.

The conclusions of Chastin and Main (2003) appear to contradict those of a recent study by Bell and Kilburn (2011). Analysing the same VT earthquake catalogue at Kilauea, Bell and Kilburn (2011) found that about one third of eruptions and intrusions were preceded by well-resolved and prolonged (more than a few hours) increases in VT earthquake rate. Given the important practical implications of the contrasting conclusions, it is important to identify the origin of the contradiction. By analysing the seismicity preceding many similar volcanic events, it is possible to identify statistical patterns among precursors that may not be apparent in data for a single event. Two underlying requirements for such analyses are that the sequences being compared indeed reflect similar precursory conditions and that potential artefacts from inconsistencies in the earthquake catalogue have been removed. Whereas Chastin and Main (2003) used unprocessed data and included all eruptions in their stacking analysis, Bell and Kilburn (2011) used data filtered according to a minimum magnitude and maximum depth to investigate individual precursory sequences. Consequently, it is possible that the discrepancy between the results of the two studies originates in the different data selection criteria they employed.

Previous analyses of precursory VT trends at Kilauea

Kilauea volcano, Hawaii is an ideal volcano to study precursory patterns of VT earthquakes, owing to a high frequency of historical eruptions and a long-established monitoring network. Although the volcano has been active almost continuously since the start of the Pu'u O'o eruption in 1983, its previous behaviour was characterized by frequent, episodic eruptions and intrusions (Klein et al. 1987), during which time VT seismicity was recorded by the monitoring network of the Hawaiian Volcano Observatory (Nakata 2006). The result is a database of VT seismicity associated with 57 eruptions and non-eruptive shallow magma intrusions between 1959 and the start of the Pu'u O'o eruption.

The episodic eruptive activity at Kilauea has been attributed to the arrival of magma into a shallow reservoir, about 3–5 km below the summit caldera, and its rapid release into one or both of two rift zones on the east and south-west flanks (Fig. 1; Klein et al. 1987; Tilling and Dvorak 1993). As a result, pre-eruptive VT seismicity is most likely to occur below or close to the summit region. Bell and Kilburn (2011) found that, between 1959 and 1983, about one third of the eruptions and intrusions were preceded some 61 to 248 days beforehand by increases in VT earthquake rate in the area surrounding the summit caldera. These accelerating sequences were best modelled by exponential increases in VT earthquake rate with time and, in agreement with earlier studies (Klein 1984; Klein et al. 1987), appeared to be the same whether the final magmatic event was an eruption or intrusion.

In contrast, Chastin and Main (2003) applied a stacking methodology to analyse the precursory VT sequences before Kilauea's eruptions between 1959 and 1983. Developed to investigate precursors to tectonic earthquakes, the stacking method is designed to reveal an underlying trend among a collection of sequences subject to significant noise, by assuming that (1) each sequence shows the same behaviour, and (2) that random noise fluctuations from different sequences will tend to cancel each other and so enhance the signal-to-noise ratio. Applied to tectonic seismicity, the method has revealed power-law accelerations in foreshock occurrence rates before earthquakes in the global catalogue (Jones and Molnar 1979), in Japan (Maeda 1999) and on the East Pacific Rise (McGuire et al. 2005).

Chastin and Main (2003) examined changes in the stacked rate of VT earthquake rates over intervals of 100 days before eruptions. They describe an apparent power-law increase in rates of VT earthquakes in the final 10–15 days before eruption, consistent with Voight's relation for the approach to eruption under quasi-static loading (Voight 1988), where the stacked daily rate of VT earthquakes (dN/dt) was observed to change with time, t according to:

$$\frac{\mathrm{dN}}{\mathrm{dt}} = k(t_{\mathrm{e}} - t)^{-p} \tag{1}$$

where t_{e} is the eruption time and k and p are constants. Thus, they concluded that, for 10–15 days before eruption, the precursory sequences in VT earthquake rate at Kilauea

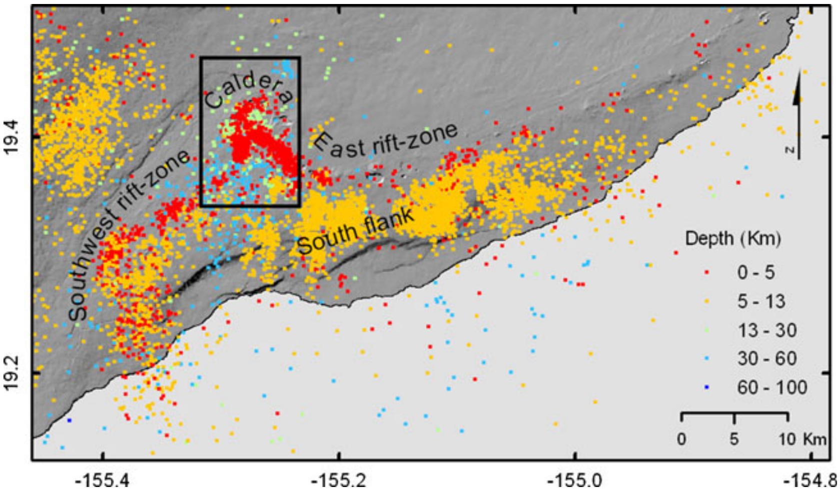


Fig. 1 Seismicity of Kilauea volcano. *Coloured squares* indicate locations of VT earthquakes of magnitude 2.5 and greater that occurred between 1969 and 1983, with the hypocentre depth being indicated by the colour scale. *Black box* indicates the Klein region used to select the epicenters of earthquakes that are likely to be associated with precursory unrest

followed a power-law acceleration that was typically masked during individual sequences by high levels of stochastic noise.

A similar result was obtained by Collombet et al. (2003) from a stacking analysis of 15 sequences of VT earthquake rate before eruptions at Piton de La Fournaise, on Réunion Island, between 1988 and 2001. Given that Kilauea and Piton de La Fournaise are both located on basaltic ocean–island volcanoes, two immediate possibilities are that, at such volcanoes, (1) Eq. 1 applies generally to stacked sequences of accelerating VT earthquake rate at least 2 weeks before eruption, and (2) stochastic noise may prevent the trend from being recognized during individual sequences.

The discrepancy between the findings of Chastin and Main (2003) and Bell and Kilburn (2011) has significant implications for the possibility of forecasting basaltic eruptions. If stochastic fluctuations in VT earthquake rate do indeed mask an underlying power-law trend that can only be identified by stacking many sequences, there is little prospect for using VT earthquake rates as a reliable forecasting tool more than a few hours before eruption. However, if a proportion of eruptions are in fact preceded by clear accelerating rates of VT earthquakes, it may be possible to incorporate these as part of a forecasting procedure.

It is therefore important to understand the origin of the discrepancy in results from the two analyses of the same original data from Kilauea. Here we focus on methods of data selection, where several potentially important factors can be identified, including methods for (1) filtering out background earthquakes that are not related to precursory sequences, (2) accommodating changes in the quality of recorded data after enhancements in the monitoring network at Kilauea between 1959 and 1983 and (3) allowing for the possible double counting of earthquake rates when successive eruptions occurred at intervals short enough for some VT earthquakes to be counted as parts of more than one precursory sequence (Klein 1984).

Data and techniques

Spatial distribution of data

Previous studies of Kilauea have identified that pre-eruptive seismicity and deformation are concentrated at depths of 5 km or less beneath the summit caldera, which lies above an enduring shallow magma reservoir; the top of which is located at a depth of 3–4 km (Klein 1984; Klein et al. 1987; Tilling and Dvorak 1993). Chastin and Main (2003) considered all earthquakes within an area of 8.7×14.6 km around Kilauea's caldera, following the original grouping of data by Klein (1984) (hereafter referred to as the ‘Klein region’). This spatial selection criterion is similar to that used by Bell and Kilburn (2011) and unlikely to be the cause in the discrepancy between the two studies. We will not investigate the effect of changing the lateral data selection criterion and will only use earthquakes located within the Klein region. However, given the evidence that precursory earthquakes are predominantly located at shallow depths above the magma reservoir, we do compare the results for the full data set with one filtered to only include earthquakes that occurred in the upper 5 km.

Magnitude completeness

Seismic monitoring networks have a finite sensitivity, so that earthquakes of lower magnitude are less likely to be recorded than those of higher magnitude. The sensitivity of the seismic monitoring network at Kilauea was enhanced several times between 1959 and 1983. As a result, the completeness magnitude of the catalogue also changed with time and, if not taken into account, this can lead to unrepresentative estimates of the rates of earthquake occurrence. This effect is apparent in Fig. 2, where the minimum magnitude of earthquakes reported in the Klein region clearly varies systematically with time. Chastin and Main (2003)

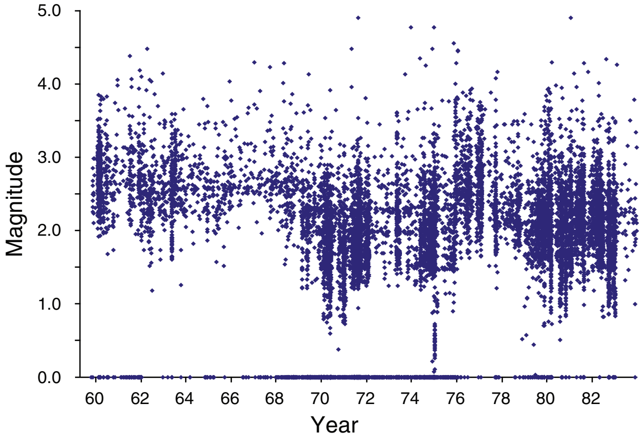


Fig. 2 Local magnitudes of VT earthquakes reported in the Hawaii Volcano Observatory catalogue for the Klein region of Kilauea 1959 and 1983

did not filter the earthquake catalogue to apply a minimum magnitude threshold, but preferred to include all recorded earthquakes. The results from such an approach are highly susceptible to artefacts caused by temporal changes in the completeness magnitude and it is established practice to apply a minimum magnitude threshold to catalogue-based analyses.

Figure 3 shows the frequency of magnitudes reported in the Klein region between 1959 and 1983. The completeness magnitude of a catalogue is defined as the lowest magnitude at which all earthquakes are recorded, usually identified by a deviation from the Gutenberg–Richter distribution (Wiemer and Wyss 2000). Determining a robust value for the completeness magnitude is a considerable challenge, especially for volcanic data where the value can change rapidly in time and the frequency–magnitude distribution may not be Gutenberg–Richter in nature. The aim of this operation is to define a value that (1) avoids artefacts and discrepancies due to temporal and spatial catalogue heterogeneity and (2) includes as many earthquakes as possible in the analysis.

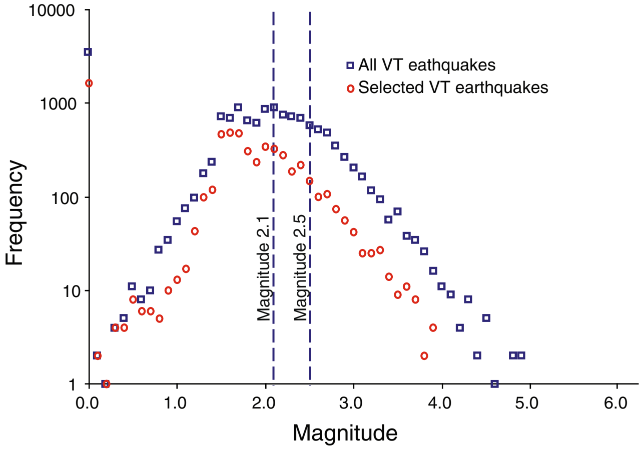


Fig. 3 Frequency–magnitude distribution for VT earthquakes recorded in the Klein region of Kilauea between 1959 and 1983 for (1) all earthquakes and (2) selected earthquakes that occur in the 100-day pre-eruptive window and with a maximum depth of 5 km

The completeness magnitude is commonly estimated by applying either the maximum curvature method or the goodness-of-fit method to the frequency–magnitude distribution (Wiemer and Wyss 2000). Of the two approaches, the goodness-of-fit method routinely yields higher estimates of completeness magnitude (Wiemer and Wyss 2000). Applied to the Klein region for 1959–1984, the estimated completeness magnitudes are 2.1 and 2.5 for the maximum curvature and goodness-of-fit (at the 95 % level) methods.

Our analysis does not involve the entire catalogue, but only those earthquakes that occur in 100-day windows before volcanic events. The rate of earthquakes (and levels of tremor) during and immediately after eruptions and intrusions is often significantly higher than during precursory sequences. Smaller earthquakes are less likely to be detected during high rates of seismicity and so we expect a lower completeness magnitude before eruptions than afterwards. For the 100 days preceding eruptions (Klein region, 1959–1984, depth less than 5 km), the maximum curvature method gives a value of 1.6, which visual inspection suggests is a considerable underestimate (Fig. 3), and the goodness-of-fit method gives a value of 2.1–2.2; in comparison, 100-day windows after eruptions yield higher corresponding values of 1.7 and 2.8. Applied to precursory sequences, therefore, we consider the value of 2.1 from the goodness-of-fit method to be a realistic estimate of the true completeness magnitude.

Our analysis will evaluate the effect of applying a minimum magnitude threshold on pre-eruptive trends by comparing first the results of the stacking method using all recorded earthquakes with those using earthquakes with magnitudes greater than 2.1. To check the robustness of the results, we will also investigate the effect of using a conservative estimate of 2.5 for completeness magnitude.

Eruptions and intrusions

Thirty-five eruptions were recorded at Kilauea between 1 October 1959 and the Pu'u O'o eruption in 1983, many of which are associated with elevated earthquake rates (Fig. 4) (Klein 1984; Klein et al. 1987). Chastin and Main (2003) stacked the changes in VT earthquake rate for 100-day intervals before each eruption. At Kilauea, however, eruptions can occur at intervals of less than 100 days. Hence, by using 100-day intervals, some VT earthquakes will also be associated with the precursors that developed before the preceding eruption. Such overlapping seismicity is not necessarily meaningful to precursory trends of the latest eruption and may introduce significant errors into the stacked data. In addition to including all eruptions in the analysis, therefore, we here also apply the selection criteria, proposed by Klein (1984), that (1) the entire sequence associated with an eruption or intrusion is excluded from the analysis if it occurs within 2 days of the end of the preceding eruption, and (2) the duration of an eruption is capped at 30 days. Following this selection, two pre-eruptive sequences have been omitted: those associated with the eruptions on 7 May 1973 and 12 December 1973. However, if the stacked trend really does describe robust mean-field behaviour, the omission of these sequences should not significantly alter the shape of the stack.

Twenty-three episodes of intrusion were also identified between 1959 and 1983 (Klein 1984; Klein et al. 1987). When considered individually, the spatial and temporal patterns of seismicity associated with these intrusions are indistinguishable from those preceding eruptions, and Klein (1984) and Bell and Kilburn (2011) have argued that the physical processes are identically independent of whether a precursory sequence culminates in an eruption or intrusion. As a second test of the stacking method, therefore, we have applied the procedure to precursory trends before intrusions, using the same selection criteria as for the pre-eruptive trends and allocating 1 day for the duration of an intrusion. This filtering excludes from analysis the intrusions of 24 August 1965 and 22 October 1980.

Results

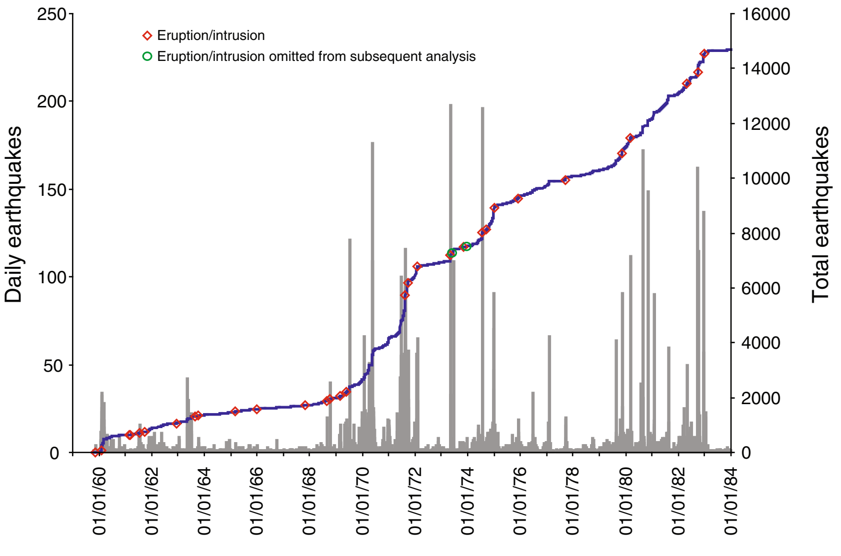
In order to validate our stacking methodology, we show in Fig. 5 the stacked daily rate of all recorded earthquakes for 100 days before and after all eruptions using a linear time axis. The data show an increase in the stacked earthquake rate in the 10 days before eruption, a very high rate on the day of the eruption, followed by a decrease in rate over the 20 days following eruption. The high rate of earthquakes coinciding with the day of eruption and post-eruptive decay in earthquake rate are consistent with observations from individual eruptions and confirm that the sequences are correctly stacked.

We now focus on the pre-eruptive sequence and repeat the analysis using the selection criteria of Chastin and Main (2003). As for that study, we plot our results on double-logarithmic axes, with the *x*-axis plotted as $t_e - t$, in which space a power-law trend would be evident as a straight line, with slope equal to the power-law exponent (Fig. 6a). These criteria almost reproduce Fig. 2a of Chastin and Main (2003), but in order to reproduce it exactly, the *x*-axis must be offset by 1 day (Fig. 6b). This offset is due to a plotting error in Chastin and Main (2003) and can be confirmed by inspection of Fig. 5 where the data are plotted on a linear temporal axis. We note that the day before eruption (omitted from Fig. 2a of Chastin and Main 2003), it has a lower stacked earthquake rate than the day 2 days before the eruption; however, the general trend in this dataset is still of increasing rates in the final 10 days before eruption.

Figure 7 illustrates the effect on the pre-eruption stacked earthquake rates of introducing maximum depth and minimum magnitude thresholds. Introducing a maximum depth threshold of 5 km has little effect, as this leaves a total of 11,226 out of 14,687 earthquakes. The additional criteria of minimum magnitude thresholds of 2.1 and 2.5 have a much more significant effect, leaving only 4,225 and 1,961 earthquakes respectively. With these criteria applied, only the data point for 2 days before eruption is significantly above the level of fluctuation outside the final 10–15-day window.

The earthquake rates illustrated in Figs. 5, 6 and 7 are the result of stacking all 35 recorded eruptions. However, the 100-day precursory sequences of two of these eruptions significantly overlap with other sequences. Figure 8 shows the stacked earthquake rates for the 33 precursory sequences

Fig. 4 Daily and cumulative total numbers of all VT earthquakes recorded in the Klein region of Kilauea between 1959 and 1983. Occurrences of eruptions are indicated by *red squares*; 7 May 1973 and 12 December 1973 events excluded from the analysis due to proximity to other events are indicated by *green circles*



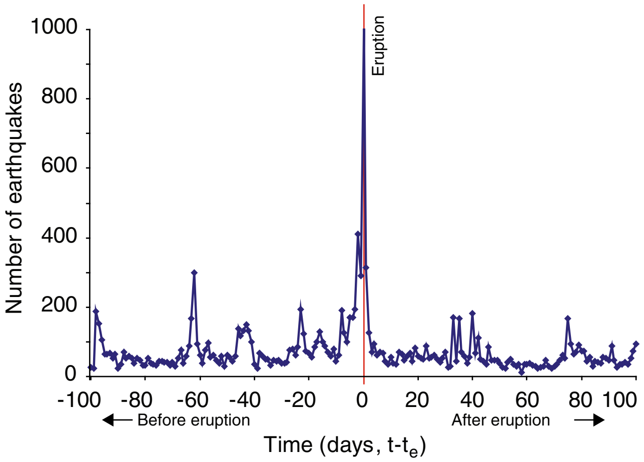


Fig. 5 Stacked daily earthquake rate for all earthquakes (in units of total earthquakes per day) occurring within the Klein region for 100 days before and after all eruptions at Kilauea between 1959 and1983

that do not overlap, using a minimum magnitude threshold of 2.1 and a maximum depth threshold of 5 km. Only removal of the eruption on 7 May 1973 has a significant effect on the resulting stacked trend because 84 earthquakes were recorded during an eruption on 5 May 1973, 2 days before the event. This number is about 25 times greater than the average earthquake rate at this time (note that typically the final earthquake rate is only at most twice the background rate). With this eruption omitted, the stacked trend shows a much less pronounced increase in earthquake rate during the 10 days before eruption; indeed, the earthquake rate hardly increases during the final 8 days before eruption. Apparently, therefore, part of the power-law increase in earthquake rate indicated by the stacked trends for Kilauea have been determined by the large earthquake rates shortly before the eruption on 7 May 1973.

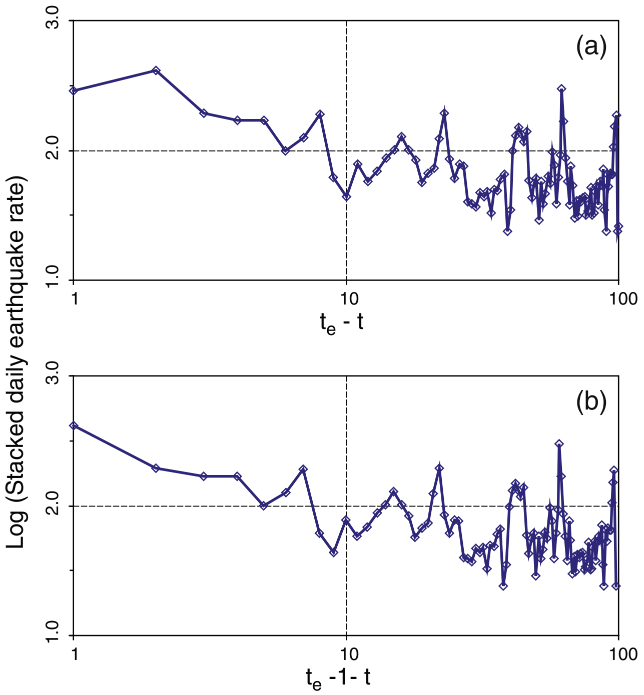


Fig. 6 **a** Logarithm of the stacked daily earthquake rate against the time preceding eruption, t_e-t, (in units of days) for all eruptions at Kilauea, using all earthquakes within the Klein region and no depth or magnitude filtering. **b** as for (**a**), but translated by 1 day towards the eruption

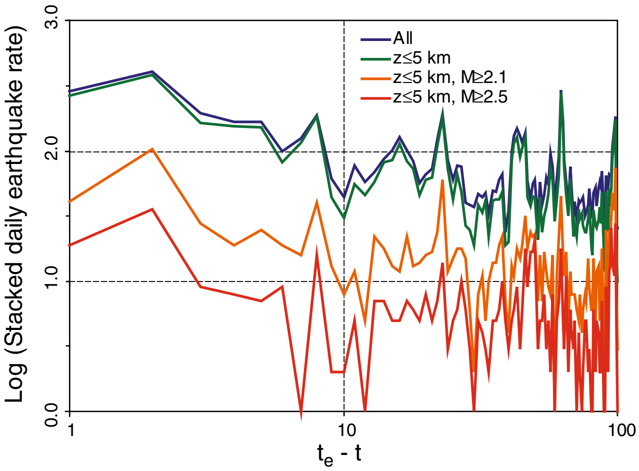


Fig. 7 Logarithm of the stacked daily earthquake rate against the time preceding eruption, with (a) no depth or magnitude thresholds, (b) maximum depth of 5 km, (c) maximum depth of 5 km and minimum magnitude of 2.1 and (d) maximum depth of 5 km and minimum magnitude of 2.5

To investigate the influence of sequence selection, we apply two statistical approaches. Firstly, we compare the performance of two models to explain the final 10 days of

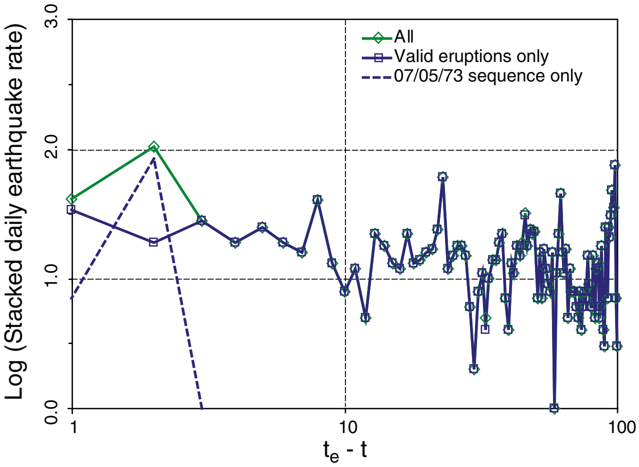


Fig. 8 Logarithm of the stacked daily earthquake rate against the time preceding eruption, excluding the overlapping 7 May 1973 and 12 December 1973 pre-eruptive sequences, using earthquakes with a maximum depth of 5 km and minimum magnitude of 2.1. The data for all eruptions and the 7 May 1973 eruption are shown by *dashed lines*

stacked earthquake rates for (a) all 35 pre-eruptive sequences and (b) the 33 precursory sequences that do not overlap (Fig. 9). In both instances, we use earthquakes with magnitudes of 2.1 or greater and depths of 5 km or less. We compare two simple models: (a) a power-law increasing rate (as in Eq. 1) and (b) a constant rate of earthquakes. We fit both models using a generalized linear model (GLM) method (Bell et al. 2011b), using the Poisson error distribution appropriate for counting data, and a log-link function to fit the power-law model. We compare the performance of the models using the Bayesian information criterion (BIC), given by:

$$\mathrm{BIC} = -2 + P\ln(n) \qquad (2)$$

where ll is the log-likelihood of the observations given the model, P is the number of free parameters and n is the number of observations (Bell et al. 2011a). For the power-law model, P=2 (the k and p values in Eq. 1). For the constant rate model, p=1 (the single amplitude term). The BIC is a pragmatic tool for comparing the performance of models, penalizing increased model complexity. In making an inference, the preferred model is more likely to have the lower BIC. For the stack containing all 35 sequences, the power-law model (BIC =81) is preferred to the constant rate (BIC=147) model. For these data, the number of observations n=10. The best-fit power-law p value is 0.61. For the stack containing only the 33 non-overlapping sequences, the difference between the models has diminished considerably; however, the power-law model (BIC=13) is still slightly preferred to the constant rate (BIC=18) model. The best-fit power-law p value has decreased to 0.24 and is much lower than values commonly reported (Voight 1988; Kilburn 2003; Smith et al. 2007; Bell and Kilburn 2011).

To further test the robustness of the stacked trend to sequence selection, we remove 4 (approximately 10 %) of the 35 sequences at random and use a GLM method with Poisson errors and a log-link function to fit a power-law model (Eq. 1), returning the estimate of the p value. We repeat this process 1,000 times, removing a randomly selected four sequences each time, to investigate the dependence of the p value on sequence selection. The resulting frequency distribution for the p value is shown in Fig. 10. The distribution does not have a single maximum. Rather there are distinct peaks at 0.77, 0.63 and 0.23. All stacked earthquake sequences including the 7 May 1973 sequence have a p value of 0.5 or greater; all stacked earthquake sequences excluding the 7 May 1973 sequence have a p value of less than 0.5. Clearly, the data within the 7 May

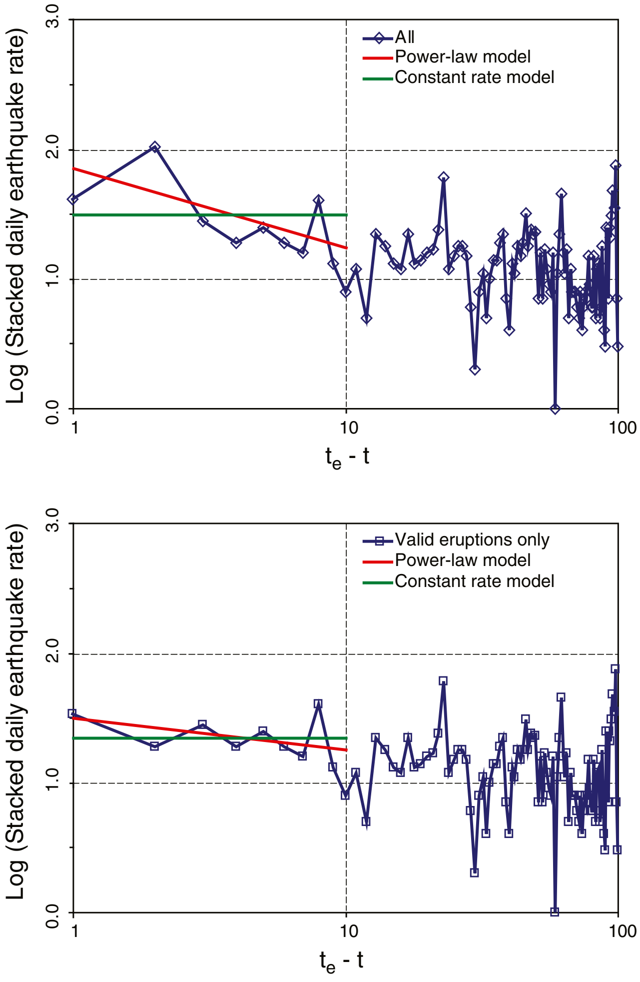


Fig. 9 Best-fit power-law (pl), constant rate (cr) models for the first 10 days of stacked daily earthquake rate against time preceding (**a**) all eruptions and (**b**) all eruptions excluding 7 May 1973 and 12 December 1973 pre-eruptive sequences. Models are fit using a GLM method, with a Poisson error function. Bayesian information criteria for models are: (**a**) pl=81 and cr=148 and (**b**) pl=13 and cr=18. Earthquakes were selected with a maximum depth of 5 km and minimum magnitude of 2.1

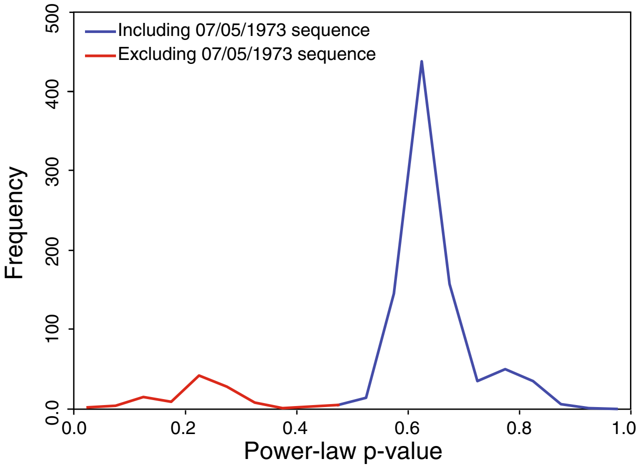


Fig. 10 Distribution of GLM estimates of power-law model p value for 1,000 combinations where four randomly selected pre-eruptive sequences are omitted from the stacked daily earthquake rate. Earthquakes were selected with a maximum depth of 5 km and minimum magnitude of 2.1

1973 are controlling the form of the increase in the stacked earthquake rates preceding eruption.

Figure 11 shows that the stacked trends for changes in earthquake rate before the 23 non-eruptive dyke intrusions are very similar to that before eruptions, with only a small increase in rate in the final 10–15 days. This observation supports the idea that the precursory process for eruptions and intrusions at Kilauea is identical (Klein 1984; Bell and Kilburn 2011)

Discussion

Evaluation of results

The analysis of Chastin and Main (2003) suggested that the stacked rate of earthquakes at Kilauea evolves according to a power-law acceleration in the final 10–15 days before eruption. Their results can be duplicated provided that: (1) the time of the magmatic event is set 2 days before the observed eruption time; (2) all pre-eruptive sequences (including the 7 May 1973 eruption) are included in the stack; (3) non-eruptive intrusions are not included in the analysis; and (4) the earthquake data are not filtered by magnitude or depth.

After basic data quality checks are performed and the 7 May 1973 sequence has been removed from the stack, the increase in earthquake rates before eruption is much less pronounced (Fig. 8). The maximum depth criterion makes little difference to the results as most earthquakes in the Klein region are shallower than 5 km. The two magnitude criteria we test do exclude a significant number of earthquakes. However, when undertaking this type of analysis, a minimum magnitude cut-off is essential to ensure the results are robust. The sensitivity of the monitoring network at Kilauea improved considerably from 1959 to 1983 (Bell and Kilburn 2011; Fig. 2) and not applying the magnitude threshold is likely to introduce a bias towards the later sequences, for which proportionally more small earthquakes are recorded. The goodness-of-fit method used to determine the completeness magnitude suggests that a value of 2.1 is the lowest that can be reasonably justified. Any results using a completeness magnitude value lower than this, or none at all, must be seriously questioned.

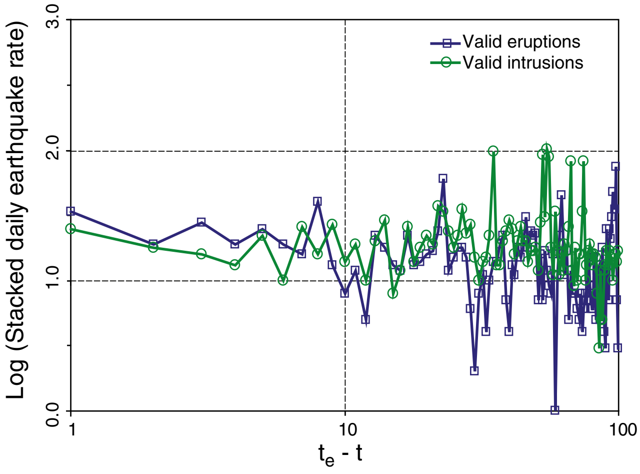


Fig. 11 Logarithm of the stacked daily earthquake rate against the time preceding eruption, for (a) eruptions (excluding the overlapping 7 May 1973 and 12 December 1973 pre-eruptive sequences) and (b) for non-eruptive intrusions at Kilauea, using earthquakes with a maximum depth of 5 km and minimum magnitude of 2.1

Increasing the number of data selection parameters potentially increases the chance of observing a result through tuning (e.g. Hardebeck et al. 2008). We do not allow selection parameters to vary freely and then optimize them to find a particular result. Rather, we apply a set of fixed criteria which are strongly supported by the findings of previous studies. We consider this approach unlikely to lead to artificial results.

The strong influence of the 7 July 1973 pre-eruptive sequence raises two key points. Firstly, it is almost certainly necessary to exclude certain sequences from the stack to avoid double counting of earthquakes and to exclude co-eruptive earthquakes for one eruption from the precursory sequence of another. Secondly, for the stacked trend to truly represent a persistent underlying process, it must be robust to the exclusion of a small proportion of the total number of sequences, irrespective of the selection criteria used. For an initial set of 35 sequences, removal of one sequence represents a loss of only 3 % of the data and so should be too small to have a significant influence on the stacked trend. The simplest interpretation, therefore, is that the variability of some individual sequences is too great for a robust mean trend to be determined from only 35 pre-eruptive sequences.

In addition, the stack of sequences associated with non-eruptive intrusions at Kilauea does not show any pronounced increase in rate towards intrusion. There is considerable evidence that the physical processes preceding non-eruptive dyke intrusion at Kilauea are indistinguishable from those preceding eruptions, the only difference developing during the dyke intrusion itself. Consequently, we conclude that the absence of a pronounced increase preceding non-eruptive dyke intrusions is further support for the absence of the same trend before eruptions.

The mean precursory trend from 15 sequences at Piton de La Fournaise (Collombet et al. 2003) resembles the results from Chastin and Main (2003) for Kilauea. The published data show a large scatter among individual sequences about the stacked trend, and as a result, removal of a single sequence (about 7 % of the dataset) could potentially significantly alter the aggregated trend. Once again, the implication is that the apparent power-law acceleration in VT earthquake rate before eruptions does not reflect a common underlying trend.

Implications

Our analysis suggests that stacking methods provide no clear evidence for a single power-law trend in the acceleration of daily VT earthquake rate before eruptions at Kilauea. Although formally a power-law increase is just preferred to a constant rate of VT earthquakes, the increase in rate is small and the power-law *p* value is unusually low. Such a weak increase could arise by chance. One possible interpretation is that variations in earthquake rate are simply stochastic fluctuations about a constant background rate, so that no consistent precursory changes in earthquake rate can be expected before eruptions.

An alternative explanation is that repeatable precursory changes do occur before some eruptions, but that these are lost when combined with data from a large number of eruptions for which there is no precursory signal. For example, Fig. 12a shows the stacked daily rates of VT earthquakes preceding the 33 eruptions and 25 intrusions at Kilauea, applying the maximum depth threshold of 5 km and a minimum magnitude threshold of 2.1. Comparing the power-law and constant rate models for the full 100-day interval (n=100 in Eq. 2), the power-law model is again just preferred (with a BIC of 743, compared with 764 for the constant rate model) but with an exceptionally low *p* value of 0.08. In contrast, Fig. 12b shows the stacked daily rates of VT earthquakes for the seven eruptions and intrusions identified by Bell and Kilburn (2011) as occurring after a sequence of accelerating rates of earthquakes. In this case, an accelerating trend is strongly preferred (with p=0.32 and a BIC of −154, compared with −39 for the constant rate model). Indeed, as shown by Bell and Kilburn (2011), the acceleration may be even better described by an exponential, rather than power-law, trend. The key point here is that a subset of eruptions and intrusions are preceded by prolonged (>10 day) increases in the rate of earthquakes, but that their signal is lost when combined within the larger data set for all eruptions.

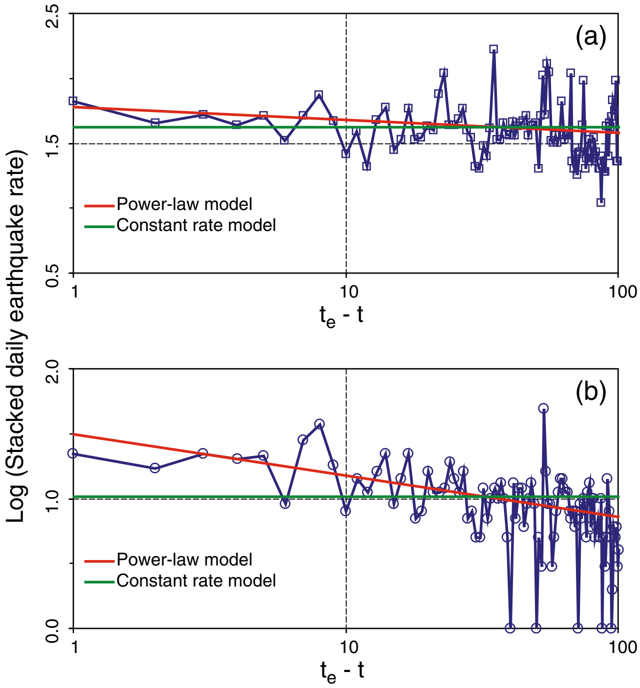


Fig. 12 **a** Logarithm of the stacked daily earthquake rate against the time preceding eruption for combined eruptions (excluding the overlapping 7 May 1973 and 12 December 1973 pre-eruptive sequences) and non-eruptive intrusions at Kilauea, using earthquakes with a maximum depth of 5 km and minimum magnitude of 2.1. (**b**) as for (**a**) but only including sequences preceding the seven eruptions and intrusion identified as occurring at the culmination of an accelerating sequence of earthquakes. Best-fit power-law (pl) and constant rate (cr) models for full 100 days of both data sets are also shown. Bayesian information criteria for models are: (**a**) pl=743 and cr=764 and (**b**) pl=−154 and cr=−39. Earthquakes were selected with a maximum depth of 5 km and minimum magnitude of 2.1

Whether accelerating precursors are developed may depend on the physical conditions that prevail during the build-up to an eruption or intrusion. Thus, accelerating precursors may develop preferentially in crust that must be strained significantly before eruption. However, if the crust is already close to failure, only a small change in magma pressure or confining stress may be sufficient to trigger reservoir failure, without being associated with significant additional seismicity (Bell and Kilburn 2011).

An alternative explanation is that accelerating trends normally develop only among earthquakes with magnitudes less than the completeness threshold. We consider this unlikely because clear accelerating trends are observed in individual pre-eruptive sequences at Kilauea when only larger magnitude earthquakes are included (Klein 1984; Lengliné et al. 2008; Bell and Kilburn 2011). Small-magnitude earthquakes undoubtedly contain important information regarding volcanic deformation. Detailed case studies of eruptions where exceptionally high-quality data are available provide considerable further insight into pre-eruptive processes. As the number of well-monitored eruptions increases, we are sure that similar comparative studies on better quality data will lead to greater understanding and more reliable quantification of eruption precursors.

Conclusions

The nature of pre-eruptive changes in the rate of earthquakes is important for understanding the predictability of future events. When we apply a minimum magnitude threshold corresponding to the catalogue completeness magnitude of 2.1 and exclude specific eruptions to avoid double counting, we find no evidence for a power-law acceleration in the stacked daily rate of VT earthquakes in the final 10–15 days preceding eruptions at Kilauea. Similarly, no trend is found before non-eruptive intrusions. As the stacked trend is sensitive to the exclusion of a small fraction of the total number of sequences, we conclude that even the extensive dataset from Kilauea is too small to constrain the true underlying dynamics for all eruptions. Instead, when the data are filtered to only include a small number of eruptions and intrusions that have been previously identified as being preceded by accelerating rates of earthquakes, there is a more pronounced increase in the daily earthquake rate over the precursory 100-day interval. These observations are consistent with there being at least two types of precursory sequences of VT earthquakes before eruptions and intrusions at Kilauea: (1) a small proportion of eruptions and intrusions occur at the culmination of sequences of accelerating rates of VT earthquakes that evolve over timescales of weeks to months; and (2) the majority of eruptions and intrusions occur with only a few hours of elevated VT seismicity. In this second case, forecasting on the basis of VT earthquake rates only will only be able to provide warning a few hours at most before the onset of eruption.

Acknowledgments This research was funded by the UK Natural Environment Research Council (AFB). During writing, AFB was funded by NERC project Ne/H02297x/1. We thank the USGS Hawaiian Volcano Observatory for access to the Hawaiian earthquake catalogue, Ian Main for helpful discussions and Phil Dawson and an anonymous reviewer for their constructive comments.

References

Bell AF, Kilburn CRJ (2011) Precursors to dyke-fed eruptions at basaltic volcanoes: insights from patterns of volcano-tectonic seismicity at Kilauea volcano, Hawaii. Bull Volcanol 74(2):325–339

Bell AF, Greenhough J, Heap MJ, Main IG (2011a) Challenges for forecasting based on accelerating rates of earthquakes at volcanoes and laboratory analogues. Geophys J Int. doi:10.1111/j.1365-246X.2011.04982.x

Bell AF, Naylor M, Heap MJ, Main IG (2011b) Forecasting volcanic eruptions and other material failure phenomena: an evaluation of the failure forecast method. Geophys Res Lett 38. doi:10.1029/2011gl048155

Chastin SFM, Main IG (2003) Statistical analysis of daily seismic event rate as a precursor to volcanic eruptions. Geophys Res Lett 30(13):1671. doi:10.1029/2003GL016900

Collombet M, Grasso JR, Ferrazzini V (2003) Seismicity rate before eruptions on Piton de la Fournaise volcano: implications for eruption dynamics. Geophys Res Lett 30(21). doi:10.1029/2003GL017494

De la Cruz-Reyna S, Reyes-Davila GA (2001) A model to describe precursory material-failure phenomena: applications to short-term forecasting at Colima volcano, Mexico. Bull Volcanol 63(5):297–308. doi:10.1007/s004450100152

Hardebeck JL, Felzer KR, Michael AJ (2008) Improved tests reveal that the accelerating moment release hypothesis is statistically insignificant. J Geophys Res Solid Earth 113(B08310). doi:10.1029/2007JB005410

Jones LM, Molnar P (1979) Some characteristics of foreshocks and their possible relationship to earthquake prediction and premonitory slip on faults. J Geophys Res 84(B7):3596

Kilburn CRJ (2003) Multiscale fracturing as a key to forecasting volcanic eruptions. J Volcanol Geotherm Res 125(3–4):271–289. doi:10.1016/S0377-0273(03)00117-3

Klein FW (1984) Eruption forecasting at Kilauea volcano, Hawaii. J Geophys Res 89(NB5):3059–3073

Klein FW, Koyanagi RY, Nakata JS, Tanigawa WR, Decker RW, Wright TL, Stauffer PH (1987) The seismicity of Kilauea's magma system. In: Volcanism in Hawaii. pp 1019–1185

Lengliné O, Marsan D, Got JL, Pinel V, Ferrazzini V, Okubo PG (2008) Seismicity and deformation induced by magma accumulation at three basaltic volcanoes. J Geophys Res Solid Earth 113 (B12):12. doi:10.1029/2008JB005937

Maeda K (1999) Time distribution of immediate foreshocks obtained by a stacking method. Pure Appl Geophys 155(2–4):381–394

Main IG (1999) Applicability of time-to-failure analysis to accelerated strain before earthquakes and volcanic eruptions. Geophys J Int 139(3):F1–F6

McGuire JJ, Boettcher MS, Jordan TH (2005) Foreshock sequences and short-term earthquake predictability on East Pacific Rise transform faults. Nature 434(7032):457–461

Nakata J (2006) Hawaiian volcano observatory seismic data, January to December 2005. U.S. Geological Survey Open-File Report 122

Smith R, Kilburn CRJ, Sammonds PR (2007) Rock fracture as a precursor to lava dome eruptions at Mount St Helens from June 1980 to October 1986. Bull Volcanol 69(6):681–693. doi:10.1007/s00445-006-0102-5

Soosalu H, Einarsson P, Porbjarnardottir BS (2005) Seismic activity related to the 2000 eruption of the Hekla volcano, Iceland. Bull Volcanol 68(1):21–36. doi:10.1007/s00445-005-0417-7

Tilling RI, Dvorak JJ (1993) Anatomy of a basaltic volcano. Nature 363(6425):125–133

Voight B (1988) A method for prediction of volcanic eruptions. Nature 332(6160):125–130

Voight B (1989) A relation to describe rate-dependent material failure. Science 243(4888):200–203

Wiemer S, Wyss M (2000) Minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the Western United States, and Japan. Bull Seismol Soc Am 90(4):859–869. doi:10.1785/0119990114

Zobin VM, Luhr JF, Taran YA, Breton M, Cortes A, De La Cruz-Reyna S, Dominguez T, Galindo I, Gavilanes JC, Muniz JJ, Navarro C, Ramirez JJ, Reyes GA, Ursua M, Velasco J, Alatorre E, Santiago H (2002) Overview of the 1997–2000 activity of Volcan de Colima, Mexico. J Volcanol Geotherm Res 117(1–2):1–19. doi:10.1016/s0377-0273(02)00232-9