RESEARCH ARTICLE

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

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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

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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 preo(ca)14.o6.2(p)02.3(p3g0i15(li2T(ca)14.72T(cau)-6u)15.5T(cac)-6u)18.9wag (fo)-((
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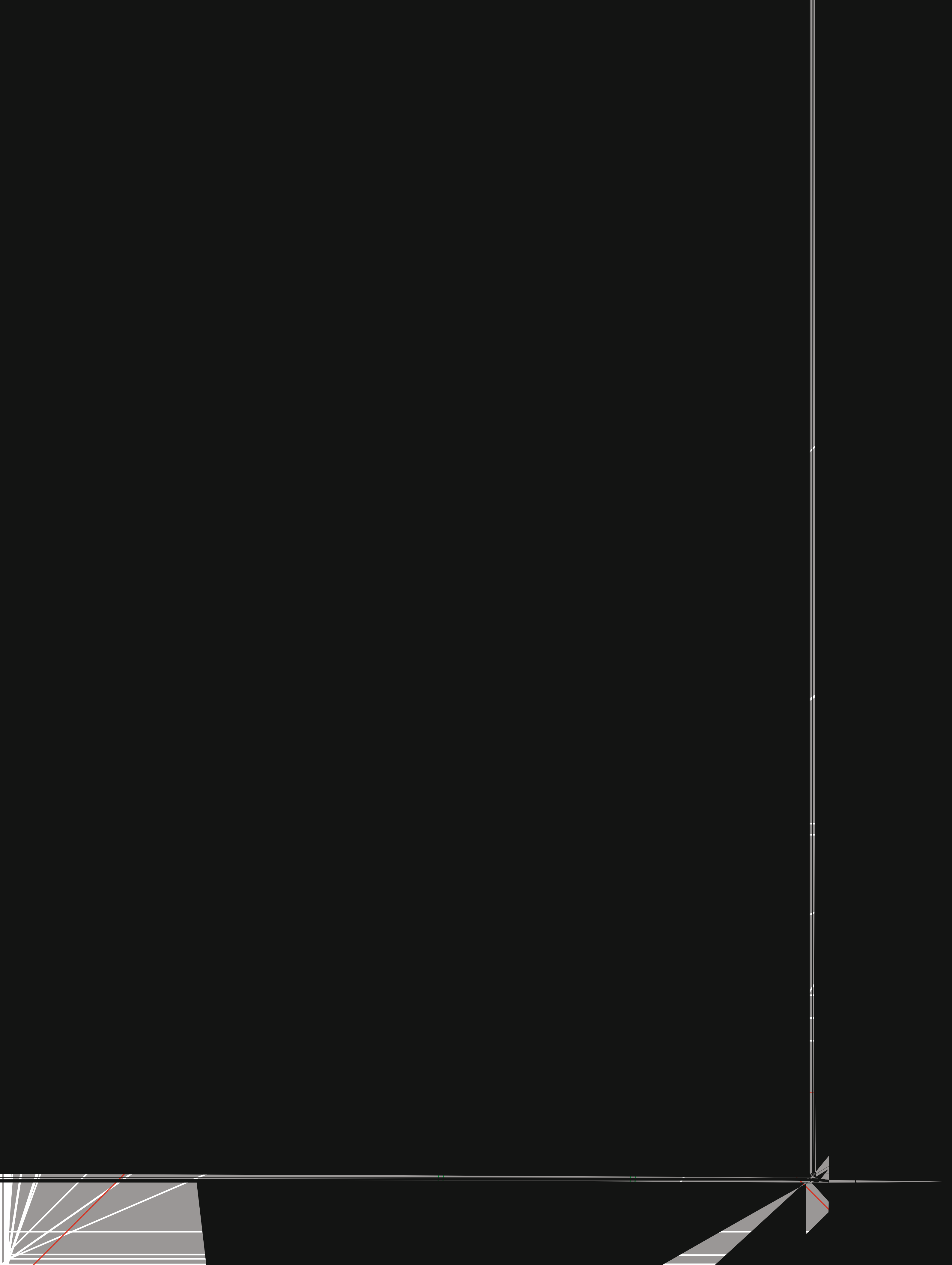

that do not overlap, using a minimum magnitude threshold of 2.1 and a maximum depth threshold of 5 km. Only removal of the eruption on 7 May 1973 has a significant effect on the resulting stacked trend because 84 earthquakes were recorded during an eruption on 5 May 1973, 2 days before the event. This 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.

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 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:

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

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

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 exponenbefore 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