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Forecasting deflation, intrusion and eruption at inflating volcanoes

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ABSTRACT

A principal goal of volcanology is to successfully forecast the start of volcanic eruptions. This paper introduces a general forecasting method, which relies on a stream of monitoring data and a statistical description of a given threshold criterion for an eruption to start. Specifically we investigate the timing of intrusive and eruptive events at inflating volcanoes. The gradual inflation of the ground surface is a well-known phenomenon at many volcanoes and is attributable to pressurised magma accumulating within a shallow chamber. Inflation usually culminates in a rapid deflation event caused by magma escaping from the chamber to produce a shallow intrusion and, in some cases, a volcanic eruption. We show that the ground elevation during 15 inflation periods at Krafla volcano, Iceland, increased with time towards a limiting value by following a decaying exponential with characteristic timescale τ. The available data for Krafla, Kilauea and Mauna Loa volcanoes show that the duration of inflation (t^*) is approximately equal to τ. The distribution of t^*/τ values follows a log-logistic distribution in which the central 60% of the data lie between $0.99 < t^*/\tau < 1.76$. Therefore, if τ can be constrained during an on-going inflation period, then the cumulative distribution function of t^*/τ values calibrated from other inflation periods allows the probability of a deflation event starting during a specified time interval to be estimated. The time window in which there is a specified probability of deflation starting can also be forecast, and forecasts can be updated after each new deformation measurement. The method provides stronger forecasts than one based on the distribution of repose times alone and is transferable to other types of monitoring data and/or other patterns of pre-eruptive unrest.

1. Introduction

Forecasting the onset, size, location, style and duration of a volcanic eruption is an important and challenging goal of volcanology. In terms of forecasting the start of an eruption, one approach is to use a time series of monitoring data to extrapolate to the time at which the measured parameter will reach a known threshold value at which an eruption starts (Chadwick et al., 2012; Nooner and Chadwick, 2016). The theoretical basis of this approach is exemplified by the materials failure forecast method (Voight, 1988) and relies on the eruption threshold condition being known precisely. This approach can, in principle, predict the time at which failure is reached, and an eruption starts. In practice, however, uncertainty in the data, in the model of the time-dependence of the measured quantity, in the fitting of data to a model, and in the extrapolation of the fitted trend result in uncertainty in the predicted eruption onset time, although the uncertainty diminishes with increasing time (Bell et al., 2011, 2013).

Alternatively, monitoring data can be used to make a judgement of the likelihood of an eruption starting within some future time window, such as "the next N days" (Dzierma and Wehrmann, 2010), rather than pin-pointing the eruption time. This type of approach may use a statistical analysis of a volcano's long-term record of repose periods (reviewed by Marzocchi and Bebbington, 2012), or interpretation of on-going short-term unrest (e.g., Swanson et al., 1983, 1985; Linde et al., 1993; Harlow et al., 1996; Chadwick et al., 2012; and reviews by Sparks, 2003; Bell et al., 2015; Pallister and McNutt, 2015). Useful measures of unrest for this purpose include the rates of seismicity (Voight, 1988; Cornelius and Voight, 1994, 1995; Kilburn, 2012; Robertson and Kilburn, 2016), changes in the seismic properties of the volcano (Brenguier et al., 2008; Chouet and Matoza, 2013; Crampin et al., 2015), the gas composition or emission rate (Carapezza and Federico, 2000; Laiolo et al., 2012; Aiuppa et al., 2007; Carapezza et al., 2009; De Moor et al., 2016), thermal remote sensing data (van Manen et al., 2013; Reath et al., 2016), crustal deformation

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(Linde et al., 1993) and ground surface deformation (Chadwick et al., 2012; Segall, 2013). Methods which combine two or more types of data have also been advocated (e.g., Klein, 1984; Schmid et al., 2012; Pallister and McNutt, 2015). Given an empirically-defined statistical model connecting the magnitude of unrest and the time remaining to an eruption onset, then quantitative probabilistic forecasts of an eruption starting within a particular time window can be made. An example is the forecasting of explosive eruptions during dome-forming episodes of Bezymianny volcano using thermal remote sensing data (van Manen et al., 2013). The forecasting of eruption duration using historical data (Sparks and Aspinall, 2004; Gunn et al., 2014; Wolpert et al., 2016) relies on the same type of analysis. This paper applies this statistics-based approach to the surface inflation that precedes eruptions and shallow intrusions, presenting general expressions for forecasting the probability of an event happening within any user-defined time interval.

In some cases, pre-eruptive surface inflation proceeds at a constant rate (e.g., Chaussard et al., 2013; Delgado et al., 2014; Champenois et al., 2014), whereas in other cases an exponentially decreasing rate of inflation has been measured such that tilt, vertical and horizontal displacement, or volume of the inflation dome follows

$$\Delta D = a\big(1 - \exp(-t/\tau)\big), \tag{1}$$

where ΔD is the change in the measured deformational quantity since the start of inflation at time $t = 0$, a is a constant equal to the value of ΔD that would be attained at time $t = \infty$, and τ is a characteristic e-folding timescale (Dvorak and Okamura, 1987; Lu et al., 2003; Lengliné et al., 2008; Dzurisin et al., 2009). This behaviour is readily explained by physics-based models of the growing over-pressure within a replenished shallow magma chamber that is contained in elastic country rock and fed at a rate determined by the pressure gradient along the feeding conduit (Lengliné et al., 2008; Pinel et al., 2010). Inflation, being proportional to chamber over-pressure, increases up to the point when a threshold over-pressure breaks open the chamber (Blake, 1981). Magma then escapes from the chamber, causing the ground surface to deflate, and a dyke propagates away from the chamber and may intercept the ground surface. The start of deflation is thus the time at which magma withdrawal starts and an intrusion is initiated, in some cases feeding an eruption. Whether an intrusion actually breaks the surface (and how long after the start of deflation, and where the location of any eruptive vents is) is likely to depend on magma properties, rock properties, crustal stress and topography, as explored in theoretical models by Buck et al. (2006), Heimisson et al. (2015a) and Pinel et al. (2017).

According to Eq. (1), if deflation is triggered when the amount of deformation is ΔD^*, then this happens at time t^* which is proportional to the exponential timescale (τ)

$$t^* = -\tau \ln(1 - \Delta D^*/a), \tag{2}$$

This implies that if early monitoring data can constrain the value of τ, then a forecast of the time at which magma withdrawal starts, t^*, can be made within the limits of variation in $-\ln(1 - \Delta D^*/a)$.

In Section 2, Eq. (1) is fitted to inflation periods at Krafla volcano which preceded intrusions (as detected by seismic and deformational evidence) and, in some cases, eruptions. The results, together with published results from Kilauea and Mauna Loa, show that t^* seems to be proportional to τ, with the ratio t^*/τ falling in a narrow range. In Sections 3 and 4 the statistical distribution of t^*/τ values is used to calculate the probability that deflation will start within any user-defined time interval. We also calculate the size of the time window in which the probability has a particular value, and show how forecasts can be continuously updated

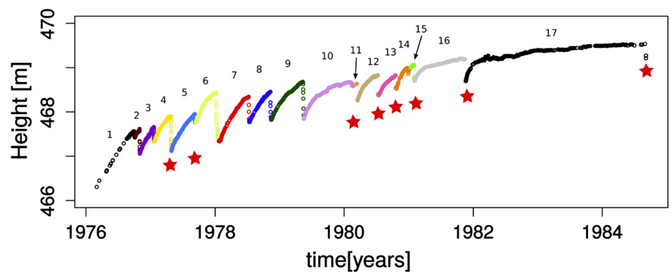

Fig. 1. Elevation above sea level of station FM5596 at Krafla (data from Björnsson and Eysteinsson, 1998) showing the 17 periods (represented with different colours for clarity) of gradual inflation followed by rapid deflation. Deflation events that were accompanied by an eruption are indicated with a red star. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

on the basis of new monitoring data. Section 5 discusses how our method can be adapted to make the same type of forecasts using other types of pre-eruptive measurements that follow a given time-dependent function.

2. Ground inflation, deflation and eruptions at Krafla

The Krafla volcanic system is situated in Iceland's Northern Volcanic Zone. It has a 12-km diameter caldera and a system of ground fissures and vents which extend beyond the caldera to the North and South. An active geothermal system lies within the caldera. In 1975–1984 a repeated sequence of activity occurred in which gradual ground inflation centred within the caldera was interrupted by rapid deflation accompanied by rifting and sometimes basaltic eruptions (e.g., Björnsson et al., 1979; Ewart et al., 1990, 1991; Buck et al., 2006; Wright et al., 2012). Seismicity accompanying rifting has been interpreted to have resulted from dominantly lateral propagation of dykes carrying basaltic magma from a shallow magma chamber below the caldera. An S-wave shadow zone (Einarsson, 1978; Brandsdóttir and Menke, 1992; Brandsdóttir et al., 1997) and modelling of ground deformation (e.g., Björnsson et al., 1979; Johnsen et al., 1980; Ewart et al., 1990, 1991; Heimisson et al., 2015b) place the shallow chamber, or a complex of magma storage compartments, at about 2 to 4 km depth.

Here, we investigate the record of ground inflation using the data on surface elevation provided by Björnsson and Eysteinsson (1998) (see Fig. 1) pertaining to levelling station FM5596 located about 1 km from the centre of deformation. Measurements were typically recorded on a daily to hourly basis. We designate as inflation period 1 the measured inflation which started in February 1976, following the end of the first eruptive event in the 1975–1984 activity, because this marks the start of frequent measurements of inflation. The elevation at which deflation started generally increased over time, rather than occurring at a more or less constant threshold elevation, as appears to be the case at Axial Seamount (Chadwick et al., 2012; Nooner and Chadwick, 2016). At Krafla, the threshold elevation is variable and is likely to be a function of time-dependent magmatic, tectonic and topographic stresses (Buck et al., 2006).

Of the 17 inflation periods which preceded deflation (Fig. 1), all but the two most recent periods (lasting from 04/02/1981 to 18/11/1981 and from 22/11/1981 to 04/09/1984) are described well by the single exponential function of Eq. (1). These are the 15 periods plotted in Fig. 2 and listed in Table 1. They lasted from tens of days to hundreds of days and inflation stopped (when deflation and eruption/intrusion started) after inflation of 0.2 to 1.2 m. Note that although elevation increases during each inflation period at a decreasing rate through time, some irregularity occurs because of occasional rapid but small deflations and inflations. These are