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Understanding cyclic seismicity and ground deformation patterns at volcanoes: Intriguing lessons from Tungurahua volcano, Ecuador

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ABSTRACT

Cyclic seismicity and ground deformation patterns are observed on many volcanoes worldwide where seismic swarms and the tilt of the volcanic flanks provide sensitive tools to assess the state of volcanic activity. Ground deformation at active volcanoes is often interpreted as pressure changes in a magmatic reservoir, and tilt is simply translated accordingly into inflation and deflation of such a reservoir. Tilt data recorded by an instrument in the summit area of Tungurahua volcano in Ecuador, however, show an intriguing and unexpected behaviour on several occasions: prior to a Vulcanian explosion when a *pressurisation* of the system would be expected, the tilt signal declines significantly, hence indicating *depressurisation*. At the same time, seismicity increases drastically. Envisaging that such a pattern could carry the potential to forecast Vulcanian explosions on Tungurahua, we use numerical modelling and reproduce the observed tilt patterns in both space and time. We demonstrate that the tilt signal can be more easily explained as caused by shear stress due to viscous flow resistance, rather than by pressurisation of the magmatic plumbing system. In general, our numerical models prove that if magma shear viscosity and ascent rate are high enough, the resulting shear stress is sufficient to generate a tilt signal as observed on Tungurahua. Furthermore, we address the interdependence of tilt and seismicity through shear stress partitioning and suggest that a joint interpretation of tilt and seismicity can shed new light on the eruption potential of silicic volcanoes.

1. Introduction

The combined monitoring of ground deformation and seismicity on active volcanoes provides one of the few direct links to the internal state of volcanic activity and its changes in near real-time. The identification of cyclic patterns in seismicity and deformation offers further insights regarding the temporal behaviour of a particular volcano and is essential to guide forecasting attempts. In many previous studies, surface deformation on active volcanoes has been inferred as caused by pressure changes within magmatic systems at depth (Anderson et al., 2010; Widiwijayanti and Young, 2010). The tilt, defined as

$$\vartheta = \arctan \frac{dz}{dr} \quad (1)$$

where z and r are the vertical and radial co-ordinates, respectively, is the change in inclination angle of the volcanic flanks, and is a particularly sensitive indicator of surface deformation. If tilt changes are modelled as caused by shallow, isotropic pressure sources with spherical or cylindrical geometries, they will often require unrealistically high overpressures, large conduit radii or extremely yielding material properties to reach high tilt amplitudes (Voight et al., 1999, 2005). Alternatively, elongated source bodies, such as dykes, can produce high tilt amplitudes in a zone located perpendicular to the strike of the dyke (Hautmann et al., 2009). In our modelling approach we will explore a set of isotropic pressure sources and a wide variety of material parameters and geometries in order to model the observed tilt patterns. An alternative mechanism pointing towards shear stress to generate high tilt amplitudes on volcanoes has been suggested by several studies. Beauducel et al. (2000) noted a striking link between seismicity – as a proxy for magma flux – and deformation. They suggested that the shallow deformation field on Merapi volcano, Indonesia, could be controlled by magma flux rather than by magma pressure variations. For Soufrière Hills volcano, Montserrat, during periods of rapid magma extrusion in 1997, we suggested changes in shear stress within the upper 1000 m of the magmatic system to explain

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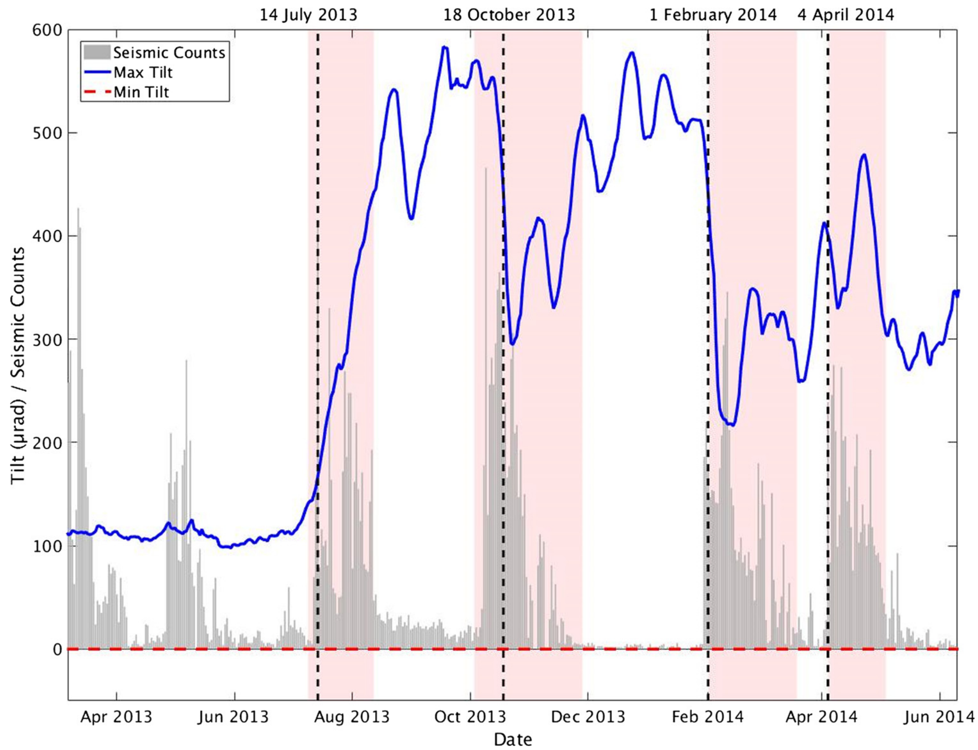

Fig. 1. Daily averaged tilt (μrad) and daily event rate of long-period earthquakes recorded at RETU. East and North tilt components are rotated into the direction of maximum and minimum tilt plotted here, maximum tilt is used for further analysis. The four Vulcanian eruptions of interest are indicated (dashed lines) along with the associated eruptive phases (shaded) and described in the text. Note the remarkable magnitude of the maximum tilt. See the supplementary material for a zoomed view into the last three events Fig. S1.

the tilt amplitude of 20 μrad as an alternative to magma pressurisation (Green et al., 2006). Other examples using shear stress include Anderson et al. (2010), Costa et al. (2012).

In addition to the high tilt amplitudes, Tungurahua exhibits another striking feature concerning the timing of the tilt signal in relation to its volcanic activity; Vulcanian explosions are often – but not always – preceded by an increase in seismicity and a *decrease* in tilt, hence an apparent deflation of the edifice, or *depressurisation* of the volcanic system several days before an eruption.

This intriguing pattern of seismicity, tilt and Vulcanian explosions has been observed on about 10 occasions, starting as early as 2006, (Fig. 1) and has been utilised by scientists in charge of volcano monitoring in Ecuador in attempts in eruption forecasting. We investigate this pattern in a modelling approach, comparing quantitatively the traditional magma pressurisation hypothesis with the effects of shear stresses along the conduit due to viscous flow resistance. We focus on periods associated with explosive activity in 2013 and 2014, which displayed strong surface deformation in the upper part of Tungurahua's cone. The results demonstrate how much important information can be obtained from a single, strategically deployed tilt- and seismometer station, and how this can guide forecasting of the short-term eruption potential of Tungurahua.

2. Cyclic deformation associated with Vulcanian-style eruptions at Tungurahua 2013–2014

Tungurahua volcano is an andesitic strato-volcano with historical eruptions ranging from 2 to 4 on the VEI scale. Its steep-sided, 3000 m relief cone has collapsed on several occasions and pyroclastic flows and ash falls are frequent hazards (Hall et al., 1999; Le Pennec et al., 2008). The present eruptive phase started in 1999 after nearly 80 yrs of repose (Mothes et al., 2015). Eruptions during the last 16 yrs have been accompanied by strong degassing (Hidalgo et al., 2014), long-period seismic activity (Kim et al., 2014), notable infrasound signals (Fee and Matoza, 2013; Mothes et al., 2015) and ground deformation (Biggs et al., 2010; Champenois et al., 2014). We base our study on the tilt cycles and seismicity associated with four eruptive periods: three Vulcanian eruptive events on 14 July 2013, 18 October 2013 and 1 February 2014, and a fourth episode on 4 April 2014 involving both Strombolian and Vulcanian-style activity.

Deformation data are obtained from an electronic tilt meter at station RETU, located at 3950 m elevation on the northern flank of the volcano, 2000 m north, and 1000 m below the summit vent (Fig. 2). The RETU tilt meter is a dual-axial platform analogue-output, model AGI, 711-2A series, with a 1 μrad resolution.

It is anchored to a massive lava flow and buried in an insulated barrel that minimizes diurnal temperature changes. Data are recorded every 5 mins and sent via analogue radio to the Tungurahua Volcano Observatory where they are decimated and stored in daily files. Several other continuously recording tilt meter stations are located lower on the volcano's flanks (Fig. 2) and have similar instrumentation, data recording and transmitting procedures. However, due to the larger distance from the conduit, these stations have been less sensitive to movements near the vent and conduit.

There is little apparent evidence for correlation between the data patterns at these distal sites with pre- and co-eruptive seismic patterns and explosive events. Therefore, in this study, we concentrate on the data from the RETU station comprising a tilt meter and a short-period seismometer.

For the current study, we use daily averaged tilt data and seismic counts recorded at RETU station. A higher resolution tilt record shows only the usual temperature dependent, small daily fluctuations, which are not relevant for the overall tilt behaviour. East and North tilt components are rotated into the direction of maximum tilt which is then used for further analysis. In contrast to