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Transient deformation associated with explosive eruption measured at Masaya volcano (Nicaragua) using Interferometric Synthetic Aperture Radar

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A B S T R A C T

Deformation caused by processes within a volcanic conduit are localised, transient, and therefore challenging to measure. However, observations of such deformation are important because they provide insight into conditions preceding explosive activity, and are important for hazard assessment.

Here, we present measurements of low magnitude, transient deformation covering an area of ~4 km^2 at Masaya volcano spanning a period of explosive eruptions (30th April–17th May 2012). Radial uplift of duration 24 days and peak displacements of a few millimeters occurred in the month before the eruption, but switched to subsidence ~27 days before the onset of the explosive eruption on 30th of April. Uplift resumed during, and continued for ~16 days after the end of the explosive eruption period. We use a finite element modelling approach to investigate a range of possible source geometries for this deformation, and find that the changes in pressurisation of a conduit 450 m below the surface vent (radius 160 m and length 700 m), surrounded by a halo of brecciated material with a Young's modulus of 15 GPa, gave a good fit to the InSAR displacements. We propose that the pre-eruptive deformation sequence at Masaya is likely to have been caused by the movement of magma through a constriction within the shallow conduit system.

Although measuring displacements associated with conduit processes remains challenging, new high resolution InSAR datasets will increasingly allow the measurement of transient and lower magnitude deformation signals, improving the method's applicability for observing transitions between volcanic activity characterised by an open and a closed conduit system.

1. Introduction

Volcanoes that transition between effusive and explosive behaviour pose a threat to nearby communities, but the dynamics behind this transition are not well-defined (Dingwell, 1996; Gonnermann and Manga, 2003). Characteristic eruptive behaviour at a volcano depends on the magma ascent rate, which is in turn determined by subsurface geometries, physical properties of the magma and overpressures within the system (Woods and Koyaguchi, 1994; Dingwell, 1996; Gonnermann and Manga, 2007). Eruptive activity can also sometimes be related to changes in the conduit structure, and particularly whether the magma plumbing system is open or closed to the atmosphere. Open conduit systems have an unrestricted connection between the magma reservoir and the surface, allowing the lava lake height to act as a pressure gauge (Patrick et al., 2015, e.g. Kılauea summit lava lake). Volcanoes that have a conduit geometry that prevents the free flow of gas and magma between the magma reservoir and the surface are known as closed conduit systems (Worster et al., 1993; Tazieff, 1994). Vulcanian eruptions, which are violent and short-lived, are thought to be due to the temporary closure of the conduit by a plug of cold, solidified magma in the conduit that allows for a build-up of pressure (Francis and Oppenheimer, 2004). These plugs are most commonly observed at silicic volcanoes, which have high viscosity magmas (Albino et al., 2011, e.g. Colima), but have also been found to form within basaltic volcanic systems (Lyons and Waite, 2011, e.g. Fuego). The presence of an ephemeral lava lake indicates that a volcano transitions between an open and closed conduit system (Tazieff, 1994), with the lake appearing or disappearing in a cyclic (periodic) or acyclic manner (Barker et al., 2003; Witham and Llewellin, 2006; Hirn et al., 2008).

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Masaya volcano in Nicaragua is an excellent example of a volcano that switches between effusive and explosive behaviour. It has a persistent high gas flux and contains an ephemeral lava lake, which suggests that the conduit system can transition between open and closed conditions. In this study, we used high temporal (1–14 days) resolution satellite data to capture transient conduit processes. COSMO-SkyMed (CSK) Synthetic Aperture Radar (SAR) acquisitions (ASI) were obtained over Masaya volcano during a period of explosive activity and no lava lake (30 April–17 May 2012). We present measurements of deformation at Masaya over 7 months spanning the explosive eruption. We use Finite Element Modelling (FEM) to investigate potential deformation source geometries and discuss potential deformation mechanisms.

1.1. Shallow deformation processes

Displacements caused by transient processes in volcanic conduits are localised and of short duration, and therefore are rarely captured by Interferometric Synthetic Aperture Radar (InSAR) (e.g. Wadge et al., 2006). A small number of studies have captured deformation and seismic signals caused by conduit processes, mostly through tiltmeter and broadband seismic measurements (Dzurisin et al., 1983; Chadwick et al., 1988; Rowe et al., 1998; Iguchi et al., 2008; Anderson et al., 2010; Voight et al., 2010; Albino et al., 2011; Lyons and Waite, 2011; Pinel et al., 2011; Lyons et al., 2012; Salzer et al., 2014; Mothes et al., 2015) (see Supplementary Table 1).

Models developed to explain ground deformation resulting from conduit processes involve changes in flow dynamics within the volcanic conduit, which generate shear and normal stresses (e.g. Chadwick et al., 1988; Bonaccorso and Davis, 1999; Beauducel et al., 2000; Green et al., 2006), and/or changes in surface loads due to dome growth or collapse (e.g. Beauducel et al., 2000). Early analytical models developed to describe inflation of a vertical conduit include a closed pressurised pipe, a dislocating pipe, and inflation-deflation patterns of a vertical conduit, which were shown to be due to the removal of a blockage within the pipe (Bonaccorso and Davis, 1999). Numerical experiments performed by Albino et al. (2011) to examine the deformation field due to plug evolution within a conduit showed that the contribution of magma conduit flow to the radial deformation field is only significant for distances of less than 0.2 of the conduit length (e.g. 200 m away from the vent for a 1 km length conduit), with almost negligible contribution to the vertical displacement field at distances greater than a few hundred meters from the vent.

In the case of plug emplacement within a conduit, there are 2 potential mechanisms for plug removal (Albino et al., 2011): (1) stick-slip transition resulting from changes in overpressure beneath the plug (Lensky et al., 2008) or brittle failure conditions of the magma (Collier and Neuberg, 2006), and (2) changes in conduit wall permeability that prevents lateral degassing and removes the plug either by reducing its length or its viscosity contrast (Edmonds et al., 2003; Iguchi et al., 2008).

1.2. Previous studies of pre-eruptive displacement

Deformation related to conduit processes has primarily been observed days to seconds before the onset of explosions (e.g. Dzurisin et al., 1983; Chadwick et al., 1988; Rowe et al., 1998; Anderson et al., 2010; Voight et al., 2010; Albino et al., 2011; Lyons and Waite, 2011; Iguchi et al., 2008; Salzer et al., 2014; Mothes et al., 2015). This has included inflation, marking a transition between an open and closed conduit, for example ~7 h before the start of eruptions at Colima (Salzer et al., 2014), but only a few seconds before the eruption at Erebus (Rowe et al., 1998). Another common feature at several volcanoes is contraction within the conduit prior to or at the onset of explosive activity (e.g. Voight et al., 2010; Iguchi et al., 2008; Lyons and Waite, 2011; Mothes et al., 2015). At Sakurajima, Semeru and Suwanesojima volcanoes, inflation occurred minutes before explosive activity, followed by contraction a few minutes to immediately before the explosions took place (Iguchi et al., 2008). Similarly, cycles of pressurisation-depressurisation prior to explosive activity have been observed at Soufrière Hills Volcano, at Mount St. Helens and at Fuego (Anderson et al., 2010; Voight et al., 2010; Lyons and Waite, 2011). The general interpretation of these pressurisation cycles is of plug emplacement and subsequent removal when the overpressure exceeded the plug strength. Plug ascent within the conduit has also been recorded by tiltmeters at elevation as an uplift-subsidence pattern (Mothes et al., 2015, e.g. Tungurahua). Other studies have found that shear stresses provide a better explanation for within the conduit radial displacements at Mount St. Helens (observation period 1981–1982), Mount Merapi and Soufrière Hills Volcano (Dzurisin et al., 1983; Chadwick et al., 1988; Beauducel et al., 2000; Green et al., 2006).

2. Geological setting of Masaya volcano

Masaya volcano (11.984N, 86.161W, 635 m) is a basaltic caldera located in south-western Nicaragua, and contains Masaya Lake, and several nested crater pits (namely San Pedro, Nindirí, Santiago, Masaya) and cones (namely Nindirí, Masaya) (Rymer et al., 1998; Delmelle et al., 1999; Williams-Jones, 2001; Duffell et al., 2003 see Fig. 1). Ring faults seen in an exposed section of the Nindirí crater pit dip outwards from the crater at an angle of ~80° (Rymer et al., 1998; Harris, 2009). The red dashed lines in Fig. 1 indicate the inferred location of a larger ring fault within the caldera, along which the most recent vents at Masaya are also located (Crenshaw et al., 1982; Rymer et al., 1998; Mauri et al., 2012; Caravantes Gonzalez, 2013; Zurek, 2016). The exact location and orientation of this larger ring fault, however, has not been well-constrained. Several profiles constructed using geophysical field methods (magnetics and Very Low Frequency (VLF) electromagnetics) suggest that the ring fault is inclined inwards into the caldera (Caravantes Gonzalez, 2013).

Masaya has atypical activity for the Central American Volcanic Arc (CAVA), including persistent high flux degassing, an ephemeral lava lake (located within the Santiago crater pit) and explosive activity with little to no magma extruded (McBirney, 1956; Rymer et al., 1998; Delmelle et al., 1999; Stix, 2007). Only 2 lava flows have erupted from Masaya since the 16th century, 1670 and 1772 (McBirney, 1956; Rymer et al., 1998). The high gas flux at Santiago crater suggests a high mass of overturning magma located beneath the crater (Rymer et al., 1998; Delmelle et al., 1999; Williams-Jones et al., 2003).

Masaya has rapidly transitioned between sudden explosive activity and quiescent degassing in the past (e.g. 23 April 2001 VEI 1 explosive eruption), and thus poses a hazard to tourists visiting the volcano (Global Volcanism Program, 2001). This increases the importance of using observational methods that can provide information on transient processes occurring within the ephemeral system.

2.1. Previous observations & structural interpretation

Previous studies of Masaya have proposed several subsurface geometries based on deformation, seismicity, gas geochemistry observations and geochemical methods, and geophysical techniques (self-potential, electromagnetic and potential field methods) (Table 1). The models agree that there is a shallow magma reservoir present below Masaya, with estimated depths ranging between 0.4–5 km below the active vent (Métaxian et al., 1997; Rymer et al., 1998; Williams-Jones et al., 2003). Early models from seismicity suggest an open system at Masaya, in which the source locations from permanent tremor indicate a shallow source at 400 m below