Earth and Planetary Science Letters 388 (2014) 166–174

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The influence of cooling, crystallisation and re-melting on the interpretation of geodetic signals in volcanic systems

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ARTICLE INFO

Article history:
Received 4 May 2013
Received in revised form 9 October 2013
Accepted 1 December 2013
Available online 24 December 2013
Editor: L. Stixrude

Keywords:
geodetic signals
petrology
thermal modelling

ABSTRACT

Deformation of volcanic edifices is typically attributed to the movement of magma within the volcanic plumbing system, but a wide range of magmatic processes are capable of producing significant volume variations and may also produce deformation. In order to understand the evolution of magmatic systems prior to eruption and correctly interpret monitoring signals, it is necessary to quantify the patterns and timescales of surface deformation that processes such as crystallisation, degassing and expansion of the hydrothermal system can produce. We show how the combination of petrology and thermal modelling can be applied to geodetic observations to identify the processes occurring in a magmatic reservoir during volcanic unrest. Thermal modelling and petrology were used to determine the timescales and volumetric variations associated with cooling, crystallisation and gas exsolution. These calculations can be performed rapidly and highlight the most likely processes responsible for the variation of a set of monitoring parameters. We then consider the magnitude and timescales of deformation produced by other processes occurring within the vicinity of an active magma system. We apply these models to a time series of geodetic data spanning the period between the 1997 and 2008 eruptions of Okmok volcano, Aleutians, examining scenarios involving crystallisation, degassing and remelting of the crystallising shallow magmatic body and including a viscoelastic shell or hydrothermal system. The geodetic observations are consistent with the injection of a water-saturated basalt, followed by minor crystallisation and degassing. Other scenarios are not compatible either with the magnitude or rate of the deformation signals.

1. Introduction

Driven by the increasing availability of satellite technology such as InSAR and GPS, the number of volcanoes for which geodetic measurements exist is growing rapidly, as is the spatial and temporal resolution of those measurements (e.g. Sparks et al., 2012). The global catalogue of volcanoes known to be deforming now exceeds one hundred (Fournier et al., 2010), but remarkably few of these fit simple cycles of magma chamber recharge and discharge within an elastic medium. A new paradigm is required. In this paper, we couple existing thermal models with petrologic constraints to estimate the contributions of crystallisation and degassing on the magnitude and time scales of surface deformation. We then consider the timescale and magnitude of other processes, such as perturbation of the hydrothermal system and evolution of the physical properties of the crust, which are known to play a role in controlling deformation in regions of active volcanism.

Of over a hundred volcanoes known to be deforming, roughly twenty volcanoes are thought to be undergoing long-term subsidence (Table 1). This has been attributed to the cooling and crystallisation of magma bodies (e.g. Medicine Lake; Poland et al., 2006) or associated hydrothermal activity (e.g. Kiska; Lu et al., 2010; Lu and Dzurisin, 2010). Sudden pulses of uplift are typically linked to magmatic intrusions (e.g. Three Sisters; Wicks, 2002), but discrete pulses of subsidence (e.g. Suswa; Biggs et al., 2009) are more challenging to explain. In several cases, exponentially decaying subsidence is observed immediately following pulses of inflation (e.g. Okmok; Fournier, 2008; Fournier et al., 2009; Alutu; Biggs et al., 2011). The diversity of these observations illustrates that we must consider not only the spatial pattern and magnitude of the deformation, but also its temporal evolution if we are to identify the processes driving volcanic unrest.

In this paper, we use Okmok volcano, Alaska (Fig. 1A) as a case study because a 15-year geodetic record including InSAR, continuous and campaign GPS measurements is available. The time series, shown in Fig. 1B, covers major eruptions in 1997 and 2008 and provides detailed time-series of inter-eruptive deformation

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0012-821X/$ – see front matter
http://dx.doi.org/10.1016/j.epsl.2013.12.002

Table 1
Global compilation of subsiding volcanoes.

Volcano	Method and coverage	Rate (cm/yr)	Diameter (km)	Inferred depth (km)	References
Aniakchak	I: 92–02	1.3 (const.)	10	∼4	Kwoun et al., 2006
Askja	L: 83–98 G: 93–98 I: 92–00	5 (83–98), 2.5–3.0 (00–09), decaying	<25	3.2–3.8	Sturkell et al., 2006; Pagli et al., 2006; de Zeeuw-van Dalfsen et al., 2012
Campi Flegrei	G: 85–05 I: 93–96	1.4–2.8, (decaying 1985–)	∼12	2–4.2	Fernandez et al., 2001; Lundgren et al., 2001; Gottsmann et al., 2006.
Cerro Blanco	I: 92–00	1.8–2.5 (decaying)	<30	<4.8	Pritchard and Simons, 2004
Copahue*	I: 02–08	2 (const.)	2–3	∼4	Euillades et al., 2008; Fournier et al., 2010; Velez et al., 2011
Fisher Caldera	G: 99–01	–	>10	>1.6	Mann and Freymueller, 2003
Kiska*	I: 95–01	1.6	3	<1	Lu et al., 2002
Krafla	L: 89– G: 93–95 G: 00–05 I: 92–	5 (89–92) 0.3 (00–05)	∼10	1.5–2.5	Sigmundsson et al., 1997; de Zeeuw-van Dalfsen et al., 2006; Sturkell et al., 2008
Medicine Lake	G: 96–04 L: 54, 89, 90, 99 I: 93–00	∼0.9–1.2	∼12	–	Dzurisin et al., 2002; Poland et al., 2006
Sakurajima	L	∼0.1 (79–)	Oct-20	–	Dvorak and Dzurisin, 1997; Mogi, 1958; Yokoyama, 1986.
Okmok	I: 92–12 G: 00–12	Variable (Fig. 1)	∼8	03-Apr	Miyagi et al., 2004; Lu et al., 1998, 2000, 2005, 2010; Lu and Dzurisin, 2010; Mann et al., 2002; Fournier et al., 2009; Biggs et al., 2010

The table lists the details of the observation method and temporal coverage, the rate and temporal behaviour of the subsidence, the diameter of the deformation pattern and the estimated source depth. Okmok volcano is given for comparison. G—GPS, I—InSAR, L—Leveling. * refers to volcanoes at which the deformation has been attributed to hydrothermal processes.

(Lu et al., 2010; Lu and Dzurisin, 2010; Fournier et al., 2009; Biggs et al., 2010). The petrology of this system is well characterised, which is fundamental for quantifying the volumetric variations associated with crystallisation and eventual exsolution of volatiles from the residual melt phase.

Following a magma intrusion, each part of a magma body will experience a unique cooling history depending on the depth of emplacement, thermal state of the crust, and magma composition, which ultimately controls the variation of crystallinity and volume with decreasing temperature. Cooling leads to magma crystallisation and because minerals are generally denser than the melt from which they crystallise, to a decrease in volume (Lange, 1994). The rate of crystallisation, and therefore of volumetric variation, is a function of the shape, area and volume of the cooling magma intrusion, the thermal state of the surrounding rocks and the amount of latent heat released during crystallisation. Hence thermal modelling is necessary to calculate the appropriate rates of magma contraction or expansion that could be the source of deformation observed in volcanic systems. In volatile bearing magmas, crystallisation is accompanied by a relative enrichment of volatiles in the residual melt. Once the saturation limit is reached, volatiles exsolve from the residual melt generating gas bubbles (second boiling) and leading to a volumetric increase of the crystallising magma. The variations of magma density during cooling control the rate and magnitude of volumetric variation and thus surface deformation. Any model of subsidence in a magmatic system must therefore incorporate not only appropriate thermal models, but also petrological information on the relationships between temperature and melt/crystal/volatile fractions.

Here we focus on three scenarios that could be envisaged to explain the sequence of inflation and deflation signals observed at Okmok between 1997 and 2008: (1) injection of basalt in the country rock followed by crystallisation; (2) injection of H_2O bearing basalt followed by cooling and degassing; (3) interaction between the injected H_2O bearing basalt and a partially crystallised andesitic magma that may be present in the system as a residuum of previous eruptions (Finney et al., 2008). Here crystallisation, melting and gas exsolution are considered to have only volumetric effects:

(1) In the first scenario, cooling of a volatile-undersaturated magma produces volumetric contraction with an associated subsidence rate that can vary depending on the ratio between the density of the crystallising phases and the density of the residual melt along the crystallisation sequence, the shape and dimensions of the magma intrusion, the magma composition and the thermal state of the crust.
(2) If the magma present in a reservoir is volatile saturated, crystallisation leads to the exsolution of gas bubbles, which, in turn, within years, results in an inflation signal not related to magma injection and eventual subsidence if the system becomes permeable and gas can be expelled from the subvolcanic reservoir.
(3) For the last scenario, the injection of a volatile-saturated magma into a crystal mush can potentially cause partial re-melting of the host. In this case, volatiles released from the injected magma can potentially be resorbed by the volatile-undersaturated melt produced by re-melting. The result is inflation (exsolution) followed by subsidence (resorption) but no significant degassing observable at the surface.

In the following, we show how geodetic measurements, detailed petrology, and thermal modelling can be combined to identify the most likely processes occurring in a magmatic reservoir