Earth and Planetary Science Letters 439 (2016) 58–70

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Tracking timescales of short-term precursors to large basaltic fissure eruptions through Fe–Mg diffusion in olivine

Margaret E. Hartley[a,b,*], Daniel J. Morgan[c], John Maclennan[b], Marie Edmonds[b], Thor Thordarson[d]

[a] School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[b] Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK
[c] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[d] Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland

ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 13 January 2016
Accepted 14 January 2016
Available online 3 February 2016
Editor: T.A. Mather

Keywords:
olivine
diffusion
crystal mush
CO_2 outgassing
Laki
Iceland

ABSTRACT

Petrological constraints on the timescales of pre-eruptive crystal storage and magma degassing provide an important framework for the interpretation of seismic, geodetic and gas monitoring data in volcanically active regions. We have used Fe–Mg diffusion chronometry in 86 olivine macrocrysts from the AD 1783–1784 Laki eruption on Iceland's Eastern Volcanic Zone to characterise timescales of crystal storage and transport in the lead-up to this eruption. The majority of these olivines have core compositions of Fo < 76, and rim compositions in the range Fo_{69}–Fo_{74} that are close to equilibrium with the Laki melt. Diffusion modelling using the greyscale intensity of backscattered electron images as a proxy for olivine composition reveals that the most probable Fe–Mg diffusion timescale for Laki olivines is 7.8 days, which reflects the characteristic olivine residence time in the carrier melt prior to eruption. A small population of Fo > 81 olivines record Fe–Mg diffusion timescales of ∼124 days; these crystals are likely to have formed in mid-crustal magma chambers, been transferred to storage at shallower levels and then entrained into the Laki melt prior to eruption. Typical Fe–Mg diffusion timescales of 6–10 days are shorter than the average time interval between discrete episodes of the Laki eruption, indicating variable or pulsed disaggregation of stored crystals into the carrier liquid prior to the onset of each episode. The diffusion timescales coincide with historical accounts of strong and frequent earthquakes in southeast Iceland, which we interpret as being associated with mush disaggregation related to melt withdrawal and the initiation of dyke propagation from a crustal magma reservoir at $\sim 6 \pm 3$ km depth to the surface. We calculate pre-eruptive CO_2 fluxes of 2–6 Mt d^{-1}, assuming a pre-eruptive CO_2 outgassing budget of 189.6 Mt for the Laki eruption and a constant rate of CO_2 release in the 6–10 days preceding each eruptive episode. Our dataset indicates that petrological constraints on the timescales of magmatic processes occurring in the days leading up to historic eruptions may enhance our ability to forecast the onset of future large eruptions, both in Iceland and further afield.

1. Introduction

Many active volcanoes exhibit significant changes in seismicity, ground deformation and gas release in the hours, days and weeks preceding an eruption. One of the principal challenges in modern volcanology is to interpret these signs of volcanic unrest in terms of subsurface processes such as the pre-eruptive storage, transport and degassing of magma. Over the past decade, diffusion chronometry in zoned magmatic crystals has become an indispensable tool for recovering the timescales over which these processes occur (e.g. Costa et al., 2008; Costa and Morgan, 2010). The re-equilibration of different elements across compositional zones can be used to map the passage of crystals through complex magmatic systems, thereby gaining insight into different aspects of magma genesis. Similarly, because different elements diffuse through crystals at different rates, diffusion chronometry is able to recover timescales ranging from minutes to tens or hundreds of years.

Perturbations in the composition, volatile content, temperature, pressure and oxidation state of the magmatic environment are often reflected in the compositional zonation of magmatic crystals, as the equilibrium crystal chemistry responds to these chang-

* Corresponding author at: School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL, UK.
E-mail address: margaret.hartley@manchester.ac.uk (M.E. Hartley).

http://dx.doi.org/10.1016/j.epsl.2016.01.018

ing magmatic variables. If the responses in crystal chemistry to these magmatic variables are known, either through thermodynamic or experimental models, then the compositional changes across discrete crystal zones can be linked with the magmatic processes responsible for the zonation. By modelling the relaxation of these compositional changes with diffusion chronometry, it is possible to constrain the timescales over which the processes that created the zonation are occurring. This method has been successfully used to determine characteristic crystal residence timescales and magma recharge rates in various volcanic settings, using Sr, Mg and Li diffusion in plagioclase (Zellmer et al., 1999; Costa et al., 2003; Martin et al., 2010; Charlier et al., 2012; Druitt et al., 2012; Saunders et al., 2010); Ba diffusion in sanidine (Morgan et al., 2006); Ni diffusion in olivine (Ruprecht and Plank, 2013); and Fe–Mg diffusion in olivine (Gerlach and Grove, 1982; Costa and Chakraborty, 2004; Martin et al., 2008; Ruprecht and Plank, 2013), clinopyroxene (Morgan et al., 2004; Costa et al., 2013) and orthopyroxene (Allan et al., 2013).

Petrological records of magmatic processes can also be temporally linked with contemporaneous monitoring records in the lead-up to eruptions. Links between petrological observations and seismic, geodetic and/or gas monitoring records have been inferred for eruptions at Mt St Helens (Saunders et al., 2012); Etna (Kahl et al., 2011, 2013) and Ruapehu (Kilgour et al., 2014). Evidence of strong links between diffusion chronometry in magmatic crystals and contemporaneous monitoring records indicates that petrologically determined timescales of magma ascent, mixing and degassing may provide an important framework for the interpretation of seismic, geodetic and gas monitoring data in regions where the last known volcanic eruption occurred before the advent of modern monitoring techniques. One such region is the Laki–Grímsvötn system on Iceland's Eastern Volcanic Zone (EVZ). The most magmatically productive of Iceland's neovolcanic zones, the EVZ accounts for 82% (~71 km^3) of the magma volume erupted in Iceland since its settlement in AD 874 (Thordarson and Larsen, 2007). Magmatism on the EVZ over the Holocene period has been typified by flood lava eruptions (>1 km^3), which include the 8.6 ka Thjorsárhraun, AD 934–938 Eldgjá and AD 1783–1784 Laki eruptions (e.g. Thordarson et al., 2003b; Thordarson and Höskuldsson, 2008). These large-volume, long-lived eruptions have historically produced significant global climatic, environmental and societal impacts (e.g. Thordarson et al., 1996; Larsen, 2000; Thordarson et al., 2001; Thordarson and Self, 2003; Chenet et al., 2005; Oman et al., 2006; Fei and Zhou, 2006; Schmidt et al., 2010), and similar effects may be expected in the event of future flood lava eruptions (Schmidt et al., 2011).

In this study, we use diffusion chronometry to characterise the timescales of crystal storage and transport in the lead-up to the AD 1783 Laki eruption. By comparing petrologically constrained timescales with historical accounts of seismic unrest in the days and weeks preceding eruption onset, we assess the utility of petrological data in interpreting seismic and gas flux monitoring signals in Iceland's Eastern Volcanic Zone.

2. The AD 1783–1784 Laki eruption

The AD 1783–1784 Laki eruption is one of the best-documented small-scale analogues of a flood basalt eruption (e.g. Thordarson and Self, 1993; Thordarson et al., 2003a). Historical accounts report that the eruption was preceded by weak seismicity between 15 and 29 May 1783, and by stronger and more frequent earthquakes between 29 May and 8 June 1783. The eruption began on 8 June 1783 with an explosive event on a short fissure; four days later, lava flows from the Laki vents had reached the lowlands, ~35 km away. Lava continued to flow, with variable magma discharge rates from the vents, until the end of the eruption on 7 February 1784 (Thordarson et al., 2003a). Over the eight months of the eruption, a total of 14.7 km^3 of basaltic lava and ~0.4 km^3 dense rock equivalent of tephra was erupted from the 27 km-long Laki fissure.

The Laki fissure is marked by scoria and spatter cones that define 10 *en echelon* fissure segments which opened sequentially from SW to NE over the course of the eruption. The opening of each fissure segment is considered to be a distinct eruptive episode (Thordarson and Self, 2003). Episodes I–V correspond to the five fissure segments located to the southwest of Laki Mountain, from which the eruption gets its name; episodes VI–X correspond to fissure segments northeast of Laki Mountain. Historical accounts of the eruption report that many of the episodes were preceded by seismic swarms, with earthquake strength and frequency increasing immediately before the opening of each new fissure (Thordarson et al., 2003a). Each episode is thought to have commenced with a short period of explosive activity of sub-Plinian intensity, followed by Hawaiian fire fountaining and lava effusion. The eruptive episodes have been interpreted in terms of variable magma supply rates to the Laki vents (Thordarson and Self, 1993). The chronology of the eruption, reconstructed from the examination of historical accounts and field studies of the preserved volcanic stratigraphy, is summarised in Fig. 1.

2.1. Magmatic mush entrainment at Laki

Whole-rock compositions of Laki lava and tephra samples vary linearly with the total mass fraction of macrocrysts, where the term 'macrocryst' refers to crystals larger than the groundmass and within the size interval ~0.2–10 mm. Samples with the lowest incompatible element concentrations have the highest mass fraction of macrocrysts. This correlation has been explained by the disaggregation and entrainment of a crystal mush into the Laki carrier liquid prior to eruption (Passmore et al., 2012). The importance of disaggregation and entrainment of crystal mushes into magmatic liquids has been explored in a number of recent studies (e.g. Gurenko and Sobolev, 2006; Costa and Morgan, 2010; Thomson and Maclennan, 2013; Moore et al., 2014), several of which have focused on Iceland's Eastern Volcanic Zone (Hansen and Grönvold, 2000; Holness et al., 2007; Halldorsson et al., 2008; Neave et al., 2014).

Geochemical analysis of the Laki crystal cargo, coupled with high-resolution analyses of compositional variability in individual macrocrysts, has provided a detailed record of the processes operating within the Laki magmatic system (Neave et al., 2013). Clinopyroxene-liquid thermobarometry indicates that the bulk of olivine, plagioclase and clinopyroxene crystallisation took place at mid-crustal pressures of 2–5.4 kbar, which is in good agreement with calculated saturation pressures of high-CO_2 (>1500 ppm CO_2) melt inclusions (Hartley et al., 2014). Macrocrysts, and mono- and polymineralic glomerocrysts, are typically surrounded by evolved crystal rims with compositions close to equilibrium with the Laki carrier liquid. These textures imply the formation of polymineralic mushes in the mid-crust, which were then disaggregated and transported to shallower levels where rim crystallisation occurred. The signature of mush addition identified by Passmore et al. (2012) is likely to have been generated at the final depth of equilibration between the melt and the observable rims of olivine, clinopyroxene and plagioclase crystals (Neave et al., 2013). Melt barometry calculations indicate that this occurred at 2 ± 1 kbar (Neave et al., 2013), but it is not clear whether these pressures represent equilibrium crystallisation as magma temporarily stalled in the shallow crust, or dynamic growth of crystal rims during magma ascent from deeper levels.

The proportion of mush crystals entrained into the Laki carrier liquid is thought to vary over the course of the eruption. Erupted products from episodes VI–X contain larger average mass fractions