

## Degassing-driven crystallisation in basalts

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### ABSTRACT

Syn-eruptive crystallisation can drastically increase magma viscosity, with profound implications for conduit dynamics, lava emplacement and volcanic hazards. There is growing evidence that crystallisation is not only cooling-driven, but can also occur almost isothermally during decompression-induced degassing on ascent from depth. Here we review field and experimental evidence for degassing-driven crystallisation in a range of magma compositions. We then present new results showing, for the first time, experimental evidence for this process in basaltic magma.

Our experiments use simultaneous thermogravimetric analysis and differential scanning calorimetry coupled with mass spectrometry (TGA-DSC-MS) to monitor degassing patterns and thermal events during heating and cooling of porphyritic basaltic samples from Mt. Etna, Italy. The partly degassed samples, which contained 0.39–0.81 wt.% total volatiles in the glass fraction, were subjected to two cycles of heating from ambient to 1250 °C. On the first heating, TGA data show that 30–60% of the total volatiles degassed slowly at <1050 °C, and that the degassing rate increased rapidly above this temperature. DSC data indicate that this rapid increase in the degassing rate was closely followed ( $\leq 3.4$  min) by a strongly exothermic event, which is interpreted as crystallisation. Enthalpies measured for this event suggest that up to 35% of the sample crystallises, a value supported by petrographic observations of samples quenched after the event. As neither degassing nor crystallisation was observed at high temperature during the second heating cycle we infer that the events on first heating constitute degassing-driven crystallisation. The rapidity and magnitude of the crystallisation response to degassing indicates that this process may strongly affect the rheology of basaltic magma in shallow conduits and lava flows, and thus influence the hazards posed by basaltic volcanism.

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## 1. Introduction

Magma rheology is of critical importance in determining the eruptive style of volcanoes, and hence the potential volcanic hazards. Rheology depends on many factors, including composition, temperature, volatile content, vesicularity and crystallinity. The crystallisation of magma can result from cooling or from decompression-induced degassing. Volatile loss raises the magma liquidus temperature to produce an undercooling (e.g. Sparks and Pinkerton, 1978; Hort, 1998), the magnitude of which depends on the extent of degassing. Undercooling drives crystallisation, and the magnitude of the undercooling strongly controls the rate of crystal nucleation (Paul, 1990) and the resulting crystal morphology (Lofgren, 1974, 1980; Kirkpatrick, 1975). Degassing and crystallisation can have competing effects on magma rheology. Because degassing is an endothermic process, it can act to cool the magma (Richet et al., 2006), thus increasing the melt viscosity. The loss of water and the crystallisation of mafic phases will result in increased melt polymerisation, so will also increase the viscosity. Increasing crystal contents lead first to increased bulk viscosity, then to yield strength development. Conversely, the release of latent heat during crystallisation may increase the overall magma temperature by several tens of degrees (Couch et al., 2003; Blundy et al., 2006), thus reducing bulk viscosity.

Observations of volcanic eruptions and eruption products with a wide range of compositions have confirmed that syn-eruptive degassing-driven crystallisation can influence eruption dynamics by profoundly altering a magma's texture and thus its multiphase rheology (Lipman et al., 1985; Swanson et al., 1989; Cashman, 1992; Crisp et al., 1994; Hammer et al., 1999; Cashman and Blundy, 2000; Sparks et al., 2000; D'Oriano et al., 2005; Riker et al., 2009).

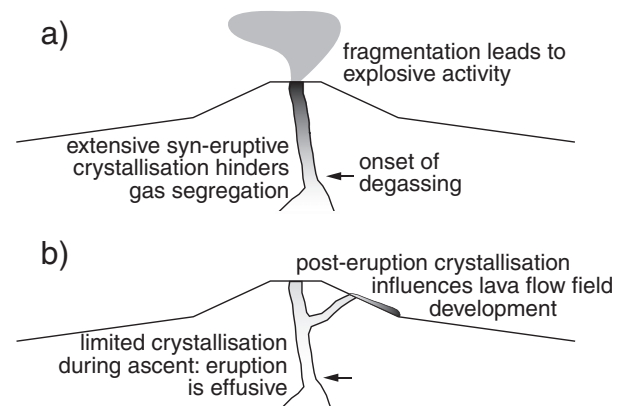
### 1.1. Previous studies of degassing-driven crystallisation

Degassing-driven crystallisation has been studied in the laboratory using decompression quenching experiments on natural and synthetic samples of rhyodacitic to basaltic composition (Geschwind and Rutherford, 1995; Hammer and Rutherford, 2002; Couch et al., 2003; Simakin and Salova, 2004; Szramek et al., 2006; Brugger and Hammer, 2010). Delays were observed between the generation of the undercooling and the onset of crystal nucleation in rhyodacitic to andesitic compositions. The lag times, which were of the order 4.5–49 hours for rhyodacites (decompression rates 10–0.5 MPa h<sup>-1</sup>; Brugger and Hammer, 2010) and 1–4 hours for andesites (decompression rates 110–0.1 MPa h<sup>-1</sup>; Couch et al., 2003), occur due to kinetic constraints on diffusion in the melt. Because of the compositional dependence of viscosity and diffusivity, lag times are expected to be shorter in melts with lower silica contents (Donaldson, 1979). Lags were not reported for decompression experiments on basalts (Simakin and Salova, 2004), where experimental durations were 10–225 minutes, implying that lag times are minimal or zero in basaltic melts.

The importance of degassing-driven crystallisation in influencing magma textures and behaviour at silicic volcanoes is well documented (e.g. Swanson et al., 1989; Cashman and Blundy, 2000; Sparks et al., 2000; Melnik and Sparks, 2002), and examples of degassing-driven crystallisation have been reported from several basaltic volcanoes. During the 1984 eruption of Mauna Loa, Lipman et al. (1985) observed a

20% increase in crystallinity at the vent over the first 5 days of the eruption, while the lava remained isothermal and compositionally uniform. This increase in crystallinity was inferred to result from degassing in the shallow rift zone, and may have been responsible for moderating effusion rates during the eruption (Lipman et al., 1985). Relatively recently, Plinian eruption products with basaltic composition have been identified in the geological record (Williams, 1983; Walker et al., 1984; Coltelli et al., 1998). This phenomenon has been explained by invoking rapid degassing-driven crystallisation to increase melt viscosities and alter degassing behaviour (Sable et al., 2006, 2007; Goepfert and Gardner, 2010). Most basaltic eruptions are dominated by open system degassing, so are usually only weakly explosive (Houghton et al., 2004). A rapid increase in crystallinity due to syn-eruptive degassing could increase magma viscosity sufficiently to keep the gas fraction coupled to the magma during ascent, producing a change from open- to closed-system degassing, thus allowing explosive fragmentation. Basaltic Plinian eruptions represent the most extreme consequence of degassing-driven crystallisation, but closed-system degassing can also result in a range of smaller-scale, ash-rich explosive behaviours (Taddeucci et al., 2004; Andronico et al., 2009). Changes between open- and closed-system degassing have been used to explain behavioural transitions during a number of basaltic eruptions (Kuritani, 1999; Cervantes and Wallace, 2003; Guilbaud et al., 2007; Houghton and Gonnermann, 2008).

Syn-eruptive degassing has the potential to strongly affect volcanic behaviour depending on the timescale, hence location, of significant degassing-driven crystallisation (Fig. 1). This process may have the greatest impact at basaltic volcanoes, which usually erupt effusively. Significant crystallisation of basaltic magma during ascent from depth could hinder degassing, resulting in a considerably and unexpectedly explosive eruption (Houghton and Gonnermann, 2008; Fig. 1a). If



**Fig. 1.** Sketch showing possible effects of degassing-driven crystallisation on volcanic behaviour, depending on the timing and hence location of crystallisation. Degassing is assumed to occur at the same depth in both scenarios (arrow). Shading indicates crystallinity, with darker colours representing higher crystal content. (a) If crystallisation occurs soon after degassing, significant rheological change could occur in the conduit, hindering gas segregation and resulting in magma fragmentation, and explosive activity. (b) If crystal nucleation and growth are delayed until after eruption, activity will be effusive, and the consequent rheological changes will instead play a role in determining the evolution of the lava flow field.

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