In situ thermal characterization of cooling/crystallizing lavas during rheology measurements and implications for lava flow emplacement

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Abstract

Transport properties of natural silicate melts at super-liquidus temperatures are reasonably well understood. However, migration and transport of silicate melts in the Earth's crust and at its surface generally occur at sub-liquidus temperatures and in settings where the melts undergo crystallization under various cooling and/or decompression conditions. In such dynamic situations the occurrence of processes such as the release of latent heat during phase changes, viscous heating, thermal advection and -inertia, and changing heat capacity, all represent potential influences on the state, and thereby on the physico-chemical behavior of the system. To date, rheological data at sub-liquidus temperatures are scarce and cooling-rate dependent, disequilibrium rheological data are virtually absent. In fact, no *in situ* thermal characterization of liquid or multiphase mixtures during rheological experiments, under either static or dynamic thermal conditions has been presented to date.

Here we describe a new experimental setup for *in situ* thermal characterization of cooling/crystallizing lavas *during* viscosity measurement at temperatures up to 1600 °C. We use this device to recover *in situ*, real-time, observations of the combined rheological and thermal evolution of natural, re-melted lava samples during the transient disequilibrium conditions characteristic of lava flows and shallow crustal magma migration and storage systems in nature.

We present the calibration procedure and the method employed to recover the thermal evolution of an experimental sample during flow in varying shear regimes, assess the experimental uncertainty and show the ability of the apparatus to measure the release of latent heat of crystallization during transient rheological experiments. We further report the results from a first experimental study on the rheological and thermal evolution of a basaltic lava undergoing continuous cooling at a series of different cooling rates and discuss the implications of the results for magma migration and lava flow emplacement.
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1. INTRODUCTION

1.1. Disequilibrium transport conditions in natural environments

The rheology of lava and magma is one of the key parameters governing the emplacement of lava flows and the migration of melts in the Earth's crust. Both pāhoehoe and 'A'ā flows are spatially restricted in their flow paths by the increasing strength of a growing crust, and/or high viscosity zone (Calvari and Pinkerton, 1998; Kauahikaua et al., 1998; Hon et al., 2003; Cashman et al., 2013; Castruccio and Contreras, 2016). The influence of the dynamic rheology of lava on its style of emplacement becomes especially evident in the late stages of the flow, where its resistance to flow becomes stronger and its exterior is subjected to folding and fracturing. Viscosity gradients resulting from the differential cooling of the lava surface and its interior play a significant role in the generation of flow-directing features like levees and lava tubes (Sparks et al., 1976; Lipman and Banks, 1987) as well as the sealing of dikes through heat loss at the contact with the country rock (Giordano et al., 2007).

Measurements of the flow properties of natural lavas in the field have been previously reported in the literature (Shaw et al., 1968; Pinkerton and Sparks, 1978; Pinkerton and Norton, 1995). Albeit being crucial measurements for benchmarking of experimental data, these do not allow for a systematic study on the evolution of flow properties in temperature or shear rate space.

Maximum temperatures in lava flows and active lava tubes may reach beyond 1280 °C (Flynn and Mouginis-Mark, 1994; Kauahikaua et al., 1998). Such extreme temperatures, seemingly unexpected for lavas commonly erupting at lower temperatures (generally between 1100 and 1200 °C and below), may be reached through combustion of gases released by the magma (Peterson and Swanson, 1974; Kauahikaua et al., 1998) or by viscous heating (Costa and Macedonio, 2005b).

Cooling rates of basaltic lavas, measured at the surface and within active lava channels during emplacement at a variety of locations (dominantly Hawaii, due to the relatively easy access and availability of supporting infrastructure), range from 0.01 to 15 °C/min (Flynn and Mouginis-Mark, 1992; Hon et al., 1994; Cashman et al., 1999; Witter and Harris, 2007). Cooling rates have also been evaluated through theoretical studies based on the flow geometry and crystal structures of komatiites lavas at 1–21 °C/min (Huppert et al., 1984). These values, most of which are representative for the exterior part of lava flows, can be taken as maximum cooling rates and are lower in the interior of the lava flow.

Narrow and shallow dikes may undergo cooling rates from few degrees per hour to more than 50 K/min, as the magma is introduced into a fracture; see Giordano et al. (2007) for the case of the Nyiragongo 2002 eruption. Cooling rates then decrease as a function of the size of the dike and time. After the transient stages (a few hours) magma in narrow dikes undergo cooling rates of the order of ca. 5 K/min or less.

The importance of *disequilibrium* effects on the crystallization kinetics and textural development of silicate melts has been recognized for decades (Walker et al., 1976; Pinkerton and Sparks, 1978; Coish and Taylor, 1979; Gamble and Taylor, 1980; Lofgren, 1980; Long and Wood, 1986; Hammer, 2006; Giordano et al., 2007; Arzilli and Carroll, 2013; Vetere et al., 2013). Yet, only a few experimental studies investigating the cooling- or shear-rate dependence of the transport properties of crystallizing silicate melts have been presented to date (Shaw et al., 1968; Kouchi et al., 1986; Ryerson et al., 1988a; Giordano et al., 2007).

In this manuscript we present viscosity measurements and differential thermal analysis data from experiments carried out under disequilibrium, mimicking natural conditions. The goal is to more accurately describe the flow properties of lavas and magmas under dynamic thermal conditions, pertinent to nature.

1.2. Experimental measurements of subliquidus rheology in magmatic systems

Concentric cylinder viscometry represents a widely-applied technique for measuring the viscosity of silicate melts at super-liquidus temperatures (Dingwell and Virgo, 1988; Dingwell, 1989; Webb and Dingwell, 1990; Mauro et al., 2009). In combination with either low temperature measurements, e.g. via micro-penetration viscometry (Hess et al., 1995; Hess and Dingwell, 1996) or estimation of the melt viscosity by application of a shift factor to scanning calorimetry data (Stevenson et al., 1995; Gottsmann et al., 2002; Giordano et al., 2008a), these data can be used to interpolate the temperature-dependent viscosity of a pure liquid at sub-liquidus temperatures (Hess et al., 1995; Hess and Dingwell, 1996; Gottsmann et al., 2002; Russell et al., 2002, 2003; Hui and Zhang, 2007; Giordano et al., 2008a). Recent studies have applied these experimental methods to measure the rheological evolution of silicate melts subjected to isothermal sub-liquidus conditions, where crystallization takes place (Ryerson et al., 1988a; Stein and Spera, 1992; Hoover et al., 2001; Sato, 2005; Ishibashi and Sato, 2007; Ishibashi, 2009; Vona et al., 2011, 2013; Robert et al., 2014; Sehlke et al., 2014; Chevrel et al., 2015; Sehlke and Whittington, 2015; Campagnola et al., 2016; Soldati et al., 2016). However, non-isothermal rheological data on natural melts are virtually absent in the literature.

Concentric cylinder viscometry uses the torque exerted by the liquid on a spindle inserted into a melt while rotated at a constant rate to determine the viscosity of the sample. Accurate calibration of temperature measurements at these experimental conditions ($P = 1$ atm; $T = \sim 900$–1600 °C) requires the insertion of a thermocouple (commonly PtRh Type S or B) into the sample. To date, this has been hindered in rotational viscometry, as data transmission relied on wired connections, compromising the highly sensitive torque measurement needed for accurate viscosity determination.

In temperature-stepping experiments (i.e. stepping between isothermal conditions) this issue can be overcome by calibrating the sample temperature against the furnace