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Lava flow rheology: A comparison of morphological and petrological methods

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ABSTRACT

In planetary sciences, the emplacement of lava flows is commonly modelled using a single rheological parameter (apparent viscosity or apparent yield strength) calculated from morphological dimensions using Jeffreys' and Hulme's equations. The rheological parameter is then typically further interpreted in terms of the nature and chemical composition of the lava (e.g., mafic or felsic). Without the possibility of direct sampling of the erupted material, the validity of this approach has remained largely untested. In modern volcanology, the complex rheological behaviour of lavas is measured and modelled as a function of chemical composition of the liquid phase, fractions of crystals and bubbles, temperature and strain rate. Here, we test the planetary approach using a terrestrial basaltic lava flow from the Western Volcanic Zone in Iceland. The geometric parameters required to employ Jeffreys' and Hulme's equations are accurately estimated from high-resolution HRSC-AX Digital Elevation Models. Samples collected along the lava flow are used to constrain a detailed model of the transient rheology as a function of cooling, crystallisation, and compositional evolution of the residual melt during emplacement. We observe that the viscosity derived from the morphology corresponds to the value estimated when significant crystallisation inhibits viscous deformation, causing the flow to halt. As a consequence, the inferred viscosity is highly dependent on the details of the crystallisation sequence and crystal shapes, and as such, is neither uniquely nor simply related to the bulk chemical composition of the erupted material. This conclusion, drawn for a mafic lava flow where crystallisation is the primary process responsible for the increase of the viscosity during emplacement, should apply to most of martian, lunar, or mercurian volcanic landforms, which are dominated by basaltic compositions. However, it may not apply to felsic lavas where vitrification resulting from degassing and cooling may ultimately cause lava flows to halt.

1. Introduction

Morphological dimensions of lava flows are commonly used in planetary sciences to infer the rheological properties (viscosity, yield strength) of the erupted material, which are in turn used to estimate the silica content of the lava. Simple isothermal models of lava flow emplacement have been used to extract these properties, and the assumption has typically been made that lava flows have a single viscosity value. At first, Nichols (1939) proposed the Jeffreys' equation (Jeffreys, 1925) to calculate the viscosity of a lava flow from its dimensions assuming that it exhibits a Newtonian response. Recognising that lava may no longer behave as a Newtonian fluid as it cools, but may follow a Bingham law, a method was later proposed by Hulme (1974) to estimate the lava yield strength from its morphological dimensions. Experiments with analogue materials having a known rheological behaviour confirm that the morphology of a lava flow may be used to infer the rheology (e.g., Fink and Griffiths, 1992; Gregg and Fink, 1996, 2000; Lyman et al., 2004). Furthermore, according to the studies of Walker et al. (1973), Hulme (1974) and Pinkerton and Wilson (1994), and Moore et al. (1978), some linear relationship can be drawn between the viscosity or the yield strength and the bulk silica content. In recent decades, with the release of high-resolution images and topographic data of planetary surfaces, in particular for Mars, this approach has been largely used (e.g., Zimbelman, 1985, 1998; Wilson and Head, 1994; Baloga et al., 2003; Glaze et al., 2003; Glaze and Baloga, 2006; Hiesinger et al., 2007; Vaucher et al., 2009; Wilson et al., 2009; Hauber et al., 2011;

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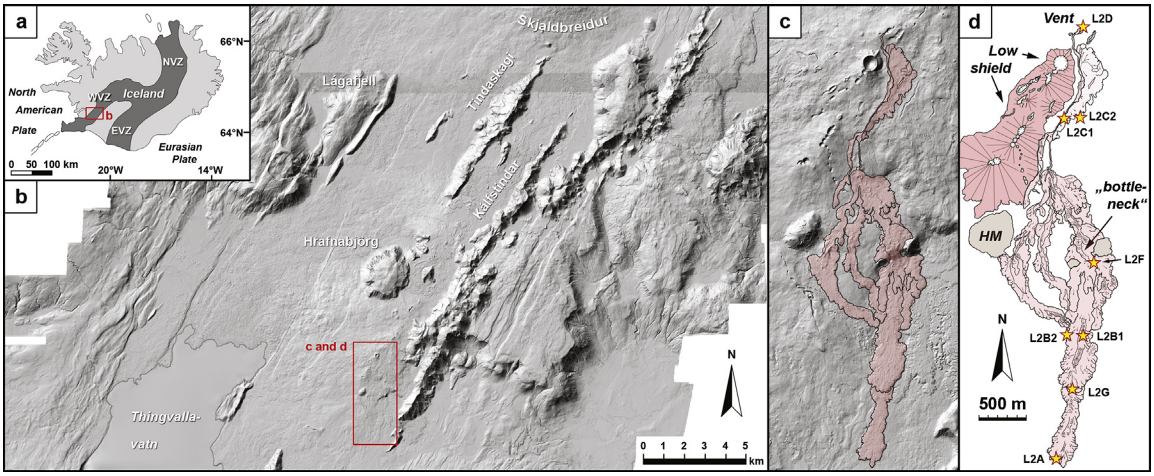

Fig. 1. (a) Location of the Western Volcanic Zone (WVZ) in Iceland; (b) Shaded elevation model of the area acquired with the HRSC-AX camera and location of the lava flow. (c) Highlight of the lava flow on the Data Elevation Model; (d) Map of the lava flow (light pink) and location of the sampling.
*HM (Hyaloclastite Mounds).

Jaeger et al., 2010; Pasckert et al., 2012; and references therein). Estimates of lava viscosities on Mars range from 10^2 to 10^8 Pa s and would appear to be consistent with basaltic to andesitic compositions.

The approximation of a single viscosity value neglects important physico-chemical processes, which are expected to affect considerably the rheology of lava (e.g., Shaw, 1969; Ryerson et al., 1988; Crisp et al., 1994; Cashman et al., 1999). For example, during emplacement of basaltic lava flow, heat loss induces crystallisation and consequently changes in the residual liquid composition, which both may increase the apparent viscosity of the flow by several orders of magnitude from the vent to the point where the flow halts. Moreover, under some compositional conditions, Giordano et al., 2007 showed that the concept of a rheological cut-off provides a rheological proxy for flow emplacement temperature. During lava flow emplacement, the viscosity of lava is therefore transient, and further evaluation of the validity of interpretations made from morphological methods is imperative.

The understanding of silicate melt rheology has rapidly advanced in the last three decades; a description of the rheology of silicate liquids as a function of temperature and chemical composition is now available (e.g., Hess and Dingwell, 1996; Dingwell, 2006; Giordano et al., 2008; Hui and Zhang, 2007). A reasonable understanding of the rheological contributions of crystals (e.g., Ryerson et al., 1988; Pinkerton and Stevenson, 1992; Lejeune and Richet, 1995; Pinkerton and Norton, 1995; Saar et al., 2001; Sato, 2005; Ishibashi and Sato, 2007; Caricchi et al., 2007; Costa, 2005; Costa et al., 2009; Petford, 2009; Ishibashi, 2009; Mueller et al., 2010; Castruccio et al., 2010; Vona et al., 2011; Cimarelli et al., 2011), bubbles (Bagdassarov and Dingwell, 1992; Lejeune et al., 1999; Stein and Spera, 2002; Manga et al., 1998; Saar and Manga, 1999), and their combined effects (Bagdassarov et al., 1994; Stein and Spera, 1992; Lavallée et al., 2007, 2012; Harris and Allen, 2008; Pistone et al., 2012) is emerging. Yet, it is well accepted that the rheological impact of particles is considerable and cannot be neglected. Their effect on viscosity is described by contributions to the Newtonian behaviour as well as the onset of non-Newtonian effects. The rheology of magmatic suspensions, with its phenomena of strain and strain-rate dependence, thus generally requires a non-Newtonian description. Complexity in describing the non-Newtonian nature has led to the proposal that above a critical crystal fraction, the rheology may be simplified to a Bingham fluid (e.g., Ryerson et al., 1988; Pinkerton and Stevenson, 1992) defined by its yield strength, which is dependent on crystal fraction. Despite recent experiments on multiphase magmas challenged the existence of yield strength (Lavallée et al., 2007; Caricchi et al., 2007), the concept persists in lava flow modelling because it enables computational simplifications.

How robust then, is the description of lava flow morphology in terms of a single rheological parameter (either viscosity or yield strength) reflecting the chemical composition and crystallisation sequence associated with a particular cooling history? To address this question, we focus here on a 4000-year-old basaltic lava flow from the Western Volcanic Zone in Iceland. Our approach combines (1) the determination of the rheological parameters from high-resolution morphological analysis, and (2) the determination of the rheological evolution of the lava according to its crystallisation sequence from eruption until complete crystallisation using petrographic analysis. The applications of our results to planetary data ought to be feasible as volcanic flows on Mars, the Moon and Mercury are dominated by basaltic compositions (BVSP, 1981).

2. Methods

2.1. Morphological analysis

2.1.1. Topographic imaging

In 2006, HRSC-AX, an airborne version of the High Resolution Stereo Camera (HRSC) on board Mars Express, was used for the acquisition of stereo and colour images of the Western Volcanic Zone, Iceland (Fig. 1). The HRSC-AX is a multi-sensor push-broom instrument with 9 CCD line sensors and has a stereo capability, which can systematically produce high-resolution Digital Elevation Models (DEMs). The principles of HRSC-AX data processing are similar to that of Mars Express-HRSC processing (see Scholten et al., 2005; Gwinner et al., 2010). The orientation data of the camera is reconstructed from a GPS/INS (Global Positioning System/Inertial Navigation System). The ortho-images have a map-projected resolution of 25 cm/pixel, and the DEM has a vertical resolution of 10 cm, an absolute accuracy of ∼20 cm, and a horizontal grid spacing of 1 m.

2.1.2. Extracting rheological parameters from morphological dimensions

The following equations apply to the emplacement of cooling-limited lava flows in a laminar fashion with no inflation. All parameters used for the following equations are given in Table 1. The lava flow length (L) is related to its velocity (u) via the dimensionless Grätz number, (G_Z; Knudsen and Katz, 1958; Guest et al.,