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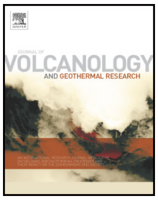

The effect of inflation on the morphology-derived rheological parameters of lava flows and its implications for interpreting remote sensing data - A case study on the 2014/2015 eruption at Holuhraun, Iceland

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ABSTRACT

Morphology-derived lava flow rheology is a frequently used tool in volcanology and planetary science to determine rheological parameters and deduce the composition of lavas on terrestrial planets and their moons. These calculations are usually based on physical equations incorporating 1) lava flow driving forces: gravity, slope and flow-rate and 2) morphological data such as lava flow geometry: flow-width, -height or shape of the flow outline. All available methods assume that no geometrical changes occur after emplacement and that the measured flow geometry reflects the lava's apparent viscosity and/or yield strength during emplacement. It is however well-established from terrestrial examples that lava flows may inflate significantly after the cessation of flow advance. This inflation affects, in turn, the width-to-height ratio upon which the rheological estimates are based and thus must result in uncertainties in the determination of flow rheology, as the flow height is one of the key parameters in the morphology-based deduction of flow properties. Previous studies have recognized this issue but, to date, no assessment of the magnitude of this error has been presented. This is likely due to a lack of digital elevation models (DEMs) at sufficiently high spatial and temporal resolution.

The 2014/15 Holuhraun eruption in central Iceland represents one of the best monitored large volume (1.5 km^3) lava flow fields (85 km^2) to date. An abundance of scientific field and remote sensing data were collected during its emplacement. Moreover, inflation plays a key role in the emplacement dynamics of the late stage of the lava field. Here, we use a time series of high resolution DEMs acquired by the TanDEM-X satellite mission prior, during and after the eruption to evaluate the error associated with the most common methods of deriving lava flow rheology from morphological parameters used in planetary science.

We can distinguish two dominant processes as sources of error in the determination of lava flow rheology from morphology 1) wholesale inflation of lava channels and 2) post halting inflation of individual lava toes. These result in a 2.4- to 17 - fold overestimation of apparent viscosity and a 0.7- to 2.4 - fold overestimation of yield strength. When applied in planetary sciences, this overestimation in rheological parameters translates directly to an overestimation of the respective lavas silica content. We conclude that, although qualitatively informative, morphological analysis is insufficient to discern lava rheology and composition. Instead, in-situ analysis together with high resolution remote sensing data is needed to properly constrain the compositions involved in planetary volcanism.

1. Introduction

The rheology and composition of lava flows observed on other planets is commonly estimated from the morphology of lava flows (Baloga et al., 2003; Glaze and Baloga, 2006; Glaze et al., 2003; Hulme, 1974; Moore et al., 1978; Warner and Gregg, 2003; Wilson and Head, 1994). These approaches have been developed and tested on analogue materials (Gregg and Fink, 2000; Griffiths and Fink, 1992; Pinkerton and Wilson, 1994). The individual approaches including all input parameters and limitations are discussed in detail in Section 3 of this manuscript. Deducing flow properties from the 3D-shape of lava flows is a useful tool to establish paleo-emplacement conditions of lava flows on both Earth and other terrestrial planets and their satellites, informing estimates of the variability of compositions of lavas on planets where direct measurements are lacking (Baloga et al., 2003; Bruno et al., 1994;

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Chevrel et al., 2013b; Glaze et al., 2003; Hiesinger et al., 2007; Hulme and Fielder, 1977; Keszthelyi et al., 2006; Moore et al., 1978; Warner and Gregg, 2003; Wilson and Head, 1994; Zimbelman, 1985).

Such deductions of flow parameters from geometric measurements are obtained from static post-emplacement morphologies and must therefore be seen to be a cumulative result of the entire deformational history of the flow during emplacement. Inferring rheological parameters such as viscosity and/or yield strength from post-emplacement flow morphology is, therefore, based on a number of assumptions, namely: 1) the rheology did not change during emplacement (Hiesinger et al., 2007; Hulme, 1974; Moore et al., 1978), 2) the geometry is representative of the lava at flow conditions (Glaze and Baloga, 2006; Glaze et al., 2003; Hulme, 1974; Pasckert et al., 2012; Warner and Gregg, 2003; Wilson and Head, 1994), and 3) the lava is emplaced as a single coherent isothermal flow (Baloga et al., 2001; Baloga et al., 2003; Glaze et al., 2003; Moore et al., 1978).

Direct observations of lava flow dynamics on earth show that these assumptions are significant simplifications of lava flow emplacement processes. Firstly, lava flows undergo continuous changes in rheology during emplacement (Cashman et al., 2013; Cashman et al., 1999; Chevrel et al., 2013b; Decker et al., 1987; Giordano et al., 2007; Kolzenburg et al., 2016b; Kolzenburg et al., 2017). Secondly, lava flow geometry may change significantly during emplacement and lava flows often inflate after reaching their final runout distance (Cashman et al., 2013; Hon et al., 1994; Pedersen et al., 2017; Walker, 1991). Thirdly, lava flows are often emplaced in a non-continuous and pulsating manner (Cashman et al., 2013; Favalli et al., 2010; Kolzenburg et al., 2017; Pedersen et al., 2017).

Application and interpretation of morphological methods for the determination of rheological parameters from post-emplacement geometries thus need to be reviewed in the light of the effects that all the above-mentioned processes may have on the results obtained. Some estimates of the effects of changing rheology and densification through gas loss on flow thickness have been presented in a theoretical approach by Baloga et al. (2001). The model is based on the aforementioned assumptions of flow emplacement and does not account for natural emplacement processes such as inflation. They show that even under those assumptions calculated changes in lava flow height due to different densities and viscosities may be up to 40%, depending on model input parameters.

The main issue hampering the correlation of rheology and morphology is that lava flows display complex emplacement dynamics that commonly feature a two-phase emplacement mechanism (independent of surface textures). An initial free-flow stage, where rheology can readily be deduced from the gravitational forcing of the lava as a function of density and slope of the emplacement surface (see Hiesinger et al. (2007) and Chevrel et al. (2013b) for reviews) and a subsequent inflation stage, where the lava flow is self-confined by a growing rheological contrast zone or “crust”. Although flow advance may continue to a certain degree, mainly in pāhoehoe type flows (Hon et al., 1994), the areal extent of the lava no longer increases significantly during the inflation stage. Instead newly erupted lava is accommodated via flow inflation and its height may increase by a factor of up to 10 (Cashman et al., 2013; Hon et al., 1994; Pedersen et al., 2017; Walker, 1991). This process will result in estimates of lava viscosity and yield strength higher than the actual values during flow. Thus it becomes apparent that assigning a geometry-derived yield strength to a lava is extremely problematic. This is because the lava flow height is controlled by the confinement of the developing flow-carapace (i.e. external confinement by the rheologic contract zone) rather than an apparent internal yield-strength (intrinsic rheologic parameter). It is important to note that in nature, even the fluid core of a lava flow is not actually a Bingham fluid but, being a three phase magmatic suspension, has a complex, strain-rate-dependent viscosity. The crust on the other hand contains brittle and visco-elastic portions. Therefore, the use of a Bingham rheology model represents a drastic simplification and is a significant source of uncertainty and error in the estimation of flow properties from morphology, since height is a second to fourth power parameter in the respective equations (See Section 3 for details).

Here, for the first time, use of a time series of high resolution remote sensing elevation data (morphology and texture) recorded by the TanDEM-X satellite mission during the 2014/15 Holuhraun eruption in Iceland enables the systematic assessment of the influence of lava flow inflation on the results obtained from current methods for the derivation of rheology from morphology.

2. Geological setting and eruption chronology

The Holuhraun eruption took place in the tectonic fissure swarm between the Bárðarbunga-Veiðivötn and the Askja volcanic systems in the periglacial sander plain of Dyngjujökull, an outlet glacier of the Vatnajökull ice cap in Iceland (Fig. 1). It was fed by a 47 km long, lateral dyke propagating from the subglacial Bárðarbunga volcano (Coppola et al., 2017; Ruch et al., 2016; Sigmundsson et al., 2014). The eruption lasted about six months (29/08/2014–27/02/2015) and produced about 1.5 km^3 of basaltic lava (Coppola et al., 2017; Jaenicke et al., 2014; Jaenicke et al., 2016; Münzer et al., 2016; Pedersen et al., 2017). The lava flow extends over an area of 85 km^2 with a maximum height of 48 m of the main crater (Baugur) located at the southwestern edge of the lava field (Jaenicke et al., 2014; Jaenicke et al., 2016; Münzer et al., 2016; Pedersen et al., 2017). The large volume and area of the Holuhraun flow-field makes it a great comparative counterpart to extra-terrestrial flow-fields such as King- and Aristarchus-Crater on moon (Moore et al., 1978) and Olympus-, Arisa- and Ascrae-Mons on Mars (Moore et al., 1978; Zimbelman, 1985).

Lava effusion rates during the eruption period range from 320 to 10 m^3/s. Averaged values are ~250, 100 and 50 m^3/s during the initial (August–September 2014), intermediate (October–December 2014) and final phase (December 2014 to February 2015), respectively (Coppola et al., 2017; Pedersen et al., 2017). The lava was emplaced on the central part of the Flæður floodplain north of the Dyngjujökull glacier. This outwash plain is covered by glacial and fluvial deposits, and has a regional dip of ~0.2°–0.5° to the northeast. Its small scale topography is made of decimeter to meter scale fluvial banks, bars and terraces. The gently sloping emplacement surface resulted in slow lava flow advancement rates (generally below ~1 m/min); see, Kolzenburg et al. (2017) and Pedersen et al. (2017) for details. Thus the eruption was an ideal target for scientific observations of unique detail ranging from direct ground measurements (Kolzenburg et al., 2017; Pedersen et al., 2017) over airborne platforms to satellite monitoring (Coppola et al., 2017; Jaenicke et al., 2014; Jaenicke et al., 2016; Münzer et al., 2016; Pedersen et al., 2017). The chemical composition of the lava is homogeneous throughout the entire eruption (Gíslason et al., 2015; Kolzenburg et al., 2017). This implies that neither the topography nor the composition were the driving factors for the observed changes in flow morphology.

During its emplacement history, the lava field was initially dominated by channels and horizontal expansion. Then it transitioned to grow in volume primarily by inflation, tube-fed flow (i.e. transport of lava through roofed over partially or completely filled channels) and vertical stacking of lava-lobes. The main lava channel shows significant inflation (5–10 m). Inflation intensity increases from proximal to distal sections of the lava channel, see Pedersen et al. (2017) and Section 5 for details. Pedersen et al. (2017) estimated a total lava volume of 0.09 km^3 to 0.18 km^3 (i.e. about 10% of the erupted lava volume) to produce such inflation.

As highlighted in Pedersen et al. (2017), the Holuhraun flow field illustrates that studies of long-lived eruptions based exclusively on the final surface morphology may be incapable of revealing the complex morphological evolution of composite lava-fields. Here, the high spatial and temporal resolution of monitoring data available for the Holuhraun eruption provides a unique opportunity to study the emplacement and