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The role of unsteady effusion rates on inflation in long-lived lava flow fields

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A B S T R A C T

The emission of volcanic gases and particles can have global and lasting environmental effects, but their timing, tempo, and duration can be problematic to quantify for ancient eruptions where real-time measurements are absent. Lava flows, for example, may be long-lasting, and their impact is controlled by the rate, tempo, and vigor of effusion. These factors are currently difficult to derive from the geologic record but can have large implications for the atmospheric impact of an eruption. We conducted a set of analogue experiments on lava flow inflation aiming at connecting lava morphologies preserved in the rock record to eruption tempo and dynamics through pulsating effusion rates. Inflation, a process where molten material is injected beneath the crust of an active lava flow and lifts it upwards, is a common phenomenon in basaltic volcanic systems. This mechanism requires three components: a) a coherent, insulating crust; b) a wide-spread molten core; and c) pressure built up beneath the crust from a sustained supply of molten material. Inflation can result in a lava flow growing tens of meters thick, even in flow fields that expand hundreds of square kilometers. It has been documented that rapid effusion rates tend to create channels and tubes, isolating the active part of the flow from the stagnant part, while slow effusion rates may cause crust to form quickly and seize up, forcing lava to overtop the crust. However, the conditions that allow for inflation of large flow fields have not previously been evaluated in terms of effusion rate. By using PEG 600 wax and a programmable pump, we observe how, by pulsating effusion rate, inflation occurs even in very low viscosity basaltic eruptions. We show that observations from inflating Hawaiian lava flows correlate well with experimental data and indicate that instantaneous effusion rates may have been 3 times higher than average effusion rates during the emplacement of the 23 January 1988 flow at Kīlauea (Hawai'i). The identification of a causal relationship between pulsating effusion rates and inflation may have implications for eruption tempo in the largest inflated flows: flood basalts.

1. Introduction

1.1. Flow emplacement, eruptive process, and environmental impact

The hypothesized environmental impact of eruptions greater than 100,000 cubic kilometers (such as the flood basalts of the Deccan and Siberian traps) is in part controlled by the tempo of eruptive pulses (Courtillot and Fluteau, 2014; Black and Manga, 2017; Tobin et al., 2017). The tempo of an eruption is a term used to capture the duration of effusion rate of individual pulses of high flux as well as the time between those pulses, which often occurs in a periodic manner. The proposed relationship between eruption tempo and environmental impact emphasizes the importance of constraining the rate and unsteadiness of large inflated lava flows. Sufficiently large gas emissions can overwhelm the atmosphere's ability to respond, and can thus have substantial global warming and ocean acidification implications (Black and Manga, 2017). While the rate at which gas was released in these ancient eruptions is unknown, the rate of gas release is tied to effusion rate, which controls lava flow emplacement, including surface morphology, total duration, and area covered. Our ability to understand eruption dynamics and their environmental impacts thus depends on our understanding of the link between the dynamics of lava flow emplacement and their preserved deposits.

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1.2. Lava flow morphology and vertical growth

An active lava flow can be divided into three parts: the cool brittle crust, the flexible viscoelastic transition zone, and the molten interior that is surrounded on all sides by the other two zones (Castruccio et al., 2013 and references therein). The morphology of a lava flow is determined by the thickness and flexibility of the surface crust and the degree to which it is coupled to the molten interior of the flow (e.g., Cañón-Tapia et al., 1997; Cashman et al., 1999; Duraiswami et al., 2003). Crust that is coupled with the core of the flow (typically higher viscosity lava) will result in a lava flow that is either forced to thicken by flowing on top of itself or is torn apart by the shearing force between the molten interior and the rigid crust, resulting in a disjointed morphology like ʻaʻā, spiny or slabby pāhoehoe, and blocky lava (Peterson and Tilling, 1980; Pinkerton et al., 2002). A solid crust decoupled from the molten interior, however, remains intact while the molten material passes below. Smooth surface morphology is preserved in a coherent insulating crust, which allows new lava to be injected beneath it (Hon et al., 1994; Self et al., 1997; Anderson et al., 1999; Cañón-Tapia and Coe, 2002; Reidel et al., 2013). Rapid instantaneous flow rates of lava typically lead to strong coupling and therefore broken, rubbly-crusted or channelized flows whereas lower flow rates lead to decoupling and are correlated with the formation of smooth pāhoehoe crust (Rowland and Walker, 1990). Slow instantaneous effusion rates are also correlated with lower heat input and faster cooling rates, which will create flows consisting of numerous lobes, piled on top of each other and locally resurfacing the flow when subcrustal pathways solidify and become blocked (Moore, 1975; Griffiths and Fink, 1992; Keszthelyi and Denlinger, 1996).

A separate mechanism by which lava flows grow vertically is inflation, a process that raises the unbroken, solidifying surface of a flow incrementally as the pressure builds from the injection of molten material below the cooled crust (Hon et al., 1994; Hoblitt et al., 2012). Observations of inflating flow fields have shown that the flow propagates laterally by lobes of lava, but before they can solidify as individual lobes, more material is injected beneath the still-intact crust, forming a continuous sub-surface sheet of lava (Hon et al., 1994; Kauahikaua et al., 1998). The gas in the molten interior forms vesicles that become trapped along the bottom surface of the crust, forming vesicle horizons parallel to the solidification front (Cashman and Kauahikaua, 1997). As the solidified crust thickens, and more molten material is injected, a second vesicle layer becomes trapped in the new crust, forming a repeating pattern. Actively inflating flows in Hawaiʻi have been measured as gaining eight meters of height over the course of twelve weeks (Kauahikaua et al., 1998). Time-lapse photography of these types of flows in Hawaiʻi show a cyclic, step-wise vertical growth (Hoblitt et al., 2012; Fig. 1, Supplementary Video 1). These flows were only 0.5–1 km wide but are interpreted to be analogous to the expansive flows created in flood basalt eruptions (Self et al., 1996, 1997).

In the Columbia River Flood Basalts and Deccan Traps, evidence of cyclic inflation in the form of bubble horizons are reported in large lava flows up to 50 m thick and with volumes of 100–1000 km^3 (Self et al., 1996). Bubble horizons have been documented in Hawaiian flows several meters in height and with volumes of tens of thousands of cubic meters, also interpreted to represent cycles of inflation (Hon et al., 1994; Cashman and Kauahikaua, 1997; Kauahikaua et al., 1998). In a natural system, many factors could affect the episodic nature of eruptions such as topographic barriers, magma supply rates, or lava tube constriction and dilation; however, the regularity of vesicle horizons seen in many inflated flows suggests that material is not injected at a continuous rate, but possibly in a periodic fashion on relatively short time scales (Hoblitt et al., 2012). As a result, questions are raised:

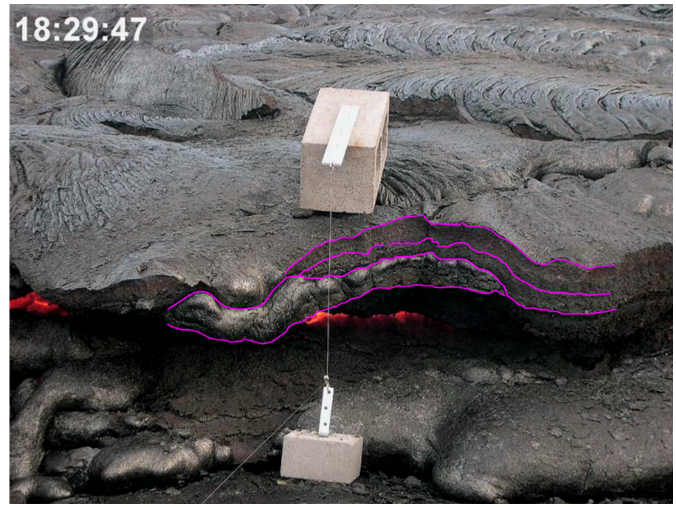

Fig. 1. A still from the Supplemental Video 1 showing an inflating section of a lava flow in Hawaiʻi (video from supplemental material in Hoblitt et al., 2012). Vertical growth of ~5 cm per pulse is shown in the video. The pink lines indicate old horizontal boundaries between the crust and molten material designated by squeeze-outs of lava or vesicle horizons trapped when the crust first formed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

What eruptive conditions can maintain a coherent crust, but also feed molten material out to the edges of the flow?; and does the regularity of bubble horizons provide information on those conditions? Here we test a mechanism that has been witnessed in active eruptions: pulsating eruption rates (Denlinger, 1997; Patrick et al., 2011; Poland, 2014). We propose that pulsating rates promote inflating lava flows by achieving a balance between faster flow rates which form coherent crust decoupled from a molten core but can also result in rupturing of the crust and resurfacing and lower flow rates that protect coherent crust but can result in stagnation and crust rupture.

1.3. Wax analog experiments

Polyethylene glycol wax (PEG) has been used to simulate volcanic phenomena including channelized flow (e.g., Hallworth et al., 1987; Garry et al., 2006; Cashman et al., 2006), flow over a slope (e.g., Gregg and Fink, 2000; Gregg and Smith, 2003; Lyman and Kerr, 2006), lava domes (e.g., Fink et al., 1993; Fink and Bridges, 1995; Griffiths and Fink, 1997; Buisson and Merle, 2002), compound lava flows (e.g., Blake and Bruno, 2000; Lyman et al., 2005), and preferred pathways and lava tubes (e.g., Griffiths et al., 2003; Anderson et al., 2005), to name a few. The thermomechanical properties of PEG allow it to be a good analog for basaltic lava in particular as it forms a thin viscoelastic crust that eventually becomes brittle upon further cooling (Fig. 2. See also Soule and Cashman, 2004). These previous experiments vary temperature, viscosity, and effusion rate, and incorporate these variables into the non-dimensional number Ψ (cf. paragraphs below and Appendix 1). Analog models of high-silica lava domes showed that aspect ratio, defined as height divided by length, increased with the number of pulses it took to emplace the same volume of material (Fink et al., 1993). Fink et al. (1993), however, did not distinguish between piling up of layers of material and the injection of material beneath the crust. They also used a significantly higher scaled viscosity than is appropriate for basaltic scenarios. Despite being a commonly cited phenomenon in mafic lava flows, inflation has yet to be studied in detail using analog models. In this study, we use PEG 600 wax (Appendix 1) to identify the ideal conditions for maximum inflation potential in a lava flow.