Journal of Volcanology and Geothermal Research 195 (2010) 121–126

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Initial advance of long lava flows in open channels

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ARTICLE INFO

Article history:
Received 25 March 2010
Accepted 16 June 2010
Available online 25 June 2010

Keywords:
effusion rate
emplacement
morphology
topography
viscosity

ABSTRACT

The initial development of long lava flows is investigated using simple theory and field evidence. Order-of-magnitude estimates of the evolving thickness and the extending length of lava are obtained by scaling arguments based on the simplification that the bulk structure can be modelled initially as a Newtonian fluid. A scaling analysis suggests that the rate of advance of the leading front evolves primarily due to temporal variations in the effusion rate and minimally due to topography. The apparent viscosity of the bulk flow increases with time at subsequent stages when effects due to cooling become important. Theoretical results are applied to the study of long lava flows that descended on Etna, Kilauea and Lonquimay volcanoes. We determine that lava flows at Kilauea extended initially like a Newtonian fluid with constant viscosity, implying that thermal effects did not significantly influence the dynamic properties of the bulk flow. In contrast, effects due to cooling played a major role throughout the advance of lava flows at Etna and Lonquimay. We show that the increasing length and volume of an active emplacement field can be monitored to estimate its evolving viscosity, which in turn allows the further advance of the lava to be predicted.

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1. Introduction

Lava flows occur when molten rock is extruded from a volcanic vent. A long channel of lava may develop down a slope, where the flow is driven by gravity and confined laterally by elevations in topography. The lava quickly cools and solidifies at the margins of the flow, where levees form and further confine the flow (Hulme, 1974; Sparks et al., 1976). The upper surface of the lava may also solidify to form a lava tube system whereby the lava continues to flow inside a completely enclosed passage (Greeley and Hyde, 1972; Hallworth et al., 1987; Calvari and Pinkerton, 1999). The confinement may insulate the interior of the channel, allowing the lava to flow efficiently, without much loss of heat, towards its leading front (Keszthelyi, 1995). The front of the flow may propagate, branch into different lobes and stagnate in a complex series of processes (e.g., Lipman and Banks, 1987), before the entire structure of the emplaced lava solidifies.

One of the motivations for understanding the morphology of lava flows is to predict and evaluate the consequences of an effusive eruption. The resultant flow of hot and destructive lava can reach distant areas, threatening lives and damaging properties (Blong, 1984). An accurate prediction of the evolution of active lava flows is helpful for identifying danger zones and assessing risks posed to areas on volcanoes. For the purposes of effective forecasting, it is useful to be able to predict the extent of lava based on conditions that can be measured prior to or during the early stages of lava emplacement.

Previous studies obtained empirical relationships showing that the final lava length is correlated to a number of factors, including the mean effusion rate at the vent (Walker, 1973), the total erupted volume (Malin, 1980) and the rheology of the lava (Pinkerton and Wilson, 1994). An idea has been put forward that the flow is either cooling-limited when it reaches a maximum length attainable for a given supply of lava from the vent or volume-limited when a considerable decline in the effusion rate prevents the flow front from reaching the maximum length (Guest et al., 1987). In either case, the final length of the lava is controlled by dynamic processes involving heat loss and depends importantly on the effusion rate (Harris and Rowland, 2009). We complement previous studies by examining dynamically how the various input factors, including variations in the effusion rate and effects due to cooling, influence the lava flow before it ultimately stops.

The dynamic processes leading to the final solidified state require understanding of the fluid dynamics of the lava (Griffiths, 2000). Of particular importance is the development of lava flows during their early stages, when the flow front advances rapidly and reaches a large proportion of its final extent. A quantitative formulation of the initial advance of long lava flows forms an important foundation for studying subsequent stages of the evolving morphology of lava. The use of scaling arguments, which are applied to the early stages, could be developed further to study other problems including the prediction of the final lava extent, which is beyond the scope of the current investigation.

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0377-0273/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2010.06.011

During the early stages, an open channel develops down a slope and directs the flow towards its advancing front (Hulme, 1974; Kerr et al., 2006). The resultant flow during the early stages is commonly modelled as Newtonian and laminar (Tallarico and Dragoni, 1999; Sakimoto and Gregg, 2001). There is a rich class of mathematical problems relevant to the prediction of lava flows (Baloga and Pieri, 1986; Bruno et al., 1996). The apparent viscosity of the bulk structure of the lava is expected to remain constant until the flow is influenced by thermal effects, which change the dynamical properties of the lava in two important ways. First, crystals may nucleate due to degassing and grow in the flow, effectively increasing the viscosity of the lava (Sparks et al., 2000). Second, a crustal layer may develop on the surface due to cooling (Griffiths and Fink, 1993), effectively introducing an additional resistance to flow. Both mechanisms reduce the flow speed considerably until the flow stagnates altogether.

Here, we consider the initial advance of lava flows supplied down open channels of different shapes. The aim is to provide theoretical insight into natural lava flows by simplifying the analysis as much as possible while including the most fundamental mechanisms. For simplicity, the lava is modelled as Newtonian and we study the effects on the bulk flow due to given variations in the topography, the effusion rate and the apparent viscosity. Theoretical results obtained are applied to describing lava flows that descended the volcanic slopes of Etna, Kilauea and Lonquimay. The theoretical treatment is presented first in Section 2, followed by applications to field data in Section 3. We demonstrate how increases in the viscosity of the lava and further advance of the flow front can be predicted solely based on prior measurements of the cumulative volume and the length of an evolving emplacement field.

2. Theory

Consider an open channel of lava flowing down a slope. The channel may represent topography confining the entire length of lava that has been extruded from a volcanic vent, as long as the flow does not split into different branches. The following analysis applies equally well to lava that has branched off from another channel and extends thereafter as a single lobe. We are concerned with the temporal evolution of the dimensions of a single channel of lava. Of interest are the characteristic height $H(t)$, width $W(t)$ and length $L(t)$ of the flow at time t. The flow is primarily along the channel, provided that the dimensions of the flow satisfy $H \ll W \ll L$.

The exact shape of the channel confining the flow of lava will depend on a number of factors, which include the pre-existing topography and the development of levees at the margins of the flow. However, as we discuss later, the details of the channel do not significantly influence the flow. Consider a general relationship between the width and thickness of the flow of the form

$$H/w_* \sim (W/w_*)^n, \tag{1}$$

where ~ denotes a relationship of proportionality, w_* is a measure of the size of the channel and n is a prescribed constant that describes the shape of the channel. For example, the limit as $n \to \infty$ is equivalent to $W \sim w_*$ and corresponds to a shallow layer of lava flowing down a flat channel of constant width w_*. Channels confining lava are approximately described by n taking some finite value greater than 1. For instance, $n=2$ corresponds to a thin layer of lava flowing inside a channel of cylindrical shape whose radius of curvature, w_*, is much larger than the characteristic flow thickness, as shown in Fig. 1. The case of $n=1$ describes flow along a wedge. Deep and narrow flows, described by $n<1$, are not considered here because they are sheared predominantly across fractures of width $W \ll H$ and do not apply to natural lava flows.

The exact velocity varies within the lava but has a common characteristic magnitude denoted by $U(t) \sim L/t$ because L is the only characteristic length scale associated with the direction of flow along the channel. In particular, U is the characteristic rate of advance of the flow front, which is estimated by considering the governing equation of Newtonian and laminar flow. The driving force of gravity must balance the resistive forces due to the viscosity of the lava, provided that inertial effects are negligible. The component of gravity in the direction of the flow is given by $\rho g \sin\theta$, where ρ is the density of the lava, g the acceleration due to gravity and θ the angle of inclination of the channel to the horizontal. The lava is sheared predominantly across its thickness because the resistive forces exerted at the sides of the flow are negligible, since $H \ll W$. The flow is sheared at the base, where we impose the condition of no slip. Shear stresses exerted by the ambient or any development of a crustal layer on the free surface are considered to be small initially. Given that the flow is sheared across its thickness, the viscous forces scale like $\mu U/H^2$, where μ is the dynamic viscosity of the lava. By balancing gravity with viscous forces and rearranging, we obtain the characteristic speed of the flow

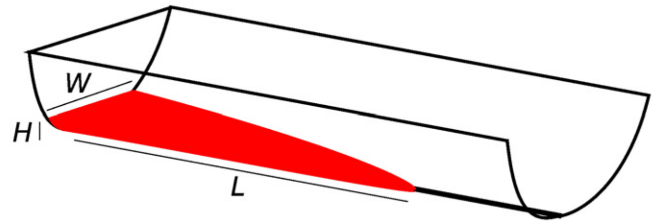

Fig. 1. A sketch of lava of typical length L, width W and height H flowing inside a channel of cylindrical shape.

$$U \sim \rho g \sin\theta H^2/\mu. \tag{2}$$

Note that Eq. (2) is consistent with an equation quantifying the surface velocity of flow down a channel with rectangular cross-section, often referred to as the Jeffreys equation (Jeffreys, 1925). The flow speed depends importantly on H, the thickness of the flow, which is set by the supply of lava into the channel.

The supply of the lava into the channel from upstream depends on the effusion rate at the vent and generally varies with time. The effusion rate corresponds to the rate of change of the cumulative volume of extruded lava. Typically, the effusion rate increases initially during a waxing phase and then decreases slowly during a waning phase (Wadge, 1981). To illustrate the effects of the lava supply on the resultant flows down open channels, we consider a simple power-law dependence of the effusion rate with time, which is expected to fit field data during the initial stages of an effusive eruption. Let the effusive activity at the vent begin at time $t=0$ such that the cumulative volume of extruded lava is given by

$$V = V_*(t/T_*)^\alpha, \tag{3}$$

where T_* is some fixed time scale at which the volume erupted is $V=V_*$. The exponent $\alpha \geq 0$ is a prescribed constant and describes the temporal evolution of the effusion rate at the vent. For example, $\alpha=0$ corresponds to a fixed volume V_* of lava extruded rapidly at time $t=0$ and no further extrusion subsequently. Another example of importance is $\alpha=1$, which corresponds to a continuous supply of lava with a steady effusion rate at the vent. A more general situation, where the effusion rate at the vent declines continuously with time, is described by α taking some value between 0 and 1. Note that the volume of extruded lava for general $\alpha>0$ in Eq. (3) grows indefinitely, which does not model the effusion rate at large times. Nevertheless, Eq. (3) provides useful insight into the development of long lava flows during the early stages of the propagation, as we investigate below.

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