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Journal of Volcanology and Geothermal Research 173 (2008) 148 – 156

Journal of volcanology and geothermal research

www.elsevier.com/locate/jvolgeores

Research paper

Surface cooling, advection and the development of different surface textures on active lavas on Kilauea, Hawai'i

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Received 20 February 2007; accepted 8 January 2008
Available online 26 January 2008

Abstract

The validity of lava flow cooling models were investigated using data from a high resolution, high frame rate thermal imaging camera on Kilauea, Hawai'i during August 2004. Once the surface temperature data for small lava flow and lobes were corrected for emissivity, viewing distance, humidity and viewing angle, it was clear that their upper surfaces were thermally stratified on eruption. The interior of a stationary lava lobe was exposed by removing the crust, and its cooling rate was measured at 30 Hz. For this flow, the measured cooling trend was successfully modelled using a finite difference cooling model. However, modelled and measured cooling rates of a pahoehoe lobe and a small channelised lava flow were only in agreement until the crust began to deform. The departure from the modelled trend at this point is attributed to two factors. One is the complex cooling regime of a highly deformed ropy crust in which exposed lava at the crests of the ropes radiates in all directions compared with lava in the troughs where radiative cooling is less effective. The second, and more important, reason for the difference is the reduced flow rate of the crust once it begins to be compressed. The underlying visco-elastic zone beneath the crust flows more rapidly than the crust and consequently advective heat flow significantly reduces cooling rates. Variations in heat loss from different flow textures and the incorporation of different advective heat components is clearly important in future flow models. One of the critical parameters in such models is the temperature at which different surface textures develop. Temperature profiles along lobes and flows also revealed that rope textures developed on pahoehoe lavas when temperatures were in the range of 700–800 °C, brittle deformation of pahoehoe crust occurred when temperature dropped below 700 °C, and small pahoehoe lobes stopped advancing at temperatures of ~600–650 °C. It is important to recognise that the flow front temperatures at which these flows stop advancing will be significantly greater than for larger flows on similar gradients. The higher internal and basal shear stresses of large lava flows will allow the flow to advance until the visco-elastic layer at the front of a front is significantly cooler than the temperatures recorded on these small flows on Kilauea.

Keywords: FLIR; advection; lava; cooling; model

1. Introduction

During effusive eruptions on volcanoes close to populated areas, areas that are liable to be inundated by lava need to be identified. This can be addressed in a number of ways. These include assessment of how far a flow can extend and spread based on multivariate statistical analysis of flow data from previous activity (e.g. Pinkerton and Sparks, 1976; Pinkerton and Wilson, 1994; Calvari and Pinkerton, 1998); 1-D mass and energy conservation modelling (e.g. Harris and Rowland 2001); 2-D momentum conservation modelling (e.g. Ishihara et al. 1989); cellular automata modelling (e.g. Wadge et al. 1994; Crisci et al. 2004); or full 3-D finite element modelling (e.g. Hidaka et al. 2005). Many physically-based lava flow models are dependent on the validity of coupled heat-loss and rheological calculations, which in turn are linked to crystal and temperature dependency of the core viscosity and yield strength. The rate of internal cooling of a lava flow involves a balance between radiative and free, or forced, convective heat loss from the flow

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doi:10.1016/j.jvolgeores.2008.01.004

upper surface and conduction through the flow, advective heat flow and heat of crystallization (e.g. Keszthelyi, 1995a, 1995b; Keszthelyi and Denlinger, 1996; Harris et al., 2005). The thermal structure of the upper surface of an active lava can thus affect the rate at which the flow interior cools and crystallizes and consequently the apparent viscosity of the core (e.g. Crisp and Baloga, 1990). This, in turn, influences the advance rate of the lava and the maximum length of a cooling-limited flow (e.g. Guest et al., 1987; Pinkerton and Wilson 1994; Wright et al., 2001). In view of the importance of its potential influence on flow models, field measurements of surface temperatures of flows and hence cooling rates are required.

A pioneering set of experiments to study cooling rates of small, stationary pahoehoe lobes was undertaken by Hon et al. (1993, 1994) and Keszthelyi and Denlinger (1996). During these studies, thermocouples were inserted into the upper surface of pahoehoe flow lobes emplaced at Kilauea Volcano (Hawai'i), and radiometers were used to measure surface temperatures. While these measurements confirmed that modelled and measured cooling rates were in excellent agreement, this validation applies only to stationary flows that do not involve advective heat flow. Likewise, Keszthelyi (1995a) and Keszthelyi et al. (2003) respectively carried out field-based experiments to determine conductive heat loss through the base of a stagnant pahoehoe lobe and that due to surface heat loss via forced convection. These field methods are considerably more difficult and potentially hazardous to apply to moving lava flows. An alternative method is required to tackle this.

The recent development of high frame rate thermal imaging cameras allows heat loss of both stationary flows, such as pahoehoe lobes and channelised lava flows to be measured (e.g. Harris et al., 2005). They can also record surface thermal structures (e.g. Calvari et al., 2005), the temperatures at which lava lobes stop advancing and new breakouts develop and other transitions, including the temperatures at which different surface textures develop on active flows (e.g. Wright and Flynn, 2003). In addition, by carefully selecting places to measure heat loss, it is possible to measure heat loss with an advective component (e.g. channelized flows) and without (e.g. stationary lobes). The currently active lava flow field on Kilauea is an ideal laboratory for this type of study. In this study, we report on measurements of small pahoehoe flows. A complementary study of heat loss from larger lava flows has recently been undertaken by Harris et al. (2007).

2. Flows, measurements and instruments used

Lava flows on Kilauea at the time of the field campaign (August 2004) formed part of the PKK flow field. This phase of activity began in January 2004 when flows overtopped the west gap and east rim of Pu'u O'o crater (HVO website, http://hvo.wr.usgs.gov//kilauea/summary/main.html). Four new vents then opened, producing short flows. In March 2004 a major breakout occurred SW of the Pu'u O'o cone, forming the Prince Kuhio Kalaniana`ole (PKK) flow. This flow developed a major tube system which extended ~9 km to feed the flows that we targeted in August 2004. The 2004 data were collected from the Pulama Pali fault scarp region at a height of ~130 m a.s.l. on the 20th August and ~300 m a.s.l. on the 21st August.

The camera used during all measurements was a Flir Systems™ S40 Thermacam (S40). The S40 was used in conjunction with a laptop PC and recorded data at a rate of 30 Hz. During all measurements, the camera was mounted on a tripod and measurements were made of relative humidity, distance between the camera and flows being measured and viewing angle.

Measurements were made at distances ranging from 5–10 m. Relative humidity ranged from 29 to 90% and ambient temperatures ranged from 28 to 33 °C. All data were corrected for atmospheric attenuation based on viewing distances, relative humidity and ambient temperature. Most of the corrections were performed using the in-built emissivity and atmospheric corrections in the Flir Systems™ analysis software.

Detailed measurements and observations were made during the formation of small pahoehoe lobes, including temperature measurements during the final stages of flow advance, stagnation and inflation, as well as during the formation of new breakouts. Surface temperature measurements were also made on a 35 m long channelised flow. These measurements were made across the proximal section extending from the point of emission and included the development of pahoehoe ropy textures, and the subsequent break-up of the cooled ropy crust into slabby pahoehoe.

Before we examine the temperature data collected on Kilauea, it is important to ensure that all measurement errors are minimised. This is addressed in the following two sections.

2.1. Emissivity

Carefully controlled laboratory measurements on lava from Etna revealed that the emissivity of Etnean lavas is 0.97 (Ball and Pinkerton, 2006), slightly higher than the value of 0.96 from Salisbury and D'Aria (1994) for lavas from Hawaii. In the absence of controlled laboratory data for Hawaiian lavas, the value of 0.96 is used in this study. The difference between the emissivities measured in the laboratory for Etna and those estimated in the field from Hawaii likely are thought to result from differences in surface roughness or composition of the lavas.

2.2. Gas release

Ball et al. (2006) highlighted the potential problem of gas release from lava flows in attenuating the signal received by a thermal imaging camera. At a skylight on Mt. Etna during the 2004/5 eruption they found up to 70 °C variations in measured temperatures due to the effect of turbulently convecting volcanic gas and aerosol passing through the field of view. Time series analysis of the Etna data showed that it consisted of high and low frequency components that were attributed to turbulent convection and variations in overall gas concentration respectively. Spectral analyses of the high frequency component of time series data from the vent region of a 35 m long flow on Kilauea reveal similar periodicities to those seen by Ball et al. (2006). However, in this case, these variations are ±8 °C and