EXPLORING INFLATED PAHOHOE LAVA FLOW MORPHOLOGIES AND THE EFFECTS OF COOLING USING A NEW SIMULATION APPROACH.

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Introduction: Pahoehoe lavas are recognized as an important landform on Earth, Mars and Io [1,2]. Observations of such flows on Earth (e.g., Figure 1) indicate that the emplacement process is dominated by random effects. Existing models for lobate a`a lava flows (e.g., [3-6]) that assume viscous fluid flow on an inclined plane are not appropriate for dealing with the numerous random factors present in pahoehoe emplacement. Thus, interpretation of emplacement conditions for pahoehoe lava flows on Mars requires fundamentally different models. A new model [7] that implements a simulation approach has recently been developed that allows exploration of a variety of key influences on pahoehoe lobe emplacement (e.g., source shape, confinement, slope). One important factor that has an impact on the final topographic shape and morphology of a pahoehoe lobe is the volumetric flow rate of lava, where cooling of lava on the lobe surface influences the likelihood of subsequent breakouts.

Basic Approach: To simulate pahoehoe lava emplacement, Glaze and Baloga [7] considered the movement of small parcels of lava with a volume equal to the size of a typical toe (70 x 70 x 20 cm^3) [8]. The model provides a set of probabilistic rules for determining the location and direction of movement for each parcel. For a constant volume flow rate feeding the lobe, a single parcel is added at each time step. However, unlike the classical random walk of Brownian motion [9], only one parcel is allowed to move at each time step. Thus many parcels may remain dormant, but fluid, for multiple time steps. The net effect of this new type of random walk is that parcels tend to accumulate preferentially within the lobe producing cross-sectional topographic profiles with a medial ridge (Figure 1), very similar to inflated pahoehoe lobes observed in the field [10]. Because lava transfers within the lobe dominate the probabilistic activity, this approach provides a basis for simulating pahoehoe inflation in terrestrial and planetary settings.

Influence of Volume Flow Rate: The objective of this current study is to characterize how volume flow rate influences the shape (both planform and cross-sectional topography) of a pahoehoe lobe. In the original algorithm [7], all positions occupied by lava at a particular time step were considered equiprobable locations for the subsequent parcel transfer. The basic framework is based solely on stochastic behaviors and contains no physical parameters other than flow rate and parcel size. The new approach described here injects the process of surface cooling and skin growth into the model by relating measured or computed expressions for cooling into the probability of a breakout.

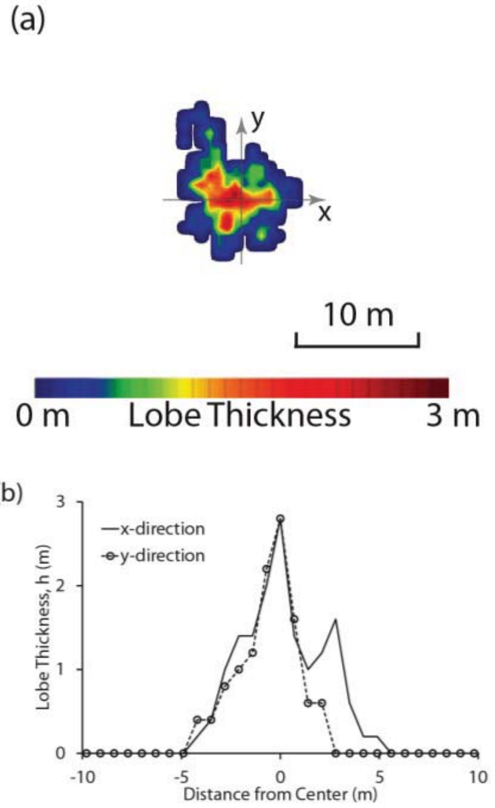

Figure 1. Example of a purely random reference simulation case with 500 parcels released from a point source. (a) plan-view of lobe (enlarged and smoothed for graphical interpretation). (b) topographic profiles taken through the origin along the x- and y-axes.

Concept of Correlation. "Correlation" is a statistical term that describes the influence of prior steps. When correlation is present, each lava parcel transfer retains some memory of earlier time steps and is no longer completely independent of prior transfers. Glaze and Baloga [7] used correlation to describe sequential breakouts at the margin of a pahoehoe lobe. Based on the logic that a recently active parcel is more likely to be the source of the next breakout at the margin, the model arbitrarily increased the probability of a sequential breakout (additional parcel added at the same location in the same direction) for the most recent parcel transfer [7]. The incorporation of correlation in this way produces simulated lobe morphologies that are consistent with data collected in the field.

Cooling Curves and Probability Distributions. Despite the encouraging results of including correltation in the random simulation model, the probability distribution applied to the selection process by [7] was not based on any fundamental physical constraints. Here we emphasize the role of skin cooling as the dominant physical process determining the shape of a pahoehoe lobe. The basic assumption of this approach is that once a cell initially becomes occupied, the parcel becomes fixed on the surface of the lobe. The mechanical strength of the crust grows with time and is thus proportional in some sense to cooling. Crisp and Baloga [11] and many others derive the skin depth,

$$\delta(t) = \frac{2k\left(T_o - T_s(t)\right)}{\sigma T_s^4(t)} \qquad (1)$$

that gives the proportionality. An increase in the residence time on the surface decreases the probability of a breakout at that location due to the growing thickness of the crust. Thus there is a relationship between measured cooling and the probability of a breakout.

The cooling curve shown in Figure 2 is thus directly related to the probability of a breakout when properly calibrated by the flow rate and normalized.The crust is no doubt significantly thinner for t_8 and t_7 than for t_2 and t_1 so they are more likely to be the sites for the next breakout. The curve with open diamonds in Figure 3 shows the distribution of probabilities for determining the location of the next time step in the series when cooling is considered (t_9 for the series shown in Figure 2). The flat curve in Figure 3 (blue diamonds) illustrates the equiprobable case for comparison. It can easily be seen in the cooling case that the probability of the next parcel transfer originating from parcel t_8 is greater than from t_1. This approach is broadly applied to larger simulations to explore the effect of correlation on the planform shape and topography.

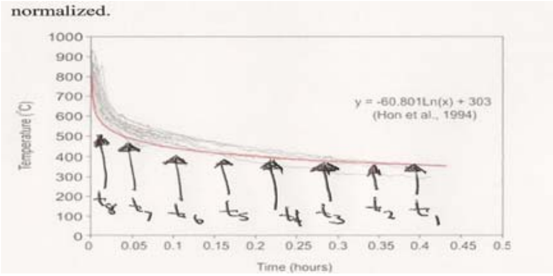

Figure 2. Based on Figure 1 from [12] illustrating field observations of surface cooling. Subscripted t's indicate the time step when each parcel (1 – 8) was effused from the source for a particular constant volume flow rate.

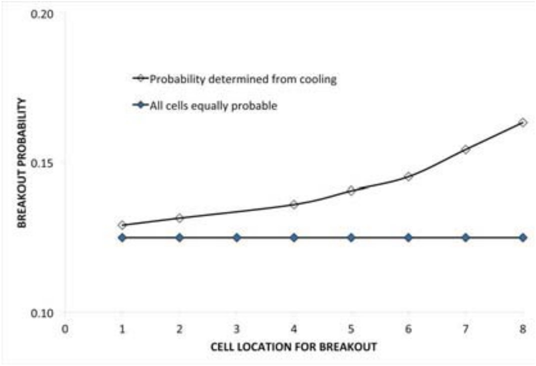

Figure 3. Probability distribution prescribed for each occupied cell location after 8 time steps.

Conclusions: Existing models for lava flow emplacement based on viscous flow on an incined plane are inappropriate for application to pahoehoe lavas where random processes are dominant. A completely new simulation approach developed recently provides a framework for exploring the effects of cooling on the final morphology of pahoehoe lobes. The basic approach assumes that the likelihood of parcel transfers is correlated with the surface temperature, with warmer parcels (most recently emplaced) having higher probabilty and older parcels being less likely.

As suggested by Figure 3, the influence of cooling on breakout locations decays with time as more cells and potential locations are added to the lobe, i.e., the fraction of hotter to cooler parcels decreases with time. Unless other factors cause a correlation in the lava transfers, the topographic profiles will always approach those of the uncorrelated cases described in [7].

Results to date indicate that a great deal of information about the emplacement of inflating pahoehoe lobes can be extracted by stochastic modeling of the random effects. Refinement of this approach will have implications for the analysis of inflated pahoehoe lobes on the Earth, Mars, Io, and possibly the Moon.

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