Exploring Inflated Pahoehoe Lava Flow Morphologies and the Effects of Cooling Using a New Simulation Approach

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Existing models for describing lava flow emplacement cannot be applied to lava flows on Mars that appear to have inflated pahoehoe morphologies.
A new modeling approach is needed!

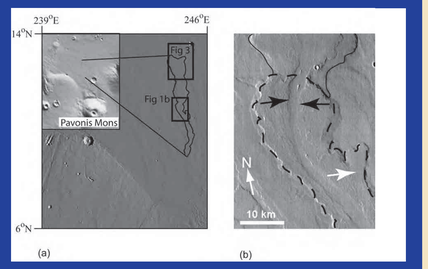
Example `a`a lava flow with well defined margins and channel with flowing lava. This type of flow can be modeled with existing deterministic models for viscous lava flowing on an inclined plane [e.g., Nichols, 1939; Danes, 1977; Baloga,1987; Baloga et al., 1998, 2001; Harris and Rowland, 2001; Baloga and Glaze, 2008; Glaze et al., 2009].

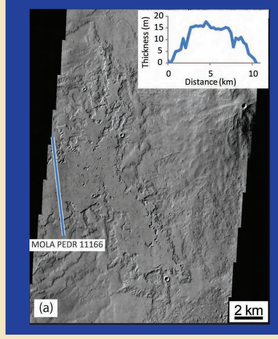
Example pahoehoe lava flows with complex morphology. Because random processes appear to dominate the emplacement, existing deterministic models are not appropriate. A new approach is required! Previous work by Baloga and Glaze [2003] suggested that pahoehoe emplacement can be thought of as a random walk.

- Pahoehoe lavas are typically found on very low slopes (< 5˚), and generally are emplaced with very low effusion rates (< 10 m^3/s).
- Pahoehoe emplacement is often dominated by random effects, such as small-scale topography, self induced topograhy, skin formation and strength, and small variations in discharge rate. Baloga and Glaze [2003] explored correlated random walk, but complex scenarios of emplacement were beyond the capability of the simple approach.
- Can pahoehoe emplacement be "modeled", and if so, how?
- What field observations/measurements are needed to constrain a model?
- Can we use the model to infer emplacement conditions on Mars?

Lava Flows on Mars

The figure at right illustrates a typical a`a channel flow on Mars. This flow, on the plains north of Pavonis, has been modeled using classical models of viscous fluid flow [Baloga et al, 2003; Glaze et al., 2009]. Using such models, if the boundary conditions at the vent are known, the behavior of the flow downstream can be predicted.





High resolution images from HiRISE and HRSC have revealed some lava flows that do not appear to be emplaced as chanellized a`a flows. The lava flow shown at left is also found in the Tharsis region of Mars, but exhibits a very different morphology than the flow above. The flow unit has a very flat top (see inset topograhic profile for MOLA PEDR 11166) that resembles inflated phaoehoe sheet flows made up of coalesced lobes. The flow also exhibits crenulated margins indicative of advance through pahoehoe lobes and toes.

References

Baloga, S, 1987, JGR 92 (B9), 9271–9279.
Baloga, S, Glaze, LS, 2003, JGR 108 (B1), 2031, doi:10.1029/2001JB001739.
Baloga, S, Glaze, LS, 2008, JGR 113, E05003, doi:10.1029/2007JE002954.
Baloga, S et al., 1998, JGR 103, 5133–5142.
Baloga, S et al., 2001, JGR 106 (B7), 13,395–13,405.
Baloga, S, et al., 2003, JGR 108 (E7), doi:10.1029/2002JE001981.
Crisp, JA, Baloga, SM, 1990, JGR 95, 1255–1270.
Crown, D, Baloga, SM, 1999, Bull Volcanol 61, 288-305
Danes, ZF, 1972, JGR 77, 1430-1432.
Glaze, LS, Baloga SM, 2013, JVGR 255, doi:10.1016/j.jvolgeores.2013.01.018
Glaze, LS et al., 2009, JGR 114, doi:10.1029/2008je003278.
Hamilton CW et al., 2013, Bull Volcanol 75:756.
Harris, AJL, Rowland, SK, 2001, Bull Volcanol 63, 20–44.
Harris, AJL, Baloga SM, 2009, GRL doi: 10.1029/2009GL039717.
Hon K et al., 1994, GSA Bull 106, 351-370.
Nichols RL, 1939, J Geol 47, 290-302.

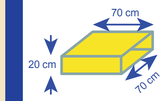
New Simulation Approach Proposed by Glaze and Baloga [2013]

The time-dependent morphology and dimensions of an inflating pahoehoe lobe are simulated by adding a lava parcel volume (see below for definition of a parcel) to an initial condition or the existing lobe at each time-step. "Simulation" means that one or more variables are selected at random from a prescribed probability distribution. Two types of random simulation models of pahoehoe lobe emplacement have been investigated. One simulation model is based on equiprobable lava transfers [Glaze and Baloga, 2013], where every potential lava transfer is equally probable and drawn from a uniform probability distribution. The new simulation model is referred to as "cooling-controlled" because the probabilistic rules governing the lava parcel transfers are determined at each time step by field measurements or theoretical surface cooling curves, i.e, some parcel transfers are more probable than others.

A basal cell (a location in a 2-D spatial array) is selected according to a user-specified probabilistic rule as a site for a lava parcel transfer. The equiprobable model considers all basal locations within the existing lobe to be equiprobable. The cooling-controlled model weights the random selection of locations according to the time-dependent temperature of the upper surface of the lobe at that location.

Both models consider the direction (North, East, South or West) of a transfer to be equally probable. If the location and direction cause a transfer to an empty cell, a breakout and lobe margin expansion occurs that increases the area of the lobe. If the lava transfer is to an occupied location, the lobe locally inflates, increasing the lobe volume without affecting the lobe area.

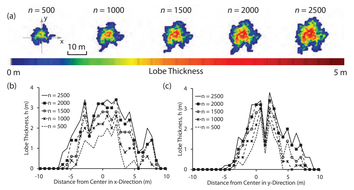
A Lava "Parcel"



Crown and Baloga (1999): Typical toe V = 0.09 m^3

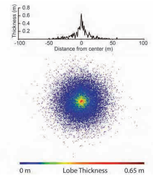
- Single parcel of volume, V, added at each time step, G
- For constant source of supply, volume flow rate, Q = V/G
- Parcel volume equivalent to a pahoehoe "toe"
- Parcel becomes a toe when affixed at the surface or margin of a lobe
- Parcels remain fluid and mobile in the lobe interior

Example: Equi-probable, Point Source



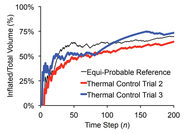
- Planform shape qualitatively similar to observed pahoehoe lobes
- Topographic profile qualitatively similar to observed pahoehoe lobes
- Incorporates inflation with dormant parcels

Signficant Difference from Classical Random Walk



In the Classical Random Walk, every walker must move at every time step. This results in a very diffuse distribution that is about 100 m wide for the N=2500 case shown here for comparison (example is an average of 10 runs). More importantly, the topographic profile shows a concave upper surface.

Inflation



A fundamental feature of the new model is that the random walkers remain dormant but fluid for multiple time steps. For the N=2500 equi-probable example above, this results in a lobe that is 15-20 m wide and concave down. This approach naturally accomodates "inflation" defined as an increase in lobe volume without a corresponding increase in lobe area. Inclusion of thermal control (at right) has minimal influence on the degree of inflation.

Conclusions

- Cooling of individual surface parcels has a profound influence on the 2-D aspect ratio (in the basal plane) of an inflating pahoehoe lobe. This results directly from the assumption that the probability of a breakout is proportional to the temperature of each surface parcel at each time step.
- Cooling of surface parcels significantly increases the lobateness of flow emplacement, compared to the equiprobable model of Glaze and Baloga [2013], even though the direction of internal parcel transfers and margin breakouts is purely random in both approaches.
- Due to cooling, the overall directionality of the lobe is largely established by the random influences during the early stages of emplacement. Even though random effects remain important throughout all phases of emplacement, the lobe retains a 'memory' of the early phases. Thus surface cooling produces a statistical correlation in the random movements of lava parcels. This is analogous to the correlation caused by bulk flow momentum and the tendency of parcels in motion to stay in motion in the same direction.
- Cooling-controlled lobes tend to be significantly longer than their equiprobable counterparts. Deposit topography lacks the degree of central thickening of the equiprobable model. When combined with the relative increase in lobe length, this causes the cooling-controlled lobes to be much thinner and narrower than those of the pure random model.
- The new cooling-controlled model still retains random meandering, overall lobe inflation, and produces noticeable prominent inflationary rises as did the predecessor isothermal random model. However, the cooling-controlled model tends to have breakouts from relatively hot parcels at the front, but intermittent and sporadic upstream breakouts also occur, as typically observed in the field.
- Despite the increased lobateness of the thermally controlled lobes, the inflation fraction is very similar to the equiprobable case.

Introduction of Correlation: Effects due to cooling lava

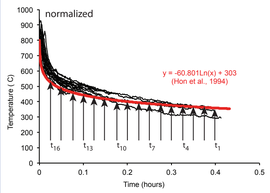
"Correlation" is a statisitcal term that describes the influence of prior steps, i.e., a memory of what occurred previously. When correlation is present, the motion of lava parcels is no longer equally probable. Here we define new probabilities for parcel transfers that are weighted according to the temperature of surface parcels (parcels begin cooling when a new basal cell is first occupied.

Cooling-Controlled Simulation Model Assumptions:

- The probability of a lava parcel transfer is directly proportional to the temperature of the parcel at the surface. The surface temperature is thus a proxy for the mechanical strength of the crust.
- The surface temperature of each surface parcel separately cools at each step according to the empirical formula shown below [Hon et al., 1994].
- Internal transfers only inflate the lobe locally and leave the pre-existing crust undisturbed and continuing to cool.
- The temperature of a breakout at the margin is reset to the initial temperature and the parcel cools subsequently according to Hon's formula.
- Heat is propagated through the crust at a very slow rate. Thus, only the surface parcels (20 cm thick) cool to any significant degree. The interior parcels remain at a constant temperature (~1050C) until they break out into an unoccupied cell.

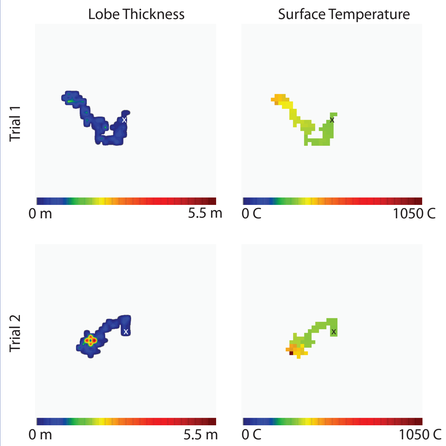
Breakout probability weighted by surface temperature

Figure from Harris and Baloga [2009]



Cooling rates of pahoehoe lavas are well-known, both from theoretical and emperical studies [e.g., Harris and Baloga, 2009; Crisp and Baloga, 1990; Hon et al., 1994]. The figure at left shows measurements of surface temperature as a function of time, as well as an emprical fit to the data from Hon et al. [1994]. We assume that warmer parcels are more likely to be the site of the next parcel transfer than cooler ones. For a lobe with sixteen parcels, the surface temperatures are indicated by the arrows, where Parcel 1 (transferred at Time t_1) is the coolest, and Parcel 16 is the warmest. The normalized transfer probability is proportional to surface temperature.

Example Results: 200 parcels; timestep = 15 s



Example results at left show two trials: Trial 1 (upper) and Trial 2 (lower). In both cases, thickness is shown on the left and surface parcel temperature at each location is shown on the right. Both trials simulate 200 timesteps. For each time step = 15 seconds (analogous to observations by Hamilton et al., [2013]), the total emplacement time represented by the simulations is 50 minutes. In each panel, the 'x' marks the location of the original source parcel. Note that weighting the probabilities by temperature results in more lobate structures. Although lobes occasionally change direction, propagation generally tends in the same direction once established, as expected. Surface temperatures in both examples indicate warmer parcels at the furthest extent from the source, however, there is clear indication of interior inflation in Trial 2.

The thermally controlled examples shown above exhibt greater excursions from the source parcel than the equiprobable reference case (top center panel). A measure of this excursion can be determined by noting the greatest distance reached by any parcel within each trial. The chart at right shows the results of this r_{max} for 300 simulations (each with 200 parcels). This chart shows that there is a great degree of variablity in the maximum lobe length, and that the average maximum excursion is larger than the equiprobable case, even with significantly fewer parcels.