# Simulation of Cooling and Pressure Effects on Inflated Pahoehoe Lava Flows

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**Abstract:**

Pahoehoe lobes are often emplaced by the advance of discrete toes accompanied by inflation of the lobe surface.  Many random effects complicate modeling lobe emplacement, such as the location and orientation of toe breakouts, their dimensions, mechanical strength of the crust, micro-topography and a host of other factors. Models that treat the movement of lava parcels as a random walk have explained some of the overall features of emplacement.  However, cooling of the surface and internal pressurization of the fluid interior has not been modeled. This work reports lobe simulations that explicitly incorporate 1) cooling of surface lava parcels, 2) the propensity of breakouts to occur at warmer margins that are mechanically weaker than cooler ones, and 3) the influence of internal pressurization associated with inflation. The surface temperature is interpreted as a surrogate for the mechanic strength of the crust at each location and is used to determine the probability of a lava parcel transfer from that location.  When only surface temperature is considered, the morphology and dimensions of simulated lobes are indistinguishable from equiprobable simulations. However, inflation within a lobe transmits pressure to all connected fluid locations with the warmer margins being most susceptible to breakouts and expansion.  Simulations accounting for internal pressurization feature morphologies and dimensions that are dramatically different from the equiprobable and temperature-dependent models.  Even on flat subsurfaces the pressure-dependent model produces elongate lobes with distinct directionality. Observables such as topographic profiles, aspect ratios, and maximum extents should be readily distinguishable in the field.

## 1. Introduction.

Numerous models with various degrees of complexity treat terrestrial and planetary lava flows as gravity-driven viscous or turbulent fluids on an inclined plane [e.g., *Nichols*, 1939; *Shaw and Swanson*, 1970; *Danes*, 1972; *Harrison and Rooth*, 1976; *Baloga*, 1987; *Baloga et al*., 1995; *Baloga et al.,* 1998; *Harris and Rowland*, 2001; *Baloga et al*., 2001; *Rowland et al*., 2004; *Baloga and Glaze*, 2008; *Glaze et al.*, 2009; *Glaze et al*., 2014]. These models consider the influence of large-scale forces like gravity, pressure, and momentum, on the bulk flow and are usually intended to estimate the emplacement parameters from the dimensions, morphology and pre-existing slope of the flows. Such parameters include volumetric flow rate, duration of lava supply, flow advance rate, and rheologic characterizations of Newtonian or Bingham fluids. Although the rubbly channelized a`a flow shown in a 1a exhibits elements of randomness, the overall dynamics of the flow are governed by the systematic force of gravity and volume conservation between the active flow and the embanking levees [e.g., *Baloga et al*, 1998*; Glaze et al.,* 2009]. As a result, the list of models above use a deterministic approach that is appropriate for a`a flows such as that shown in Figure 1a. For a given boundary or initial condition, a deterministic model always produces the identical outcome. In the case of a lava flow, once the flow rate, rheology and slope are specified, a deterministic model will always produce exactly the same advance rate and flow depth as a function of time or distance.

The recognition of inflation in pahoehoe lava flows by *Hon et al.* [1994] revolutionized thinking about the style, pervasiveness, and importance of pahoehoe emplacement on the Earth, Mars, and Io [*Self et al.*, 1996, 1998; *Thordarson and Self,* 1998; *Keszthelyi et al.,* 1999, 2000, 2006]. In contrast to the a`a flow shown in Figure 1a, the pahoehoe deposit in Figure 1b is dominated by randomness in size, shape and orientation of individual volume elements (referred to here as toes). This mode of flow emplacement is characterized by toe formation and inflation [e.g., *Rowland and Walker,* 1990*; Hon et al.,* 1994 *Keszthelyi et al.,* 1999*; Baloga and Glaze, 2003; Harris et al., 2007; Keszthelyi et al.,* 2006; *Hamilton et al*., 2013]. High-resolution images of lava flows on Mars indicate that both channelized a`a and pahoehoe styles of emplacement may also occur in planetary environments (Figure 2). In the pahoehoe toe regime, stagnation, inflation, and toe formation are most closely tied to the final topography, dimensions, and morphologic features. The combination of low slopes and low flow rates typical of pahoehoe emplacement results in minimal disruption of a rapidly forming, insulating crust [*Hon et al.,* 1994]. The efficient crustal insulation limits cooling to conduction only, allowing the interior lava to remain fluid for long periods of time in contrast to a`a flows where fresh lava is continuously exposed at the surface [e.g., *Crisp and Baloga*, 1990; *Wright and Flynn*, 2003, *Wright et al*., 2011].

Although the forces of gravity, pressure and momentum are present in pahoehoe emplacement, other influences act on each individual volume element, or parcel, of lava with a randomizing effect. The mechanical strength of the cooling surface, pressure, crystallization, micro-topography (i.e., centimeter-scale relief) and similar factors cause non-gravitational forces to dominate the dynamics of emplacement. These forces at the parcel-scale are subject to natural variations that necessitate an approach, different from the classical deterministic models, that accounts for ubiquitous random effects and inflation.

In current practice, models of a`a flows are generally set up by considering the forces that act on control volumes that slice through the flow from the underlying surface to a height characteristic of the entire flow depth. In theory, one could divide a large lava flow up into tiny volume parcels and consider the effects of these forces on each volume element. However, for large flows (e.g., channelized a`a flows), such an approach significantly increases computational complexity without adding significant new information. The essential effects of fluid flow are retained when one considers a volume element that is equal to the full thickness and width of the flow (a control volume up to many tens of cubic meters).

For pahoehoe flows that are dominated by random effects, the scale has been set in recent works at a parcel scale typical of an individual toe [*Glaze and Baloga*, 2013], with a volume of $0.75 \times 0.66 \times 0.2$ m$^3$ [Crown and Baloga, 1999]. At this scale, a parcel at the surface of a lobe is subject to many forces with random effects. These include forces associated with cooling, cracking, rupturing, stretching and various forces from neighboring parcels on the surface and beneath the parcel. A parcel in the interior of a lobe may be influenced by forces associated with internal processes such as crystallization and vesiculation, and external forces from neighboring parcels with a different rheology, momentum, shear state, crystal content and ultimately the propagated influence of the underlying lobe topography and the mechanical strength of the crust and visco-elastic layers. Thus, for a pahoehoe lobe, the behavior of the individual parcels (at the scale of a typical toe) must be considered and then aggregated together to understand the overall properties of the entire lobe.

The fundamental difficulty in developing a new model for pahoehoe lava flows is that the random effects associated with inflation, internal fluid pressure, and crustal strength dominate the emplacement [*Hon et al*. 1994*; Thordarson and Self,* 1998*; Keszthelyi et al.,* 1999*; Crown and Baloga, 1999; Baloga and Glaze, 2003; Harris et al., 2007; Glaze and Baloga, 2013]*. Thus, in contrast to a deterministic approach, a model that includes random effects produces a distribution of outcomes for the same given boundary or initial conditions. In the case of a lava flow with the same specification of flow rate, rheology and slope as a deterministic model, each run (or simulation) of a random model will result in a slightly different advance rate and flow depth as a function of time or distance.

When many runs of a random model are performed, the suite of advance rates and flow depths results in a distribution of these variables with some mean values and dispersions. Assuming the basic physics is the same for these two types of approaches, one would presume that the mean values of the random model approach those of the deterministic model if enough random simulations are performed.

The key point is that there is uncertainty associated with the outcomes of a random model. With only one run, there is no way to determine whether a particular simulation has produced an outcome near the mean value or something that is rather unlikely. This can only be determined by acquiring enough simulations to gauge the dispersion of the outcomes.

*Baloga and Glaze* [2003] developed an initial 2-dimensional model for pahoehoe emplacement based on classical uncorrelated and correlated random walks [C*handrasekar*, 1943]. They showed that a wide variety of field observables could be explained by such an approach. The topographic profiles of simple lobes, the tendency for central channel development, frontal steepening and similar pahoehoe manifestations were broadly in agreement with field observations. However, the computational requirements for further advances at that time were intractable.

*Glaze and Baloga* [2013] presented a more comprehensive model that simulated random transfers of individual lava parcels within a pahoehoe lobe as a function of space and time. The model was based on volume conservation and a set of probability rules for the parcel transfers. The output of the model (Figure 3) was 3-dimensional topography that showed how the lobe thickened and expanded with time subject to a variety of factors such as the source geometry, confining barriers, and volumetric flow rate. Of particular interest was the degree of lobe inflation, i.e., the degree to which the existing lobe thickens at the expense of expansion at the margins. The basic model described in *Glaze and Baloga* [2013] assumes that all occupied basal locations are equally likely to be the site of the next parcel transfer and is referred to here as the 'equiprobable' model.

The statistical concept of correlation [*Sheskin*, 1997] in lava transfers (i.e., the statistical dependence of one lava parcel movement on another) was also explored by *Glaze and Baloga* [2013]. Correlation in the lava transfers at the margin was shown to have a significant effect on the lateral expansion, the thickness profiles and the rate of expansion of the lobe. However, plausible physical causes for the correlation were addressed only in general terms.

The most obvious physical process omitted from the earlier models was the cooling of the outer surface of the lobe. The primary issue is the extent to which such cooling would influence the morphology, dimensions and inflation of the lobe. Another physical process omitted from the earlier models is the role of the internal fluid pressure. The simulations of *Glaze and Baloga* [2013] clearly showed local topographic highs and lows within the lobe that would pressurize all connected parts of the hot mobile fluid interior. Thus one might expect topographic gradients to influence breakouts in remote parts of the lobe as is often observed in the field.

In this work the explicit cooling of surface parcels has been added to the simulation approach Glaze *and Baloga* [2013]. The temperature of the surface units is modeled by Hon's surface cooling formula [*Hon et al*., 1994]. The probability rules of *Glaze and Baloga* [2013] have been modified to increase the probability of a transfer when the surface temperature is relatively high and decrease transfer probabilities for cooler parcels. Simulations of this process are referred to as the 'temperature-dependent' model.

Another modification of the probability rules of *Glaze and Baloga* [2013] addresses the influence of inflation within the lobe, resulting in a third distinct type of simulation. Inflation is defined here as an increase in lobe volume with no concurrent increase in lobe area. Internal transfers within an existing lobe result in a local inflation that produces topographic high points. Basic physics considerations suggest that the increase in lobe thickness causes an increase in the pressure throughout all connected parts of the fluid interior, whether near the topographic high or not. Such an increase in pressure increases the probability of a breakout at the mechanically weaker confining locations of the lobe. The third type of simulation in this work forces breakouts to occur at the weaker locations of the lobe as governed by the cooling of the surface units. Simulations of this process are referred to as the 'pressure-dominated' model. Opportunities for future theoretical and field studies are given in conclusion.

## 2. The Simulations

The term 'simulation' in this work means specifically that one or more of the input quantities of the simulation is a random variable. In a simulation, a particular value of each random variable is drawn from a prescribed probability distribution. Each simulation represents a single trial or 'realization' of all the output observables at the end of the simulation. Due to randomness, each simulation produces a different set of outcomes depending on the nature of the underlying probability distributions. Use of this simulation approach allows exploration of the range of expected outcomes for each case of prescribed probabilities.

Each of the three simulation cases examined here ('equiprobable', 'temperature-dependent', and 'pressure-dominated') is based on different sets of probabilistic rules for lava transfers that are based on different physical considerations. All simulations assume a flat pre-existing surface, with a constant rate of lava supply, where each parcel volume of 0.09 $m^3$ is equal to a typical pahoehoe toe (see *Glaze and Baloga* [2013] for more details on the basic model). Because the volume of a lava parcel is fixed, the volumetric supply rate can be adjusted by simply changing the time interval between parcel additions at the source. A time interval of 15 seconds is used in the results presented below, based on average volume supply rates observed for a small (< 10.4 $m^3$) toe lobe in Hawaii [*Hamilton et al*., 2013]. Time varying and fluctuating supply rates can be modeled by modulating the time interval between parcel additions at the source. Such analyses are reserved for future analyses.

**2.1. Equiprobable Simulations.**

In the equiprobable case, the probability of a transfer of lava at each time step of the simulation is considered to be a constant for all basal locations within a lobe that are occupied by at least one lava parcel [*Glaze and Baloga*, 2013]. There are two random selections by the algorithm at each time step. The first determines the basal cell location that will be the source of the next transfer. The second determines the direction of the next transfer from the source location (i.e., north, south, east or west). The dimensions and morphology of the lobe are updated with each time step. A comprehensive description of this type of simulation is given in *Glaze and Baloga* [2013].

The simulated equiprobable lobe shown in Figure 3 assumes a single parcel as the lobe source, and subsequent release of 2500 additional lava parcels. Using 0.09 $m^3$ as the typical volume of an individual toe [*Crown and Baloga*, 1999], the total volume of the lobe is 225 $m^3$. This is consistent with the range of volumes reported in field studies of lobes emplaced predominantly in the toe regime [*Crown and Baloga,* 1999; *Baloga and Glaze*, 2003; *Hamilton et al.,* 2013].

**2.2. Temperature-Dependent Simulations.**

Ultimately, the mechanical strength of the crust controls the movement of lava within the lobe and at its margins. The surface temperature is taken here as a proxy for the mechanical strength of the crust. The surface cooling rates of pahoehoe lavas are well known, both from theoretical and empirical studies [e.g., *Harris and Baloga*, 2009; *Crisp and Baloga*, 1990; *Hon et al.*, 1994; *Wright and Flynn*, 2003]. The fundamental assumption of the temperature-dependent approach is that warmer parcels are more likely to be the site of the next transfer than cooler ones. Specifically, it is assumed that the probability of a lava parcel transfer at a particular location is directly proportional to the temperature of the surface parcel at that location. Mathematically, the probability that basal location $j$ at time $t$ is the site of the next parcel transfer is

$$P_j(t) = \frac{T_j(t)}{\sum_i T_i(t)} \quad (1)$$

where $T_j(t)$ is the temperature of the surface at location $j$ and the $i$ summation is taken over all occupied basal locations at time $t$. Once the location for the lava transfer has been determined by (1), the current algorithm treats the four possible directions for the lava transfer as equiprobable.

The simulations assume that a parcel of lava begins to cool when a cell is first occupied and thus exposed to the atmosphere. Other parcels may be transferred to that cell location, but are assumed to increase the volume (inflate) at that location, keeping the original cell on the surface to continue cooling. The empirical formula of *Hon et al*. [1994] is used to cool each surface parcel separately for each time step of the lobe emplacement.

$$T(t) = -60.8\ln(t) + 303 \quad (2)$$

where $t$ is measured in hours and $T$ is given in $^{o}$C.

In the present model, internal transfers only inflate the lobe locally and leave the pre-existing crust undisturbed and continuing to cool. Heat is propagated through the crust very slowly [e.g., *Crisp and Baloga*, 1990; *Harris and Rowland*, 2001]. Thus, it is assumed that only the surface parcels (20 cm thick) cool to any significant degree. For the emplacement times considered here (1/2 – 5 hours) the thermal boundary layer penetrates only to a few cm or less (*Hon et al*., 1994, e.g., Figure 10; *Crisp and Baloga*, 1990)

The thermal properties of basaltic crust that insulate the fluid interior have been documented for many years (e.g., *Peck*, 1978; *Crisp and Baloga*, 1990; *Lipman and Banks*, 1987; *Moore,* 1987; *Hon et al.*, 1994). Thus in this work the interior parcels are assumed to remain at a constant temperature (~1140 ºC [*Lipman and Banks*, 1987]) until they break out into an unoccupied cell at the existing margin of the lobe. The initial surface temperature of a breakout at the margin (occupation of a new cell location) is set to 1140 ºC no matter when it occurs in the simulation. Subsequently the breakout parcel cools according to the formula of *Hon et al.* [1994].

Figure 4 shows the *Hon et al.* [1994] cooling curve for a time period of 24 minutes. For a lobe with sixteen parcels, and 1.5 minute time steps (equivalent to an extremely low volume flow rate used here for illustrative purposes only), 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.

In the temperature-dependent model, the probability for a parcel transfer is weighted by the surface temperature. The probability distribution for determining which location will be selected for the next parcel transfer is obtained by summing the temperatures of all surface parcels to obtain a normalization at that particular time step. The assigned probability for a transfer at a given location is simply the current surface temperature at that location divided by the normalization at that time step. The example in Figure 5 illustrates the companion, normalized probability (density) for the example in Figure 4, where the equiprobable case is also shown for comparison.

Two typical 200-parcel examples of the temperature-dependent simulation are shown in Figure 6. In these simulations, a parcel of lava volume was added to the lobe every 15 seconds, such that the lobe was emplaced in 50 minutes. Although there is a great deal of variability and a number of complicating factors (e.g., changes in topography, lava supply rate), such an emplacement time is reasonably consistent with a lobe volume of 18 $m^3$ (200 parcels $\times$ 0.09$m^3$).

The general topography and morphology of these lobes is very similar to the equiprobable case. The physical basis for this is that the cooling of the surface parcels is so rapid that most parcels are on the long flat end of the cooling curve (Figure 4) and thus have roughly the same probability of a transfer. There is a slight difference however, as suggested by the elevated surface temperatures at the margin.

A measurable quantity of interest is the maximum extent of the lobe from the source. This distance is denoted as $r_{max}$. To compare the temperature-dependent and equiprobable cases, 300 simulations were done for each approach. For each individual simulation the maximum distance from the source was computed for a lobe of 200 parcels. The results are shown in Figure 7a. The shape of the distribution of $r_{\max}$ in both cases is very similar to a lognormal distribution. The temperature-dependent simulations have a slightly higher mean value, meaning that the temperature-dependent cases tended to travel somewhat farther than the equiprobable cases.

Given the great degree of variability (i.e., the high standard deviations) of both simulation approaches it is highly unlikely that these two emplacement scenarios could be distinguished in the field. Moreover, there are a host of other complicating factors, such as variations in pre-existing topography, lava supply and so forth that would complicate the discrimination.

### 2.3. Pressure-Dominated Simulations.

These simulations extend the temperature-dependent algorithm by including the influence of internal fluid pressure increases due to inflation. When there is an internal lava transfer to a location within the lobe the thickness at that location increases. This local inflation increases the fluid pressure not only at that location, but also at all connected fluid locations within the lobe. This is similar to inflating a balloon with various mechanical strengths at different parts of its surface.

The pressure-dominated algorithm captures the influence above by using a combination of random and systematic influences on the parcel transfers. When there are no internal transfers (and thus no inflation), the location of the next breakout is determined randomly from the probabilities derived from the local surface temperatures, i.e., fresh locations have a higher probability than older ones (identical to the temperature-dependent case). However, the rules change somewhat after there have been internal transfers (Figure 8). After one or more internal transfers, there will eventually be a ‘breakout’ where a parcel will be transferred to a previously unoccupied cell. When this happens, the pressure-dominated model assumes that the build up of pressure results in the systematic selection of the last breakout location as the source in the next time step and only the direction of the subsequent breakout is chosen at random.

The inclusion of inflation pressure in this way has a dramatic effect on the morphology and dimensions of the lobe particularly its plan form shape and maximum length (Figure 9). The pressure influence in the algorithm provides a statistical correlation, i.e., a systematic effect imposed on the randomness. Such correlations were suggested in *Baloga and Glaze* [2003] and *Glaze and Baloga* [2013], but were only vaguely attributed to possible physical causes. Here the correlations in lava transfers are specifically attributed to an increase in the hydrostatic pressure within the lobe and a temperature-dependent weakness at the margin.

The pressure-dominated simulations have a distinct lobate morphology that is markedly different from the more axisymmetric equiprobable and temperature-dependent simulations. The examples in Figure 9 show the concentration of warmer parcels toward the front of the advancing lobes. In particular, it is interesting to compare Trial 2 to the equiprobable and temperature-dependent cases. Despite the extent of the flow being similar to the equiprobable and temperature-dependent simulations, the surface temperature distribution is quite different from those in Figure 6. The pressure-dominated simulations show a very marked directionality with the warmer parcels clustered at the end of the lobe, even though the flow has wrapped around on itself, whereas the temperature-dependent lobes have warm parcels distributed along the entire margin of the lobe.

The distribution of maximum distances from the source is shown in Figure 7b for 300 simulations of 200 parcels each at 15 second intervals. The mean value of $r_{max}$ is now 13.2 parcels, almost double the equiprobable and temperature-dependent cases. Because the total volume of all the simulations has been held fixed, the greater length of these lobes gives a much thinner overall thickness as noted in *Glaze and Baloga* (2013).

Despite the more lobate plan form and relatively smaller thicknesses, the pressure-dominated lobes exhibit comparable degrees of inflation, retaining this ubiquitous pahoehoe emplacement characteristic. Figure 10 shows the rate of inflation for a typical equiprobable reference case versus two typical examples of the pressure-dominated case, all with 200 parcel simulations. It is readily seen that the overall vertical growth the lobe is essentially the same. Unlike the morphology and extent of the lobe, this aspect of emplacement cannot be used to distinguish the underlying physical processes.

**3. Conclusions.**

This work shows that the cooling of the surface alone has little influence on the morphology, dimensions and the rates of lateral expansion and inflation compared to the equiprobable, temperature-independent simulations of *Glaze and Baloga* [2013]. Lobes with surface parcels that cool according to Hon's formula [*Hon et al.*, 1994] retain the approximate Gaussian topography and symmetric plan form identified by field observations and the earlier temperature-independent simulations [*Crown and Baloga*, 1999; *Baloga and Glaze* 2003; *Glaze and Baloga*, 2013]. The differences in morphology, dimensions, aspect ratios, and maximum extents from the source for lobes with cooling and constant temperature surface units are so slight they are unlikely to be distinguishable in the field. Such a result might be anticipated intuitively for this emplacement regime (e.g., 200 parcels released at 15 second intervals) because radiative cooling is so rapid that most locations within the lobe have approximately the same probability for an internal lava transfer or breakout at the margin.

When the internal inflation pressure originally identified by *Hon et al.* [1994] causes systematic breakouts at the warmest (and therefore weakest) margins, the morphologies and dimensions of the simulated lobes are dramatically different from the purely temperature-dependent and equiprobable cases. The internal fluid pressure due to inflation is felt uniformly with all contiguous fluid regions within a lobe so that the warmest and weakest margins become the most likely locations for margin expansion. This is a physical explanation for the correlations considered in *Baloga and Glaze* [2003] and *Glaze and Baloga*, [2013]. Both works concluded that correlation was required to explain a variety of observed lobe features such as directionality, aspect ratio, topographic cross-lobe profiles and the tendency to form channels and embanking levees.

It is the combination of inflation pressure and the mechanical weakness of the warmer and weaker margins that causes lobes to become significantly more elongate than their temperature-dependent and equiprobable counterparts. The overall thickness and plan form shapes of lobes formed by this process are readily distinguishable from the temperature-dependent and equiprobable cases. The evolving surface temperature distributions of the pressure-dependent lobes are also readily distinguishable from the purely temperature-dependent and equiprobable cases. It is noteworthy, however, that the time-dependent rate of inflation remains essentially the same in all cases.

The types of simulations performed in this work offer the promise of developing quantitative inferences about emplacement conditions from the dimensions and morphologies of pahoehoe lobes that were not observed while they were active. Comprehensive field campaigns for active lobes with a range of local discharge rates are needed to identify the appropriate model for detailed data-theory comparisons. These measurements should include pre-existing topography, time-series changes in flow morphology, and thermal imaging. This would permit isolation of the different physical processes governing the shape and dimensions of the lobe and a statistical characterization of the random effects. The next steps in advancing these models are the incorporation of an underlying regional slope and the influence of micro-topography. Such advances would provide a methodology for developing quantitative inferences about the unobserved emplacement of terrestrial and planetary pahoehoe lava flows.

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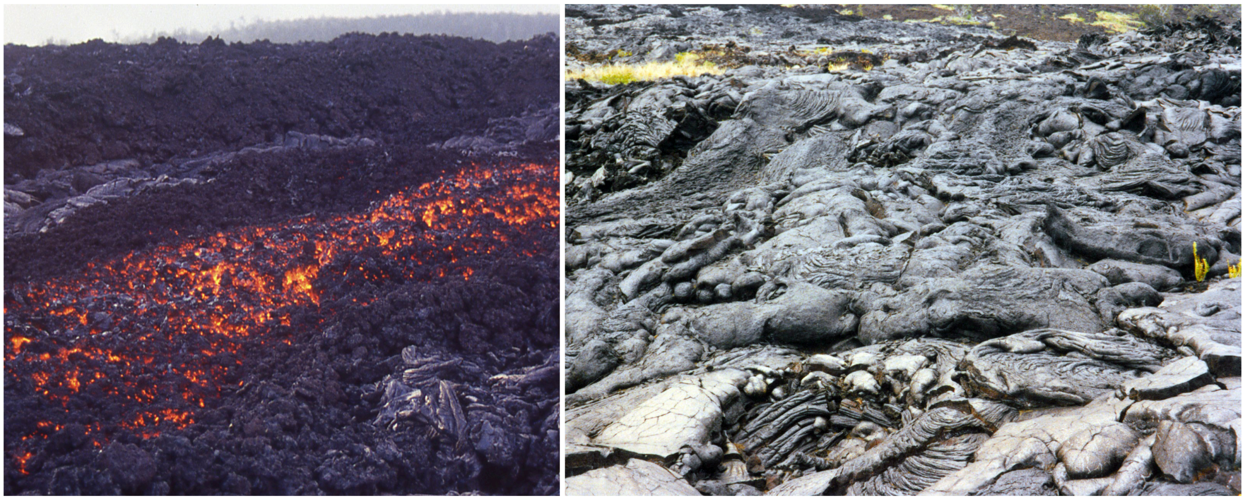
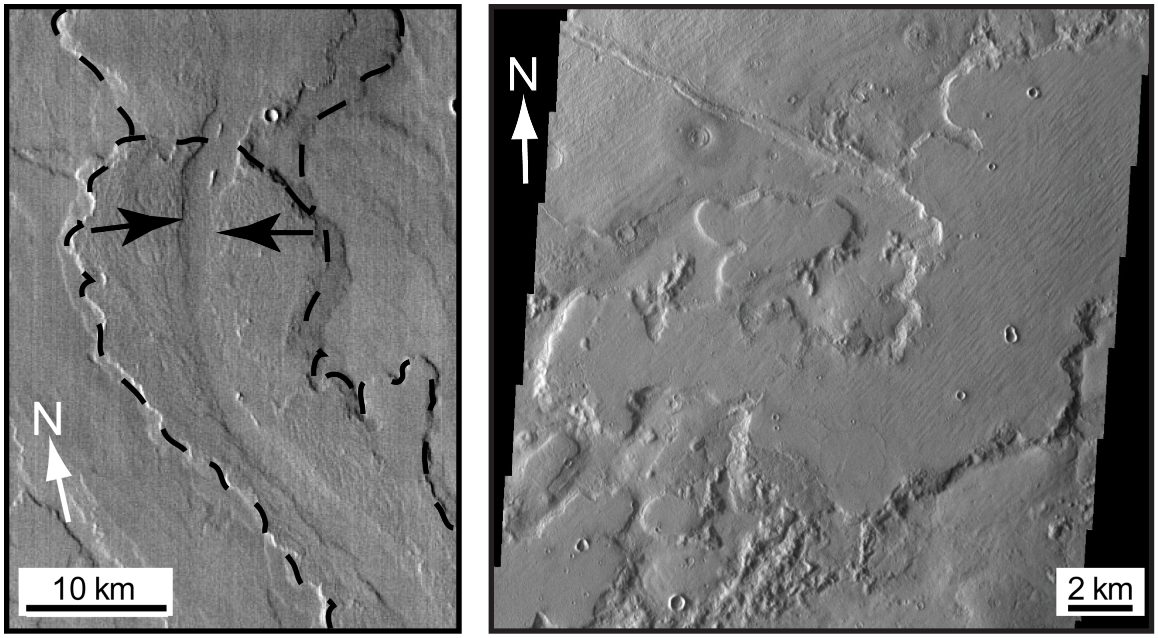
Figures and Captions



(a) (b)

Figure 1: (a) Example active channelized a`a lava flow. The key morphologic feature of a`a lava flows is the blocky surface. Indicators of lava transport processes are the raised levees along the lateral flow margins and the central channel containing the flowing lava. Image used with permission of S. Rowland. (b) Field of pahoehoe toes. The key morphologic feature of pahoehoe lava flows is the smooth, often ropy surface. The complexity of pahoehoe transport and emplacement is illustrated by the randomness in dimensions and orientations of the lava toes and lobes in this typical flow field.




(a) N of Pavonis Mons (b) NW of Elysium Mons

Figure 2: Examples of (a) a`a channelized flows and (b) putative pahoehoe lava flows on Mars. The a`a flow is characterized by lateral levees (dashed line) and a well-established channel (black arrows) for transporting lava to the flow front. The pahoehoe lava flow is characterized by a broad flat surface that lacks any evidence of a channel, and that is morphologically similar to terrestrial lava flows where pahoehoe lobes have coalesced to form flat plateaus. The flow also exhibits margins with a great deal of variability analogous to terrestrial flows that advance through pahoehoe toe lobes. Figure (a) is a Thermal Emission Imaging Spectrometer (THEMIS) infrared image (frame I01739006). Figure (b) is a THEMIS visible image (frame V14162005).

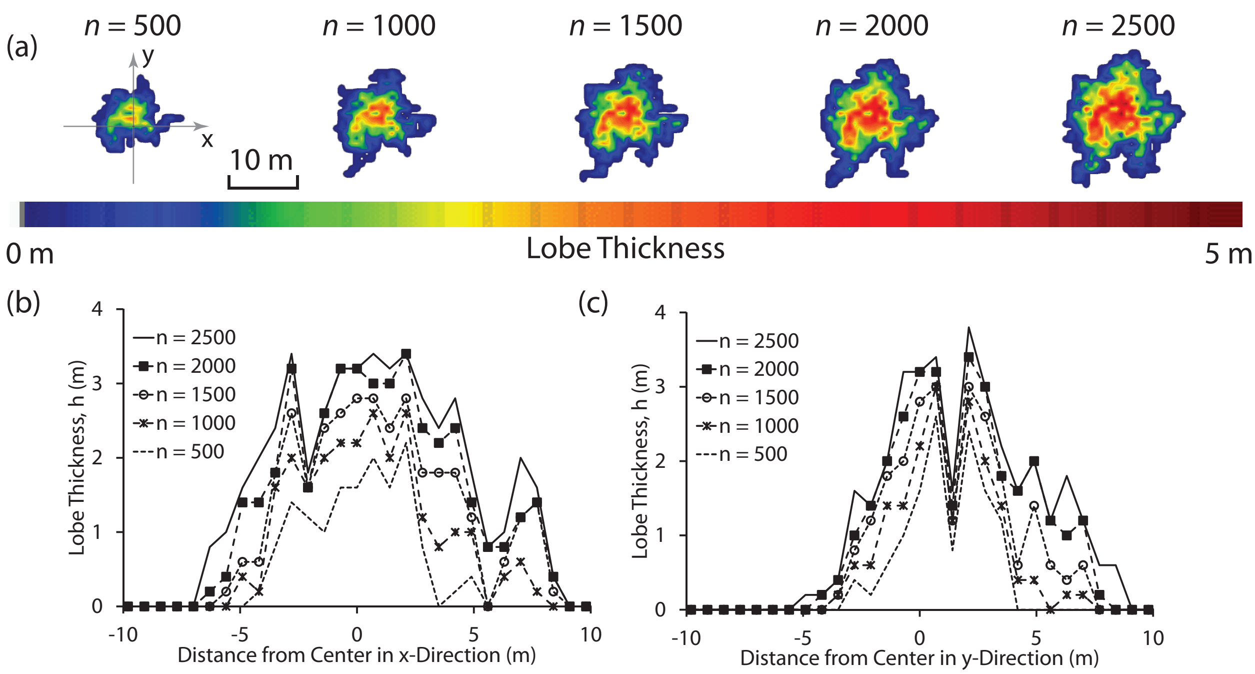



Figure 3: Typical example of an equiprobable simulation. (a) 3-dimensional topography at five time steps (n = 500, n = 1000, n = 1500, n = 2000, n = 2500). The source parcel location is located at the intersection of the *x* and *y* axes. Corresponding cross-lobe topographic profiles in the (b) *x* and (c) *y* directions are also shown. Generally the lobes are symmetric with the variability in both plan form and topography being typical of field observations. Figure reproduced with permission from *Glaze and Baloga* [2013].

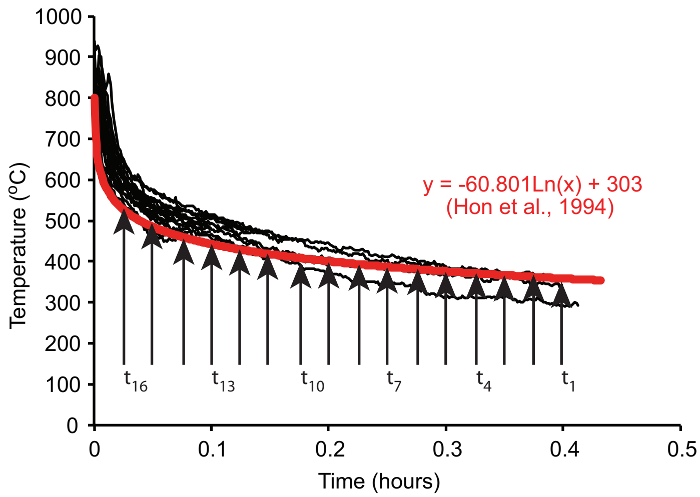



Figure 4: Pahoehoe surface cooling curves (black) adapted from *Harris and Baloga* [2009] and empirical model (red) from *Hon et al*. [1994]. Model surface temperatures are indicated for 16 time steps (where each time step is 90 seconds and every parcel is exposed at the surface for illustration purposes). The first parcel (time step 1) has been exposed at the surface for 0.4 hours (1440 s) and has the coolest surface temperature. The most recent parcel (time step 16) has only been exposed for 90 seconds and has the highest surface temperature.

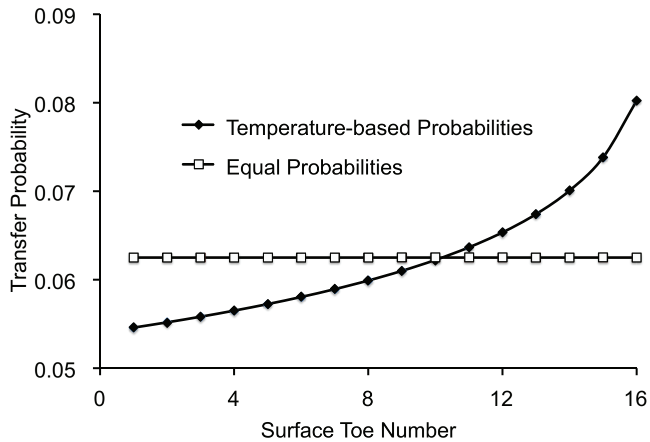



Figure 5: Transfer probabilities for the temperature dependent model (solid diamonds) corresponding to the time steps shown in Figure 4. Probabilities are directly correlated to the surface temperature and the length of time a parcel has been exposed at the surface (all parcels are exposed at the surface for this example). Toe 16 is the most recent parcel to be exposed. Thus it has the highest surface temperature and the highest likelihood to be the location of the subsequent parcel transfer. The equiprobable distribution is shown with open squares for comparison.

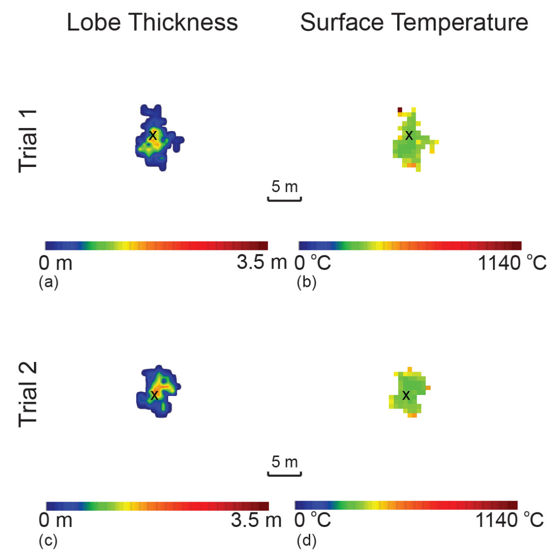



Figure 6: Two example temperature-dependent simulations (Trials 1 and 2) with 200 parcels each. The location of the initial parcel is indicated by an 'x'. In each Trial, the left panel shows a smoothed representation of the lobe thickness, and the right panel shows the surface temperature.

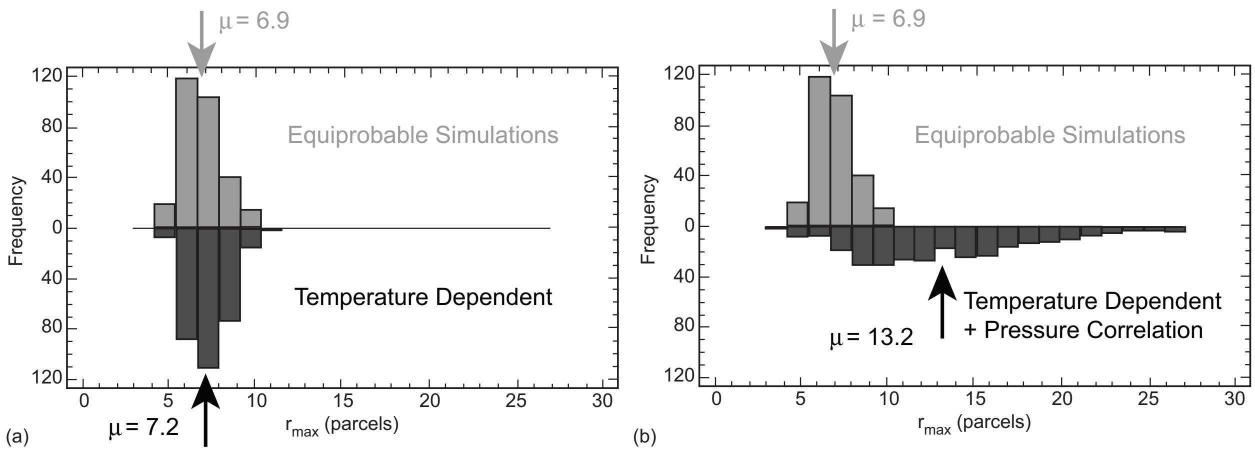



Figure 7: Distribution of maximum distance traveled ($r_{max}$) in 300 simulations. (a) Comparison of $r_{max}$ for 300 equiprobable simulations with 300 temperature-dependent simulations. (b) Comparison of 300 equiprobable simulations to 300 simulations with both temperature dependent probabilities and correlations based on increased pressure following internal transfers.

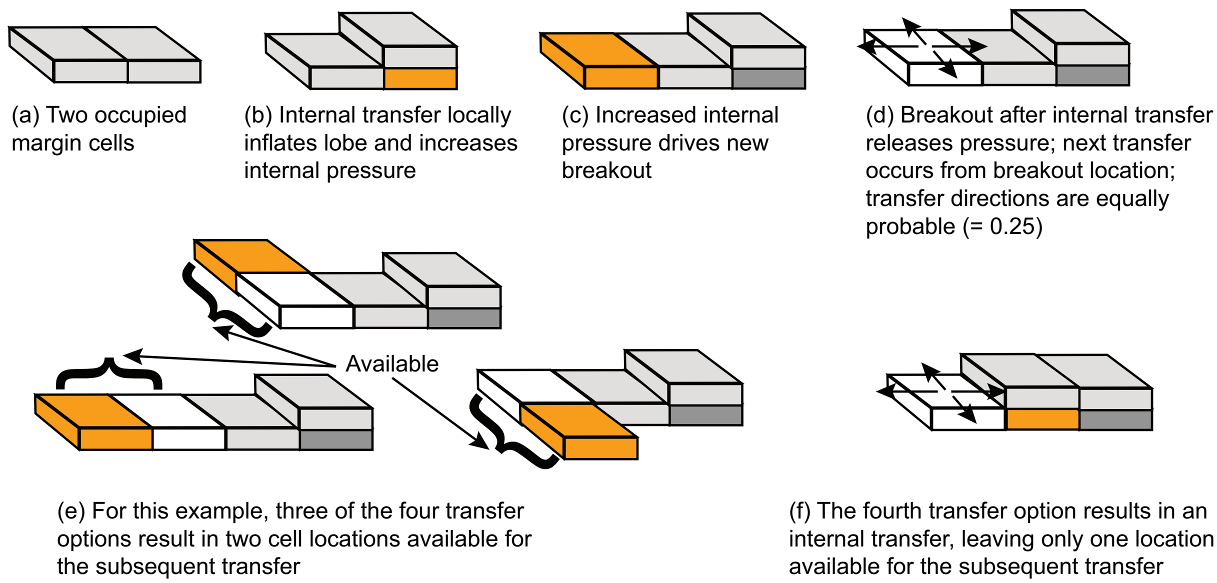



Figure 8: Cartoon illustrating the influence of pressure buildup at the location of two occupied cells along the lobe margin (a) following inflation due to one or more internal parcel transfers (b). Following a new breakout expanding the lobe's areal extent (c), only the most recently occupied locations (weakest crust) are available for future parcel transfers (d – f). The net result of the pressure effect is to elongate the planform shape of the lobe.

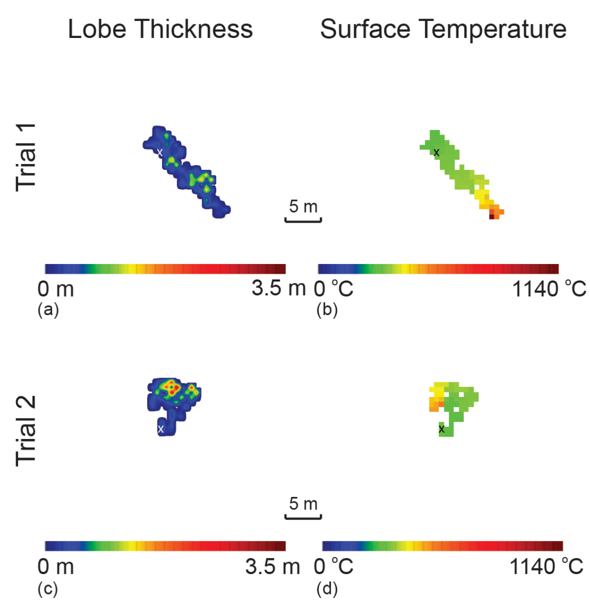



Figure 9: Two example simulations (Trials 1 and 2) with 200 parcels each with both temperature-dependent probabilities and pressure correlation. The location of the initial parcel is indicated by an 'x'. In each Trial, the left panel shows a smoothed representation of the lobe thickness, and the right panel shows the surface temperature.

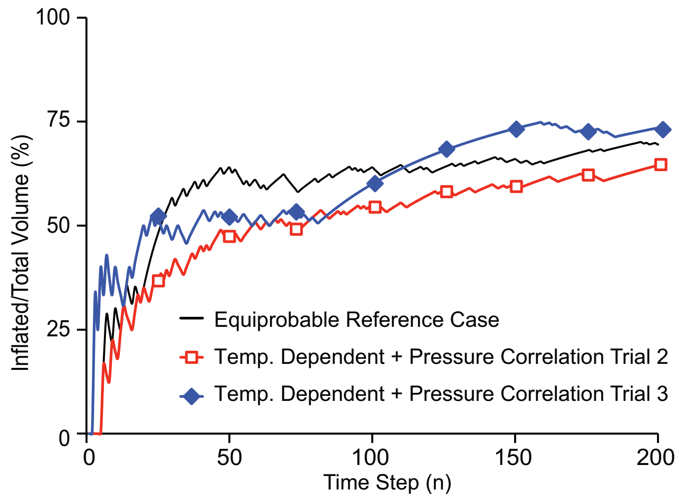



Figure 10: Three example simulations with 200 parcels each. The fraction of the total lobe volume that is represented by internal parcel transfers (transfers that increase the lobe volume without increasing the lobe area) is shown for the Equiprobable reference case as well as two independent trials of the pressure-dominated case.