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The maximum size of inflated flood lavas: implications for the origin and evolution of Athabasca Valles, Mars

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1. Introduction

Effusive volcanism is a common geologic process in the inner solar system, and basalts cover the majority of the surfaces of Earth and Mars [e.g., 1, 2]. Volcanic activity has diverse styles of eruption, but cooling-limited, inflated, pāhoehoe-like sheet flows have been hypothesized to be the standard mechanism of lava emplacement on terrestrial planetary surfaces [3, 4]. Despite the significance of such lava flows, many aspects of flow behavior remain poorly quantified. Here, we address one such question: Under realistic discharge rates, cooling rates, and flow velocities, what is the maximum areal extent a single inflated, basaltic sheet flow can obtain?

To quantify flow behavior on Mars, we use numerical models to adapt parameters observed in the field or laboratories of terrestrial lava. We use a finite element method (FEM) flow model to estimate flow velocities of Martian basaltic lavas. These velocities are input into a model of the lateral spreading and crustal thickening of the inflating lava flow. We calculate the amount of lateral extent the feature can obtain before all lava is cooled into solid, brittle crust. We apply our results to Athabasca Valles, a lava-draped channel system on Mars whose formation remains debated [5–7].

2. Flow Models

We use the open-source FEM software package Elmer to solve the Stokes equations (which are conservation of mass and momentum equations) for a multi-rheological [8] lava flow. We choose a temperature-dependent rheology [9] and physical parameters appropriate for Martian flows [e.g., 10].

We find that for a set of nominal physical parameters (lava density 2500 kg/m^3, flow thickness 40 m), the maximum velocity of a Martian basaltic flow is 8 m/s. We note this velocity is consistent with estimates derived for Athabasca Valles from simple analytic approximations [4]. As expected, velocity increases with increasing lava density or flow thickness. Interestingly, the possibility of thicker flow units on Mars compared to Earth [10] do not lead to greater Martian flow velocities compared to terrestrial lava flows because of the counteracting effect of weaker Martian gravity. Our flow model results are described more extensively in a previous report [11].

3. Lateral Spreading

An inflated lava flow's multi-rheological structure limits the surface area to which the flow can extend over. A significant fraction of newly effused lava contributes to thickening of a brittle crust, removing volume that can spread laterally. If a lava flow is continuously sourced from a single point on the surface, it will grow large enough in areal extent such that new lava cools in the crustal thickening process before it reaches the terminus of the flow. Thus, under such assumptions, cooling of lava causes effusive flows to have maximum areal extents.

We model a parcel of lava as it flows through the molten core of an inflating basaltic flow. As the lava parcel travels through the core, at each time-step, we calculate the portion of that parcel that cools and solidifies, thereby thickening the brittle crust. The cooling rate is assumed to be 0.054 m hr^{-1}, calculated using cooling models [12]. Such a rate assumes no rainfall and thus is more applicable to Mars than the empirical values reported in [8] from high-rainfall terrestrial environments.

For Athabasca Valles, we assume a flow velocity through the molten core of 8 m/s, in accordance with our FEM model results. We assume lava flows radially outward from a single point source, either in a circle or in an angular sector. We consider the high discharge rates (10^6–10^7 m^3/s) proposed in previous work specific to Athabasca Valles [4].

We find that under the assumptions described above, the Athabasca Valles flood lava cannot obtain an area >1000 km^2 in a single event (Fig. 1). The actual area covered by the lava, based on geologic mapping, is 2.5×10^5 km^2. A lava flow that grows outward in the plan-view shape of an angular sector can obtain a greater length compared to one that grows radially in all directions (Fig. 2). A Martian flow that grows in a narrow 1° angular sector obtains a maximum length of ~150 km, implying that multiple eruptive events from the same source could emplace a composite flow field with an area as high as ~7×10^4 km^2.

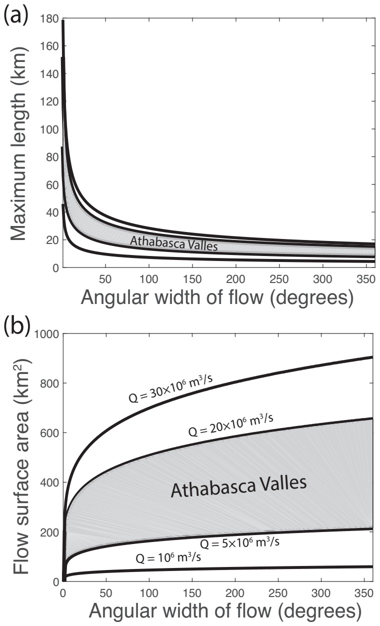

Figure 1. (a) Maximum lengths and (b) surface areas of pāhoehoe-like flood lavas on Mars for various discharge rates.

4. Conclusions

We find that a typical pāhoehoe-like inflated sheet flow of basalt cannot account for the observed shape and size of the Athabasca Valles flood lava on Mars, even for the highest allowable lava discharge rates. Therefore, the lava is unlikely to represent a standard pāhoehoe-like feature whose evolution is primarily governed by cooling and inflation.

Instead, we propose the Athabasca Valles lava likely experienced a significant degree of topographic control from preexisting structures. This result is supportive of the hypothesis that an aqueous flood carved out the valley before lava was subsequently emplaced and caused further erosion. This formation mechanism may also be supported by geologic analysis of the current topography [7].

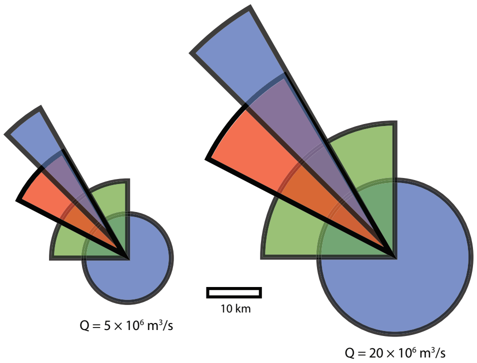

Figure 2. Scaled plan-view diagrams of the maximum surface areas covered by pāhoehoe-like flood lavas on Mars flowing radially outward from a point source.

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