SIMULATIONS OF LAHAR EMPLACEMENT ON EARTH AND MARS. S. A. Fagents[1] and S. M. Baloga[2], [1]HIGP/SOEST, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822; fagents@hawaii.edu, [2]Proxemy Research., Laytonsville MD 20882.

Introduction: Volcanic debris flows, or lahars, are common phenomena at terrestrial volcanoes where loose, unconsolidated volcanic material (e.g., ash and tephra) combines with abundant water on the flanks of the volcano to produce a fast moving, turbulent slurry. Such flows are commonly produced by the breaching and sudden draining of a crater lake, interaction with water or ice of a pyroclastic flow, or remobilization of an ash deposit by precipitation. On Earth, lahars may flow for tens of kilometers at rapid velocities and represent a significant hazard for anything in their path. On Mars, the existence, currently or in the past, of significant regolith ice stores [e.g., 1-5] polar ice caps, potential lake environments [6-8], glaciers or ice sheets [e.g. 9,10], provides ample water with which volcanic heat and friable deposits may have interacted to produce debris flows.

We have developed a mathematical treatment of the time-dependent advance of lahars and dilute debris flows that can be applied to topographic data in order to predict the depths, velocities, and transit times of such flows on both Earth and Mars. We base this model on an existing continuum model used to describe terrestrial lahar emplacement [11,12]. However, with the advent of digital elevation data, e.g., MOLA data, we are faced with an important new issue. Specifically, how to adapt such a continuum model to topography in a discrete format. This is not a trivial proposition because it requires new boundary conditions to be established repeatedly for the flow across the discretized topography, and they must be maintained for all times throughout the entire transit of the lahar. However, we have developed the method for doing this by treating the changes between each elevation as an inclined plane and demanding that the new boundary conditions for all downstream intervals satisfy both local and overall flow volume and continuity requirements. Here we describe this model and discuss the implications for lahar deposits on Mars.

Lahar Model: We consider the emplacement of a lahar on a topographic profile approximated by a sequence of N contiguous inclined planes with different slopes, $\square_1$, $\square_2$,…$\square_N$. The flow model is based on equations that must be solved simultaneously for the evolution of the flow profile and the location of the flow front. One of the governing equations is a partial differential equation that describes local conservation of flow volume:

$$\frac{\partial h}{dt} + \frac{\partial}{dx}\left(\sqrt{\frac{g\sin\square_k}{C}}\, h_k^{3/2}\right) = 0, \quad 1 \ge k \ge N \qquad (1),$$

in which h is the flow depth, g is gravity, C is the coefficient of flow resistance, and x is the downstream coordinate.

The depth profile of the flow is given by

$$h_k(x,t) = \square_k\left(\frac{1 + 2x/3\square_k\square}{1 + t/\square}\right)^2, \ \text{for } x \ge x_{k\square 1}, t \ge t_{k\square 1} \qquad (2),$$

in which x_k is the distance from the source to the end of the k^{th} interval, t_k is the transit time to that point, $\square$ is a time decay constant and $\square_k$ and $\square_k$ are constants given by

$$\square_k = \left(\frac{\sin\square_{k\square 1}}{\sin\square_k}\right)^{1/6}\left(\sqrt{\square_{k\square 1}} + \frac{2x_{k\square 1}}{3\square}\sqrt{\frac{C}{g\sin\square_{k\square 1}}}\right. \left. \square\, \frac{2x_{k\square 1}}{3\square}\sqrt{\frac{C}{g\sin\square_k}}\right)^2 \qquad (3),$$

and

$$\square_k = \sqrt{\frac{g\sin\square_k\square_k}{C}} \qquad (4).$$

When applying this model to discrete topography, it is clear that changes in the underlying slope will cause changes in the flow depth and velocity. The solution for the flow profile must therefore satisfy different time-dependent solutions at the boundary of each topographic interval. We solve this problem by demanding the continuity of flow rate between each interval such that, for all times, we require

$$u_k(x_{k\square 1}, t > t_{k\square 1})h_k(x_{k\square 1}, t > t_{k\square 1}) = u_{k\square 1}(x_{k\square 1}, t > t_{k\square 1})h_{k\square 1}(x_{k\square 1}, t > t_{k\square 1}) \qquad (5),$$

in which u_k is the velocity in the k^{th} interval.

The final step in the formulation is to solve the integral equation describing the conservation of the total flow volume, V:

$$\frac{V}{w} = \int_0^{x_1} h_1(x,t;\sin\square_1)dx + \int_{x_1}^{x_2} h_2(x,t;\sin\square_2)dx + \ldots\ldots \int_{x_{N\square 1}}^{x_N} h_N(x,t;\sin\square_N)dx \qquad (6),$$

in which w is the flow width. Experience with this continuum model, and its close relatives, in describing terrestrial lahars and debris flows appears in the literature [11-13].

With eq. (2), we can perform the integrals in (6), and hence find the flow depth and velocity as a function of x and t, as well as the transit time and to any given point along the flow path.

Applications: We have used this model to describe the emplacement of the 1969 Whangaehu lahar at Mt. Ruapheu, New Zealand. This lahar was very large by terrestrial standards, traveling 57 km from its source. We are convinced that, with an analog model of the Ruapehu topography, the governing equations provide advance rates and flow depths that are consistent with the available data [13].

In order to investigate lahar emplacement under martian conditions, we have taken the Whangaehu lahar and then applied our discrete formulation and solutions to the same lahar parameters, accounting for the martian gravity and using the topography of Pavonis Mons, where a water-laden debris flow/lahar has been conjectured [14].

Figure 1 shows a comparison of the analog topography model for Ruapehu, together with a topographic transect from the north flank of Pavonis taken from the MOLA dataset. Figure 2 shows the results of the model for both the Ruapheu and Pavonis topographies: the thickness of the flow front (normalized to the maximum flow thickness at x=0, t=0) is plotted as a function of distance from source.

The Mars case is very interesting. Even though we have taken a very large lahar by terrestrial standards, when placed similar slopes on Mars, it travels relatively slowly due to the lower gravity. Therefore, the flow depths would be greater on Mars than on Earth. However, what we see in comparing lahars on Pavonis and Ruapehu is that, although the martian flow starts out slower and thicker than the New Zealand lahar (by virtue of the relatively mild slope of Pavonis), at distances greater than a few kilometers the martian lahar becomes thinner [Figure 2] and travels more rapidly than the Ruapehu flow. This is a result of the sheer size of Pavonis compared to Ruapehu: at several tens of kilometers from the source, the lahar is still well up on the volcano's flanks, whereas the Ruapheu lahar has encountered the relatively flat-lying surrounding terrain by this time [Figure 1].

However, the significant result for both cases is that within a few tens km from the source, the lahar thins to only about a decimeter at the maximum flow depth of each topographic interval.

We infer from this that such lahars, or their deposits, and records of their movements would be difficult to detect in image or topographic datasets of Mars. This may explain the ambiguity in assessing the nature of proposed lahars in Elysium [15] or the difficulty in characterizing the type of mass flow in Hellas [16].

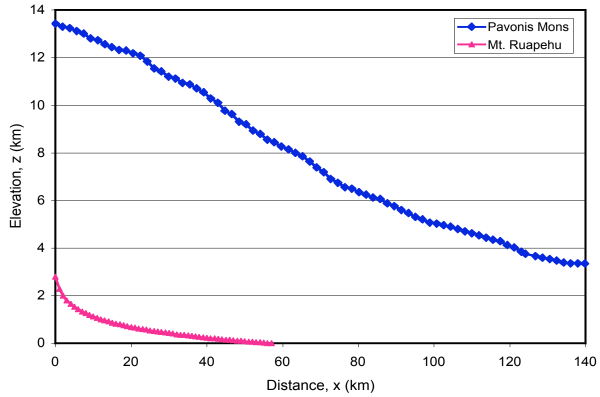

Figure 1. Topographic profiles of Pavonis Mons, Mars, and Mt. Ruapehu, New Zealand

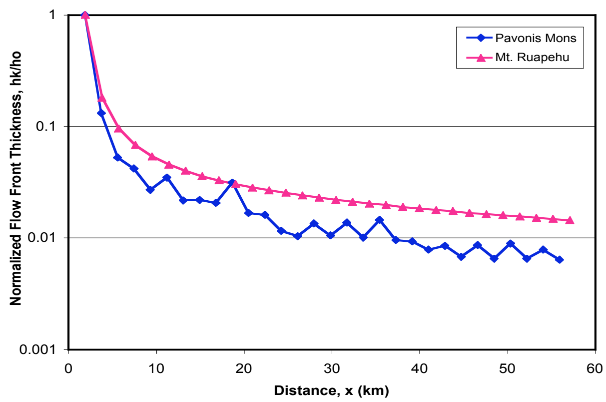

Figure 2. Normalized flow depth as a function of distance from source

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