MODELING THE EMPLACEMENT OF ICE-RICH FLOWS ON MARS USING A DEPTH-AVERAGED SHALLOW-ICE APPROACH. H. Miyamoto[1,2], D.A. Crown[2], and F.C. Chuang[2], [1]The University Museum, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan. [2]Planetary Science Institute, 1700 E. Fort Lowell Rd., Suite 106, Tucson, AZ 85719.

Introduction: Geomorphic signatures of ice-rich deposits and landforms characterize Martian mid-latitude zones and provide insights into potential Martian climate change and recent ice ages [1-4]. Such features as lobate debris aprons, lineated valley fill, and concentric crater fill are known to be concentrated in Martian fretted terrain and parts of the southern highlands (e.g. eastern Hellas) along with mantling deposits and small viscous flow lobes [5-10]. Recent studies have examined populations of lobate debris aprons and viscous flows in the eastern Hellas, Tempe/Mareotis, and Deuteronilus Mensae regions [11-16]. Our recent work has focused on geomorphic characterization of debris aprons and viscous flow lobes, with special attention to topographic controls on planform shape and surface lineation patterns, in order to characterize emplacement behavior and develop constraints for flow modeling [15-16]. Here, we incorporate new rheologic information into numerical simulations to examine the behavior of ice-rich flows under current Martian conditions.

Background: Two types of approaches have been used previously for modeling Martian debris aprons: (a) a static model to calculate a profile of a gravitationally-balanced mass of ice [e.g., 12, 17] and (b) a dynamic model to calculate time-dependent movements of an ice flow [18-19]. Although the cross-sectional shape of debris aprons can be approximated by the flow law of ice [12], even pure ice becomes too rigid to flow with temperatures lower than about 220K [19]. However, recent models indicate that flow regimes and grain sizes have considerable effects on the flow rheology of ice [20].

Although the direct applicability of laboratory studies of ice rheology to Martian flows of ice mixed with debris is not yet clear, there is merit in considering a numerical flow model that includes updated non-Newtonian rheology with grain-size effects, allowing for deposition and interaction with topography. We have extended the Colaprete and Jakosky [18] approach by including new rheology data from laboratory experiments by Goldsby and Kohlstedt [20] to test if the previous implications are still valid for a grain size-dependent flow law under current Martian conditions.

Numerical Model: In order to predict the movement of an ice-supported flow, we have developed a numerical module to integrate with an existing numerical simulation code used for simulating a variety of viscous flow types [21-22]. Our simulation code is designed to handle vertical and horizontal temperature heterogeneity [22]. However, at this point, we utilize only an isothermal version of the model for simplicity as discussed below.

The rheology of ice strongly depends on many factors, especially temperature and grain size. The spatial distribution of grain size is difficult to estimate for mass flows on Mars. Although inclusion of temperature gradients into the model is possible, this may not yield improved results, but instead more complexity, including increased numerical errors and uncertainties in the parameters. For example, heat flux can change the temperature structure inside an ice flow, but the estimate of the heat flux immediately beneath the ice flow is model dependent. Although the rheology of ice may be more complicated than our current understanding, a simple model using fixed parameter values (e.g., Glen's law) is preferable to more complicated models that yield greater uncertainty. In addition, the calculated Peclet numbers ($Pe=UH/\kappa$, where U is the average velocity, H is the average thickness, and κ is the thermal diffusivity) are around 10 for viscous flows and more than 100 for less viscous flows.

The large values of Peclet numbers and the likely laminar flow-style suggest that the interior of the flow does not cool rapidly and must become thermally and rheologically stratified. In this case, the bulk movement of the ice flow is most critically controlled by the internal part near the bottom of the flow, which has the greatest strain rate and temperature. At this part, the temperature may remain constant for a considerable time (maybe on the same order as the conductive cooling time scale). This may be compared to terrestrial lava flows/domes that have rheologies strongly dependent on temperature, though some of their morphologies are crudely explained by isothermal models [e.g., 23].

Numerous laboratory experiments with ice have shown that the best fit among shear strain rate, ε, and the shear stress, σ, is expressed by Glen's law ($\varepsilon=B\sigma^n$), where B and n are parameters [e.g., 24]. This equation is widely rewritten in the style of the Arrhenius equation as

$$\varepsilon=A\sigma^n/d^p \exp(-Q/RT),$$

where A is a material parameter, d is the grain size, n is the stress exponent, Q is the activation energy, R is the gas constant, and T is temperature [e.g., 20]. Based on creep experiments of fine-grained ice, Goldsby and Kohlstedt [20] further proposed a composite constitutive equation, which includes individual flow laws for four specific creep mechanisms:

$$\varepsilon=\varepsilon_{diff}+(1/\varepsilon_{basal}+1/\varepsilon_{gbs})^{-1}+\varepsilon_{disl},$$

where the subscripts refer to diffusional flow (diff), basal or easy slip (basal), grain boundary sliding (gbs), and dislocation creep (disl). This is derived from experimental investigations using fine-grained ice-core samples, which enabled exploration of grain-size sensitive flow mechanisms [20]. However, it is difficult to expect flow laws to be applicable to all physical conditions [e.g., 25], and therefore, the above equation might not be applicable for Martian ice flows with unknown origin and debris concentrations. Especially problematic is that the internal structure of ice masses/sheets may be highly variable due to complex deformational histories [26]. Nevertheless, the above equation is applied here because it is derived from recent systematic laboratory experiments, and it agrees well with the flow behavior determined from field measurements on glaciers and ice sheets [20]. However, further understanding of ice rheology in the future may provide important improvements relevant to Martian applications.

We assume that the horizontal scale of the flow is sufficiently larger than its vertical scale. Assuming a simple shear flow, the strain rate may be written as $\varepsilon \sim 1/2 du/dz$, where u is the velocity along the direction of the shear stress, which represents the x axis. For a gravity-driven flow on a shallow slope angle, the shear stress at depth (h-z), where h is the thickness of the flow and z is the axis parallel to h, can be written as:

$$\sigma=(\rho g \sin\alpha - \rho g d/h/x \cos\alpha)(h-z)$$

Vertically integrating the equation with a free surface boundary condition, we obtain an expression of the flux per unit width. Then we calculate the fluxes in both the x and y directions separately for calculating a time sequential movement of the flow using the continuity equation.

Discussion: We use the parameters given by Goldsby and Kohlstedt [20] as constraints. The grain size is considered as a parameter in this work, because it is unknown for the Martian cases of interest. We are currently exploring the size-range of 1 to several hundreds microns. Figure 1 shows a preliminary result, which indicates the dependencies of the grain size on flow thickness and time to achieve 150 km length.

The high spatial resolution of MOC, THEMIS, HRSC, and HiRISE images has allowed identification and characterization of a variety of small potentially ice-rich flow lobes. These small flow lobes provide an important comparison to larger ice-rich flow features, with respect to evaluating ice content and flow emplacement styles based on sensitivity to local topography. We are planning to take advantage of the semi-3D nature of our model to evaluate the rheological properties and emplacement styles of these flows from their sensitivities to local topography.

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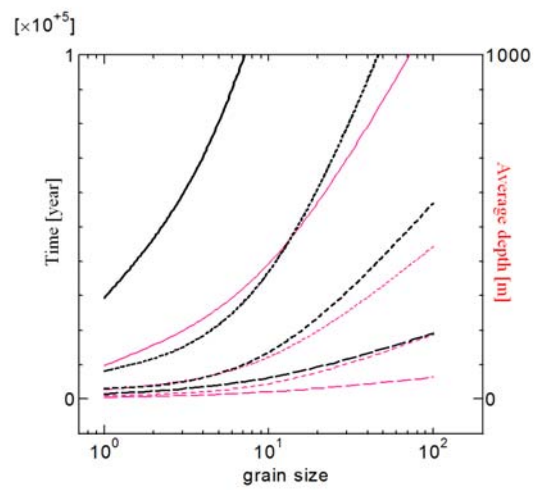

Figure 1. Preliminary results showing the dependencies of grain size on the time for a flow to achieve 150 km length and the necessary flow thickness on a 3 degree slope.