Determining the Age and Physical Properties of Martian Lobate Debris Aprons using High-resolution Topography, SHARAD Observations, and Numerical Ice Flow Modeling: A case study at Euripus Mons

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Introduction: Martian lobate debris aprons (LDAs) provide evidence of a past hydrologic cycle that was capable of redistributing large quantities of water ice from the poles to the mid-latitudes likely driven by obliquity-induced changes in insolation [1]. LDAs are massive ice deposits, $\geq$ 300 m thick [2,3] protected by a 10s of meters thick [4] regolith layer that are preserved in several regions in the northern (e.g. Protonilus/Deuteronilus Mensae) and southern (e.g. East of Hellas and Southern Argyre) mid-latitudes on Mars.

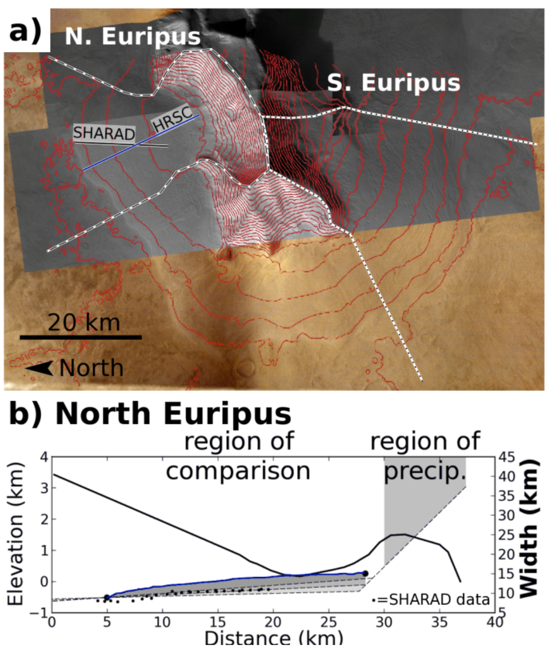

Figure 1: Topography and imagery of Euripus Mons and the ice flow model setup. a) Google Mars visible imagery of Euripus Mons (gray images are CTX) overlain by HRSC topography contours (200 m interval). Thick black dashed and dotted lines denote the ice flow drainage basins for the northern and southern LDAs; the blue and green lines indicate HRSC topographic profiles used for comparison with our ice flow model. A SHARAD radar track used to check the basal slope predicted from the model is given by the thick, solid black line. b) LDA topographic profile (blue line, left axis) for the northern Euripus LDA. The thick solid line, and the right axis give the flow width measured perpendicular to the blue topographic profile. The dashed lines give the basal slopes of 0.5, 1.0, or 1.5°. The shaded regions indicate the zone of precipitation and domain of the model that is compared to the HRSC topography. Note the ice volume under the observed HRSC topography depends on the assumed basal slope and requires that the total volume of ice to change for each of the three simulations.

By combining observations of LDA topography derived from HRSC images, basal topography constrained by SHARAD, and numerical simulations of ice flow, we can place limits on the formation timescale and the rheologic properties of the ice by comparing the topography generated from ice flow simulations with the observed topography of LDAs. We focus on a location to the East of Hellas Basin, Euripus Mons, where a number of SHARAD observations have constrained the basal slopeIn this paper, we focus on the model analysis of the Northern Euripus LDA. Given the proximity of the northern and southern LDAs found at Euripus (Fig. 1a), it is reasonable to assume that they share the same ice composition and age - future analysis of adjacent deposits will test this idea.

Observations: Euripus Mons is a 4 km mountain located east of Hellas Basin surrounded by a 20 km wide apron of coallesced LDA deposits. Figure 1a provides visual imagery of our study site shown in Google Earth. The gray CTX images capture ice flow features such as compression folds and longitudinal ridges indicative of viscous ice flow. Topographic contours derived from HRSC image 2345_0000 are overlain with an interval of 200 m basin. The high resolution (75 m per pixel) HRSC topography in combination with the flow features observed in CTX help us to delineate the ice drainage catchment shown by the thick, black dashed and dotted lines in Fig.1a.

A SHARAD radar ground track is shown in Fig. 1a and the elevation of the reflected signal is given by the small black dots in Fig.1 b - providing an additional constraint on the model.

Numerical Approach and Assumptions: Our glacial flow model simulates changes in ice thickness as ice flows outward over a flat or sloping surface in 1-D with a resolution of 75 m while accounting for influences from ice grain size, temperature, dust fraction, and the magnitude of the applied differential stress in driving viscous deformation. This model incorporates data from recent ice deformation experiments which show a change in the the rheology of ice at different applied stresses, ice grain sizes, and temperatures (these are variables in our model) [5]. Although the ice grain size is relatively unconstrained in LDAs, the lower stress (due to lower gravity) and also lower temperatures ($<$ 255 K) on Mars indicate that the appropriate ice flow is different for Mars than Earth [5]. For more details regarding the model see [6,7].

Numerical Simulation: Two observations are used as inputs into the numerical model: (1) An HRSC topographic profile of the LDA and the upland region that represents the ice drainage catchment, and (2) the geometry of the ice drainage catchment.

The model uses the observed LDA profile and an assumed basal slope (0.5, 1.0, or 1.5° for the LDA on northern Euripus Mons) to determine the total model ice volume to be used in a given simulation by subtracting the basal slope from the LDA surface. The model domain consists of 500 discrete elements and starts out ice-free, gradually accumulating ice at a rate of 5 mm/yr over 82 model cells (6150 m) on the headward scarp (Fig. 1b) during the beginning of the simulation until the total ice volume (specific to the assumed basal slope) is reached. After precipitation ceases, ice is conserved (no ablation) - making our timescale estimates biased toward larger values because we are simulating ice flow with the minimum ice volume. As an accumulated ice deposit flows downslope, the numerical model accounts for flow divergence/convergence due to changes in flow width which based on the geometry of the ice drainage catchment (Fig. 1a,b). No flow is allowed in or out of the domain, and the horizontal velocity at the base of the ice is set to zero (no basal sliding).

Comparing the model to observations: A sequence of model-generated topographic profiles ($Z'(x,t)$) taken during different times are compared with the obseverd topographic profile ($Z(x)$) in order to calculate the misfit and determine model-predicted age for the LDA given the specified ice rheology. The misfit, or "Standard Error" (Ste) is

$$Ste = \frac{1}{l}\sqrt{\sum_{i=0}^{l}(Z'_i - Z_i)^2} \quad (1)$$

where i denotes an element in the array of HRSC elevation profile values and l is the total number of elements. Ice with a grain size of 5 mm and a temperature of 205 K, flowing over a 0.5°, 1.0°, or 1.5° sloping surface produces the misfit error progression shown in Fig. 2a.

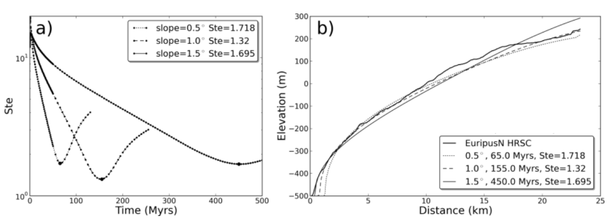

Figure 2: Comparison of model results to the HRSC topographic profile. a) Calculated misfit (*Ste*) between the observed and simulated topographic profile as flow progresses for a basal slope of 0.5° (dotted line), 1.0° (dashed line), and 1.5° (solid line). The lowest *Ste* value for each case is indicated in the legend. b) Comparison of best-fits for each basal slope case. The thick line is an HRSC topographic profile (blue line in Fig. 1a).

Ice flowing over the shallower sloping surface produces a best-fit match at an earlier time than the steeper slopes due to the larger overall ice volume (see Fig.1b) resulting in a thicker ice deposit with a higher rate of flow. Flow over a 1° basal slope produces the best-fit with the observations after 155 Myrs of flow using an ice grain size of 5 mm and a temperature of 205 K. The model-generated best-fit topographic profiles for the three basal slope cases are plotted together with the HRSC observations in Fig.2b to provide a visual indication of the degree of fit. The model-predicted basal slope of 1° is confirmed by SHARAD data which cluster around a surface sloping at that value (Fig. 1b).

The ice rheology versus LDA age trade-off: Our model, together with observations from SHARAD can better constrain the basal slope of LDA deposits. The model can place additional constraints on either the age of the LDA (if we assume an ice rheology) or the rheology (if we assume an age). This trade-off is depicted in Fig.3 where the age of the northern Euripus LDA is plotted (as contours) as a function of ice temperature (y-axis) and ice grain size (x-axis). The black squares indicate locations of this parameter space where we've conducted numerical simulations to compare with northern Euripus and the associated number gives the flow timescale, in Myrs, when the simulation produces the best-fit with the observed topographic profile. The contours were produced by multiplying the model's ice viscosity by a factor which reproduced the ages given by the three simulations shown. LDA ages constrained by crater counts (principally Dueteronilus Mensae) give ages between 40 and 500 Myrs [8, 9], and are indicated by the shaded region in Fig.3.

Further numerical simulations tailored to specific locations will provide more insight into whether the same ice viscosity will produce the same best-fit flow timescales for LDAs in different locations. This work will (1) place tight constraints on the subsurface topography below LDAs, (2) help to determine whether differences exist in the model-predicted rheology or age of LDAs among a local group or between different regions.

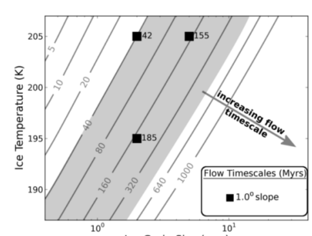

Figure 3: Calculated flow timescales (numbers next to boxes in millions of years) to produce the best match with the observations for different ice rheologies used in our ice flow simulations over a 1.0° sloping surface. Calibrating those timescales to the viscosity used in our numerical model gives the gray contour lines for different ice grain sizes (x-axis) and ice temperatures (y-axis).

References: [1] Laskar, J., et al. (2002), *Nature*, 419, 375377. [2] Holt, J., et al. (2008), *Science*, 322, 12351238. [3] Plaut, J., et al. (2009), *Geophys. Res. Lett.* 36. [4] Ostrach, L., et al. (2008), *39th LPSC* #2422. [5] Goldsby, D.L. & Kohlstedt, D.L. (2001), *J. Geophys. Res.*, 106, 11,017-11,030. [6] Parsons, R., et al. (2011), *Icarus*, 214, 246257. [7] Parsons, R., Holt, J.W., (2013), *44th LPSC* Abstract #1840. [8] Baker, D., et al. (2010) *Icarus*, 207, 186209, 2010. [9] Mangold, N., *J. Geophys. Res.*, 108, doi:10.1029/2002JE001885, 2003.