THE IMPORTANTANCE OF ICE FLOW AT THE NORTH POLE OF MARS Michael M. Sori[1], Shane Byrne[1], Christopher W. Hamilton[1], and Margaret E. Landis[1]. [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA (sori@lpl.arizona.edu).

Introduction: The north polar layered deposits (NPLD) of Mars are composed of nearly pure [1,2] water ice layers with a minor dust constituent. The NPLD are hypothesized by many researchers [e.g., 3–6] to contain a record of climate history linked to orbital variations of Mars, but the complex processes acting on the NPLD, especially those leading to a non-linear time-depth relationship, complicate the identification of an orbital signal in the stratigraphy [7, 8].

One such process that may be important in understanding the history and evolution of the NPLD is viscous flow. While radar data have revealed that the NPLD are unlikely to have experienced flow as a whole structure [9], topographic features may flow locally. Previous papers have modeled flow along a line of longitude in the NPLD [10], in troughs in the NPLD [11], and in craters on the south polar layered deposits (SPLD) [12]. In this study [13], we use a finite element method (FEM) approach to model recently discovered NPLD topography (craters and steep scarps, described below). We quantify stresses, temperatures, and flow velocities to learn about timescales over which the topography flows, constraints on the age of the features, and the importance of viscous flow at the Martian poles.

Methods: We use the FEM code Elmer/Ice [14], which was developed specifically for glaciological and ice dynamics problems. The code solves the Navier-Stokes equations for the conservation of linear momentum and mass over a volume of ice. For simulations that are not isothermal, the code solves the heat equation, and the simulation is thermo-mechanically coupled. Elmer/Ice was developed for problems in terrestrial glaciology, but we adapt the model for Mars by changing the rheology laws and other important parameters.

Studies of terrestrial ice sheets often use the non-Newtonian Glen-Nye flow law, in which strain rate is proportional to stress raised to an exponent. Here, we instead separately calculate strain rate due to different modes of deformation [15]. We take into account effects such as dust fraction [16], grain size [17], and the composition of the underlying basal unit (BU) [18]. We use a thermal model [19] to estimate surface temperatures.

Craters: Impact craters on the NPLD [20] were discovered by searches of Context Camera (CTX) and High Resolution Imaging Science Experiment (HiRISE) [21] images (Fig. 1a). Analysis of crater size-frequency distribution has yielded a crater retention age of ~kyrs for the NPLD [22], but this young age will not represent the true age of the ice if viscous relaxation is important as it is for SPLD craters [12].

We show results of (Fig. 1b) a 3D model of a 200-m-diameter NPLD crater with temperature 170 K, dust fraction 2%, and grain size 1 mm. We also show flow velocities in a cross-section of ice through the crater's center (Figs 1c,d). Flow velocities are maximized at the center of the structure, causing the floor to rise and the walls to shallow. However, these velocities do not exceed μm/yr for any reasonable combination of parameters, and are too small for viscous relaxation to appreciably modify NPLD craters presently observed. We ran models with other realistic values for temperature, crater diameter, dust content, and grain size and found this result to be robust.

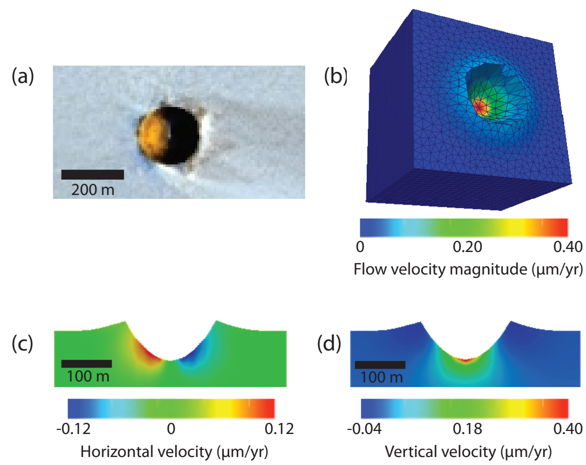

Figure 1. Results for a crater at 170 K on the NPLD, such as the one observed in HiRISE image PSP_009773_2675 (a). Total (b), horizontal (c) and vertical (d) flow velocities do not exceed μm/yr (positive directions are up/right).

Steep scarps: Scarps of ice (Fig. 2a) far steeper than typical troughs have been observed at the periphery of the NPLD [23]. HiRISE monitoring has revealed seasonally active avalanches composed of dust and CO_2 frost which do not directly transport significant mass but may have important indirect effects on scarp evolution [23]. The steep, equatorward slopes cause the scarps to experience relatively warm temperatures compared to the rest of the NPLD [19] and thus make them a prime candidate for viscous flow.

We show results of a 2D model run of a steep scarp with scarp height 800 m, scarp width 400 m, dust fraction 2%, grain size 1 mm, and immobile BU (Fig. 2b–h). Flow is outward at the scarp base and downward at the scarp top, implying the slope is shallowing with time. Flow velocities are high, with maximum velocities on the order of ~1 m/yr. We quantify the sensitivity of flow velocity to various input parameters; results for a few parameters are shown in Fig. 3. We find that ice flow is an important factor in scarp evolution for any realistic combination of input parameters.

Conclusions: NPLD craters are smaller and younger than SPLD craters, and our models show these factors are sufficient to cause viscous flow to be unimportant in the modification of present day NPLD craters. We conclude that infilling is the primary modification mechanism of NPLD craters.

In contrast, the comparatively high-relief, steep, and warm scarps that host avalanches at the NPLD margin experience ice flow fast enough (10s–100s cm/yr) to be a critical factor in scarp evolution. If there were no other processes shaping topography, scarps would flow into their presently observed shape from an initial vertical cliff in kyrs and continue flowing. However, given observations of dust/frost avalanches [23], ice block falls [24], and thermal modeling that shows thermal stresses on the scarps exceed the tensile strength of the PLD [19], it is perhaps more plausible that scouring of dust off the scarps leads to thermal stress-induced mass wasting which steepens the scarps in a competing effect to that of shallowing viscous flow.

A tantalizing prospect is the possibility of observing active flow. Our favored model (Fig. 2) yields a maximum flow velocity of ~1 m/yr. Even if viscous flow and block falls provide competing effects, the discrete nature of block falls means that a steady-state is not achieved perfectly, and the continuous viscous flow may still be observable. Additionally, flow would decrease the elevation of the scarp top (~40 cm/yr for the case in Fig. 2), which would not be countered by block falls. HiRISE images have resolutions of ~30 cm/pixel. We predict that scarps flow several pixels in an image over the lifetime of the instrument, and therefore analyses of future images and DEMs of the same scarp may be able to observe ice flow. Such observations would allow us to constrain parameters with our models; lower flow rates than predicted could indicate higher dust content or colder ice than expected.

References: [1] Picardi et al. (2005), *Science* 310, 1925–1928. [2] Grima et al. (2009), *GRL* 36, L03203. [3] Murray et al. (1973), *Science* 180, 638–640. [4] Cutts and Lewis (1982), *Icarus* 50, 216–244. [5] Laskar et al. (2002), *Nature* 419, 375–377. [6] Milkovich and Head (2005), *JGR* 110, E01005. [7] Perron and Huybers (2009), *Geology* 37, 155–158. [8] Sori et al. (2014), *Icarus* 235, 136–146. [9] Karlsson et al. (2011), *GRL* 38, L24202. [10] Hvidberg (2003), *Ann. Glaciol.* 37, 363– 369. [11] Pathare and Paige (2005), *Icarus* 174, 419– 443. [12] Pathare et al. (2005), *Icarus* 174, 296– 418. [13] Sori et al. (2016), *GRL* 43, 541–549. [14] Gagliardini et al. (2013), *Geosci. Model Dev.* 6, 1299–1318. [15] Goldsby and Kohlstedt (2001), *JGR* 106, 11017–11030. [16] Durham et al. (1992), *JGR* 97, 20833–20897. [17] Barr and Milkovich (2008), *Icarus* 194, 513– 518. [18] Herkenhoff et al. (2007), *Science* 317, 1711–1715. [19] Byrne et al. (2013), *LPSC* 44, 1659. [20] Banks et al. (2010), *JGR* 115, E08006. [21] McEwen et al. (2007) *JGR* 112, E05S02. [22] Landis et al. (2016), *GRL* in press. [23] Russell et al. (2008), *GRL* 35, L23204. [24] Russell et al. (2012), *LPSC* 43, 2747.

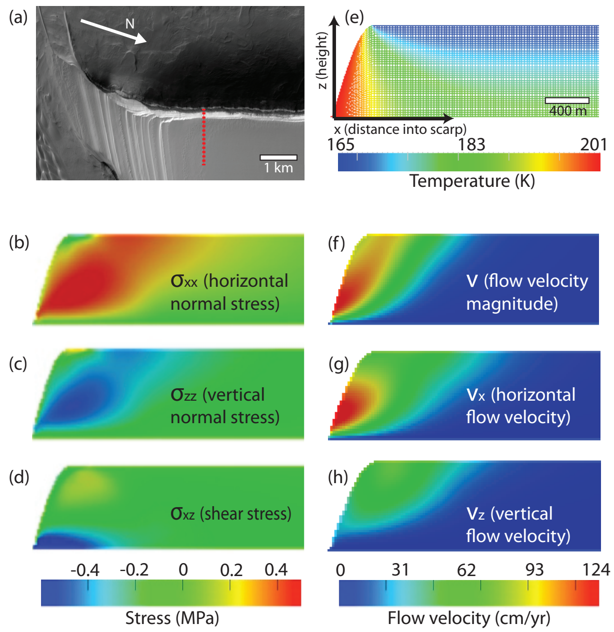

Figure 2. Results for a scarp 800-m-high and 400-m-wide, with a maximum slope of ~70°, such as the one in HiRISE image PSP_007140_2640 (a); red dotted line traces an example 2D profile as seen in the other panels. Positive directions are left/down.

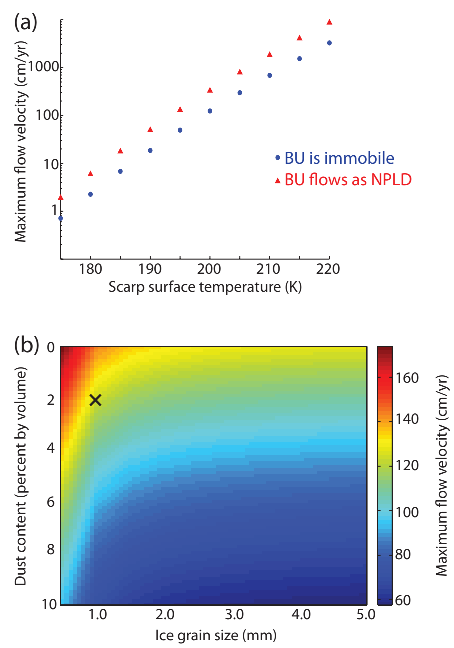

Figure 3. Sensitivity of scarp results to parameters. (a) shows maximum flow velocity as a function of the annual-average surface temperature on the steepest slope of the scarp. (b) shows maximum flow velocity as a function of ice grain size and dust content in the NPLD for an immobile BU; our nominal case is marked with an ×.