SIMULATING CONCENTRIC CRATER FILL ON MARS WITH AN ICE FLOW MODEL. N. Weitz[1], G. R. Osinski[1,2], M. Zanetti[1] and J. L. Fastook[3]. [1]Department of Earth Sciences / Centre for Planetary Science and Exploration, University of Western Ontario, London, Canada, [2]Department of Physics and Astronomy, University of Western Ontario, London, Canada, [3]Department of Computer Sciences, University of Maine, Orono, USA.

Introduction: A wide range of evidence suggests that substantial ice accumulation happened in the mid-latitudes during the late Amazonian, in the form of dissected mantle terrain (e.g. [1]), lobate debris aprons and flows (e.g. [2]) and surface ice deposits (e.g. [3]). Some workers have suggested that this ice is potentially partly preserved in the crater interiors to the present day [2, 4, 5]. Satellite imagery of concentric crater fill (CCF) show flow features such as ice lobes, ring-shaped features related to sublimation processes on the fill surface, and parallel ridges on the crater floors, interpreted to be related to glaciation [6]. It is generally accepted that CCF consists of water ice covered by dust and debris deposits, and occurs mostly in the interior of mid- to high latitude craters [6, 7, 8, 9]. Recent global climate modeling suggests that concentric crater fill develops over many cycles in which thin layers of snow and ice gradually accumulate in craters during global changes in the planet's obliquity [9, 10].

Here, we use finite element ice flow modeling to simulate the infill of impact craters in the mid-latitudes of Mars. Our work includes realistic crater geometries and non-uniform sublimation rates. Modeling the formation of CCF and comparing it to observations may help quantify the amount of ice buried in the mid-latitudes and improve climate models.

Methods: Ideal crater bed profiles are calculated based on crater morphometric properties from Garvin [11], and realistic bed profiles taken from MOLA topographic data. Using a finite element ice flow line model developed by Fastook [9,12] based on the University of Maine Ice Sheet Model (UMISM), we investigate the evolution of CCF over time. The model uses the Shallow Ice Approximation and includes an Arrhenius temperature-dependent ice rheology incorporated into Glen's flow law. An integrated momentum-conservation equation is coupled with a mass-conservation equation to yield a differential equation for ice extent and thickness as a function of time.

The ice flow model is coupled to an advection-based model of surface debris transport [12]. This debris is assumed to originate from wall erosion and eolian deposition processes (which are not included in this model) and contains rocky materials and dust. This debris is deposited on the ice near the crater walls when the ice surface falls below the crater rim. The debris is then transported inwards towards the crater center with the movement of the ice flow. Debris accumulation is applied every time step at a constant rate.

The model surface mass balance is obliquity-driven using the scenario 301003_BIN_A_P001_N from Laskar [13]. In this scenario the obliquity is relatively high for the last 40 to 5 million years; after that it gradually decreases to its current value. We use an obliquity threshold of 35 degrees. Above this threshold ice accumulates with a rate of 1mm/year (typical GCM results for high obliquity) [9], and below the threshold ice sublimates with a rate depending on the amount of debris armoring the surface [12].

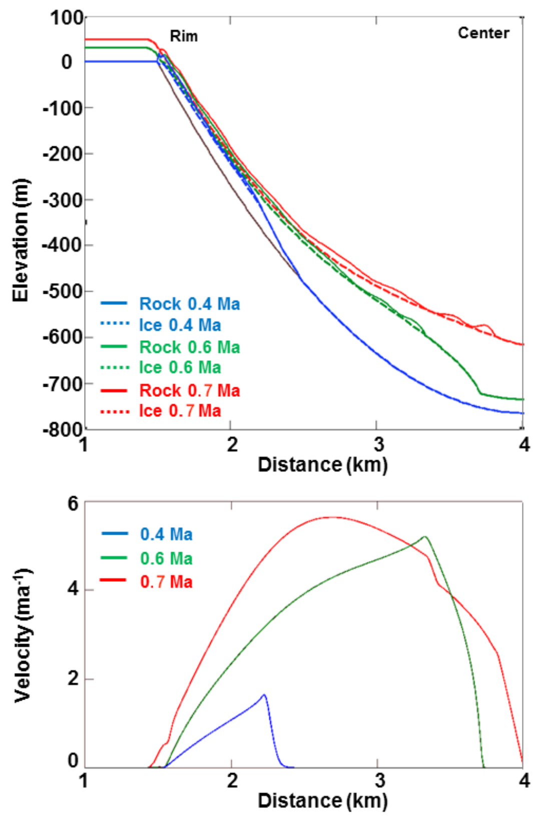

Figure 1: *A 5 km diameter ideal crater is filled with ice and surface debris (only one half of the symmetric crater is shown here). Upper panel: Filling level of ice (dashed lines) and covering debris layer (solid lines) for the initial 0.4, 0.6 and 0.7 Ma. There is distinct lobate ice flow from the walls towards the crater center. Lower panel: Respective ice velocity for the profiles above.*

Results: *The filling process.* To demonstrate how a crater fills with ice, we use the model to fill a 5 km diameter ideal crater profile, beginning in the late Amazonian.

Figure 1 shows ice thickness (dashed lines), debris layer thickness (solid lines) and accompanying flow velocities (lower panel) at intervals 0.4, 0.6, and 0.7 Ma of crater fill. After 0.4 Ma the majority of the initial ice has sublimated such that no ice is left in the crater center (blue). However, ice is preserved at the upper crater walls where it is protected by surface debris. At this time, ice velocities are highest in the middle of the crater wall, where the ice surface slope is steep and ice thickness is largest. After 0.6 Ma more ice has been deposited in the crater and ice is flowing from the walls towards the center, forming distinctive lobes (green). The surface debris layer is also transported further inwards. Ice velocities are now highest near the end of the lobes, closer to the crater center. After 0.7 Ma more ice has been deposited and the ice flow lobes have touched in the center (red), although the debris cover has not reached the center yet. Flow velocities in these early stages of crater fill can be several m/yr, whereas they later decrease to a few mm/yr as the ice surface slope flattens with increased ice deposition.

Asymmetric sublimation. Mars' obliquity during the last 3 Ma is low, resulting in enhanced sublimation and decreasing crater fill. We simulate ice sublimation using the pristine morphology of Tooting Crater (23.1ºN, 207.1ºE) as an example for how a central peak crater can be modified by CCF infilling. For this case, the sublimation rate was set to simulate enhanced sublimation on pole-facing slopes, resulting in an asymmetric ice distribution (Fig. 2a). For such a spatially non-uniform sublimation rate the ice thickness is greater on one side of the crater, surface features are not concentric, and ice flows in the direction of the ice surface slope.

Conclusions: After an initial uniform ice layer, glacial flow lobes form on the crater wall moving crater-inward with time. All CCF show lobate ice flow at their early stage. A surface debris layer must form to protect the ice from sublimation and preserve it to the present day. Asymmetric ice flow in craters can be explained with a non-uniform surface mass balance profile across crater, for example enhanced sublimation rates on the pole-facing side. This results in a tilted ice surface and non-symmetric sublimation features.

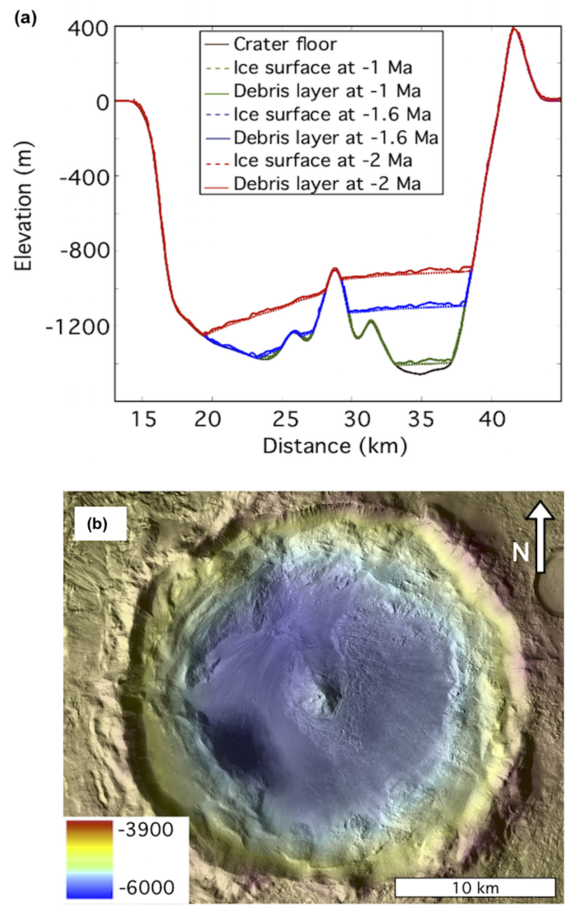

Figure 2: (a) *Model of ice sublimation for the past 2Ma using the geometry of Tooting Crater. Here, the sublimation rate was modified to simulate enhanced sublimation on pole-facing slopes (left side), resulting in an asymmetric ice distribution. (b) Example of asymmetric infill in a central peak crater at 34.6ºN, 123ºE (diameter 34 km). Shown here is a CTX mosaic with MOLA topography. Crater fill elevation is higher at the southern side and decreases towards the north. Surface ice flow follows this gradient, flowing around the central peak.*

References: [1] Milliken, R. E., et al. (2003), *JGR*, 108 (E6), 5057. [2] Dickson, J. L., et al. (2010), *Earth Planet. Sci. Let.* 294 (3-4), 332-342. [3] Stuurman, C. M. et al., (2016), *GRL*, *43*, 9484–9491. [4] Head, J.W., et al., (2010), *Earth Planet. Sci. Lett.* 294 (3-4), 306-320. [5] Kadish, S.J., et al. (2011a), *Icarus,* 215 (1), 34-46. [6] Pearce G. R., et al. (2011) *Icarus,* 212, 86-95. [7] Holt, J. W., et al. (2008), *Science*, 322, 1235-1238. [8] Plaut, J. J., et al., (2009), *GRL*, 36(2). [9] Fastook J. L., et al. (2014), *Planetary and Space Sciences*, 91, 60-76. [10] Dickson J. L., et al. (2012), *Icarus*, 219, 723-732. [11] Garvin, J.B., et al. (2003), *Sixth International Conference on Mars,* abstract #1164. [12] Fastook J. L., et al. (2014), *Icarus,* 228, 54-63. [13] Laskar, J. et al. (2004), *Icarus*, 170, 343-364.