RELAXATION OF SMALL ICY CRATERS AT MID-NORTHERN LATITUDES ON MARS IN THE ABSENCE OF FLOW BY GRAIN BOUNDARY SLIDING.

A. B. Cunje[1], A. J. Dombard[1], and E. Z. Noe Dobrea[2] [1]Dept. of Earth & Environmental Sciences, University of Illinois at Chicago, Chicago, IL 60607 (acunje2@uic.edu), [2]Planetary Science Institute, Tucson, AZ 85719.

Introduction: The high northern latitudes of Mars are inferred to host water ice in significant quantities in the near subsurface [1, 2], and the plains around the Phoenix landing ellipse north of 60˚N host both an ice-rich regolith, as investigated by the Phoenix lander [3], and an abundance of craters 1 km in diameter and smaller with varying degrees of modification. Water ice abundance values of ~60% by mass have been inferred from epithermal neutron data [1], which is reasonably consistent with the values of 30% +/- 20% inferred from landed measurements during the Phoenix mission [4] when taking into account variations and regional averages, but is inconsistent with formation by purely vapor diffusion due to the large abundances that exceed the amount expected by pore-filling. In order to investigate further the abundance of ice in the regolith and the thickness of the ice-bearing layer in these ice-rich plains to provide insight into the genesis and history of ice at high latitudes, previous works have examined and evaluated the small crater population through both photogeologic and modeling methods [5, 6, 7]. This work focuses on expanding on the previous modeling efforts, examining the relaxation magnitudes and timescales of this small crater population around the Phoenix ellipse in light of new and relevant findings from Qi et al. [8] on the processes governing creep in ice masses with particulate abundances above a critical threshold of 6%.

Implications of photogeologic study. Findings from the examination of the crater population through HiRISE and CTX images around the Phoenix ellipse include evidence for an incompetent layer of poorly consolidated fine-grained material and constraints on rates of crater degradation [5, 6 ,7]. The incompetent layer was inferred to range from 40–70 m deep, due to the observed transition in craters that feature blocky ejecta; craters smaller than 200–350 m in diameter did not feature ejecta around them while larger ones did, suggesting an excavation of more consolidated material at greater depths. Craters larger than 200 m in diameter were also observed with anomalously shallow depths and networks of concentric and radial fracture features, suggesting loss of topography by viscous creep, and retention ages were found to be of the order of a few to tens of Myr.

Findings of early modeling studies. Scaling of topographic relaxation of 2 km diameter craters in the Southern Polar Layered Deposits (SPLD), which were shown to relax in a few Myr [9], to 200 m suggested craters could relax with a relaxation time of the order of several tens of Myr. While surface temperatures and dust fractions are higher in the Phoenix lander region than the SPLD, which would have converse effects on relaxation rates, this was found to be relatively consistent with relaxation models of 200 m diameter craters emplaced on a 70 m thick ice sheet sitting on a rocky and stiff substrate [5]; relaxation of about half the initial crater depth on timescales ranging from 100 kyr to 10 Myr were determined for mechanically “soft” and “stiff” cases respectively, with cases varying by grain size, particulate fraction, and the presence of a welded or free-slip base. The “soft” case, using a free-slip base, 0.1 mm grain size, and 25% particulate volume fraction (~50% ice by mass) resulted in near complete relaxation of this small crater size in ~1 Myr, consistent with the lower bound of the expected age range, though not uniformly applicable to all small craters from the photogeologic study.

New findings on impedance of GBS. From a recent experimental investigation of the rheological behavior of ice influenced by intergranular particles, Qi et al. determined that a critical threshold exists of ~6% of particulate volume fraction, below which, samples flow as pure ice by dislocation creep and grain boundary sliding (GBS), and above which, GBS is impeded [8]. Above the threshold, ice grains occur in particle-free clusters surrounded by bands of particles mixed with fine-grained ice that act to prevent GBS in the bands of particles as well as between the ice-grain clusters. As the dusty-ice in the Phoenix landing ellipse is well above this threshold, even at its lowest particulate volume fraction, this study holds significant bearing on the relaxation of the craters by viscous creep. Because GBS flow dominates under these temperature and stress conditions, the removal of GBS would significantly reduce the strain rates and slow the flow of ice and thus relaxation rates.

This study follows these findings and the previous studies to model and determine the magnitudes and timescales of relaxation of craters ranging from 200 – 1000 m in particulate rich ice masses by viscous creep in the absence of GBS.

Methods: Following previous modeling works [e.g. 5, 10], we use the MSC.Marc finite element package using a viscoelastic rheology to evaluate the relaxation of Martian craters 200, 600, and 1000 m in diameter in a half-space of particulate-rich ice with a particulate volume fraction of 25% and a grain size of 1 mm. We also model a "thin sheet" (TS) scenario for a 200 m crater emplaced on an ice sheet of 70 m thickness above a stiff, rocky substrate, with a smaller 0.1 mm grain size, and a fixed base. Elevation profiles of the axisymmetric craters after 1 Myr and 10 Myr durations are presented. The total strain rate is typically determined as the sum of the strains from each creep mechanism [11]; however, in this model as GBS is impeded, the total strain rate

$$\dot{\varepsilon} = \dot{\varepsilon}_{diff} + \dot{\varepsilon}_{disl} + \left(\frac{1}{\dot{\varepsilon}_{GBS}} + \frac{1}{\dot{\varepsilon}_{basal}}\right)^{-1} \quad (1)$$

is only a sum of the strain rates produced by the flow laws of diffusion and dislocation creep [11, 12]. In addition, we apply the stiffening effect of particulates on the viscous flow of water ice [13] as has been used in previous similar modeling scenarios of dusty-water-ice masses [5, 14]. A constant surface temperature of 185 K is applied, with a crustal heat flow of 19 mW/m^2 [15], and we assume material parameters consistent with a mixture of water ice and basaltic silicates in the given volume fraction of 25% for all scenarios.

Results and Discussion: The results of the simulated scenarios indicate that even in the absence of GBS and the associated basal slip, relaxation of the small crater population is still significant on the timescales of 1 to 10 Myr, though at reduced rates when compared to scenarios still implementing viscous creep by GBS. As expected, larger craters relax more quickly, and large craters embedded in a thick particulate ice sheet would nearly completely relax on timescales of the order of 10 Myr. Intermediate craters for this size range would also be significantly relaxed on similar time scales, strongly relaxed in a few Myr (Fig. 1).

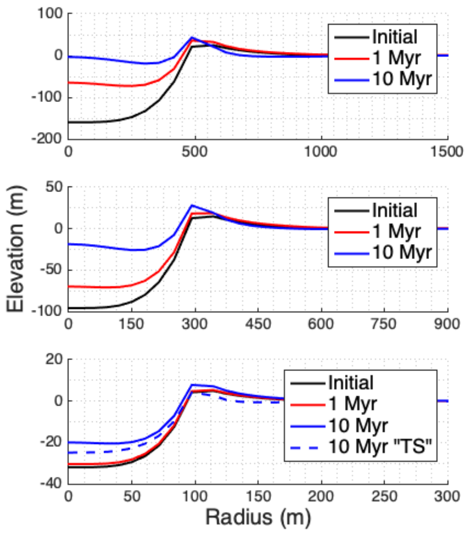

Figure.1: Radial elevation profiles of relaxed craters of varying diameters; 1000 m (top), 600 m (middle) 200m (bottom). Black curve is the initial shape, the red curve is relaxation after 1 Myr, and the blue is after 10 Myr. "TS" dashed curve shows a thin ice sheet simulation conducted with a smaller 0.1 mm grain size.

A relaxation of about a third of the original crater depth after 10 Myr is observed for the smallest crater size of 200 m embedded in a thick ice sheet, and a slightly less degree of relaxation is observed when impacting into the thin 70 m thick ice sheet as is predicted to exist in the Phoenix lander region, even with a smaller implemented grain size of 0.1 mm. These lower simulated degrees of relaxation could be increased to match observations with modest increases in surface temperature (~5-10 K) due to obliquity changes over similar timescales [16].

These results confirm that the removal of GBS reduces the relaxation rate of the craters as expected, but does not fully impede significant relaxation from occurring on predicted timescales. Though not measured in Qi et al. [8], diffusion creep is still implemented in this model, as diffusion could still occur through grain volumes and across the particulate-surrounded grain boundaries, and the additional removal of diffusion creep resulting in flow by only dislocation creep would further reduce the relaxation rates (only modest relaxation of 1000-m diameter craters in 10 Myr).

Future work will expand on these results to determine the effect of varying, grain sizes, particulate fractions, and surface temperatures, and will model larger craters in the thin ice sheet environment whose crater depth exceeds the thickness of the thin ice sheet layer, with interactions between the stiff rocky substrate and the viscously flowing particulate-rich ice mass. In addition, plasticity (i.e., continuum brittle faulting) can be added to create a more comprehensive rheological model to investigate the presence of tectonic fracture features associated with relaxation as observed in numerous craters.

References: [1] Maurice S. W. et al. (2011) JGR, 116. [2] Mellon M. T. et al. (2008) JGR, 113. [3] Smith, P.H. (2009) PhD Dissertation, U. Arizona.1 [4] Cull S. et al. (2010) GRL, 37 [5] Dombard A. J. and Noe Dobrea E. Z. (2016) *LPS XLVII,* Abstract #1766. [6] Noe Dobrea E. Z. et al. (2018) *Late Mars Wrkshp.,* Abstract #5016. [7] Noe Dobrea E. Z. et al. (2016) *Icarus,* submitted. [8] Qi C. et al. (2018) *GRL, 45(*23)*,* 12757-12765. [9] Pathare A. V. et al. (2005) Icarus, 174, 396-418. [10] Dombard A. J. and McKinnon W. B. (2006), JGR, 111, E01001. [11] Goldsby D.L. and Kohlstedt D. L. (2001) *JGR, 106,* 11,017-11,030. [12] Kirby S.H. et al. (1987) *J. Phys. C., 48,* suppl., 227-232. [13] Durham W.B. and Stern L.A. (2001) *Annu. Rev. Earth Planet. Sci., 29*, 295–330, [14] Sori M. M. et al. (2015) *GRL, 43(2),* 541-549. [15] Parro L. M. et al. (2017) *Sci. Rep. 7*, 45629. [16] Schorghofer, N. (2008) *GRL, 35,* L18201.