FORMATION OF LAYERED-EJECTA CRATERS DURING MARTIAN GLACIATIONS: INSIGHTS FROM NUMERICAL MODELING

A. M. Alexander[1,2], R.E. Grimm[1], M.R. Kirchoff[1]. [1]Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302; [2]Department of Geological Sciences, University of Colorado Boulder, Boulder, CO, 80309; Email: amanda.alexander@swri.org

Introduction: In an effort to understand the spatial and temporal evolution of tropical ice on Mars, we undertake a series of numerical simulations to model the formation of layered ejecta (LE) and radial ejecta (RE) craters. LE are observed around many martian impact craters and are thought to suggest interaction with ice, but the configuration and amounts are unclear [1-6].

Model formation ages of LE craters revealed that they formed throughout Mars geological history and ice must be available to within the last few hundred Myr, including at tropical latitudes [7,8]. Furthermore, the close proximity of RE and LE craters would require that tropical subsurface ice is spatially random with a correlation length <10 km. Instead, we suggest that the heterogeneity is temporal rather than spatial. We hypothesize that LE craters form under the influence of surface ice during glaciations (i.e., at high obliquity for the tropics). RE craters are formed during interglacial periods, or where ice cover is insufficient. Accumulation of tens of meters of ice in the tropics [7-10] is possible and, under this hypothesis, the existence of LE craters at all latitudes on Mars is consistent with global ice migration throughout martian history.

Senft and Stewart [11] explored the formation of craters in icy layered terrain for both surface and buried ice using CTH. They demonstrated that ice thickness and depth have an effect on crater morphology and ejecta behavior, but their investigation into surface ice was limited to relatively large thicknesses, >100 m. This motivates the question we address in this work: *how thin can the surface ice layer be to form LE craters and is it consistent with estimations for ice thicknesses expected at tropical latitudes during periods of glaciation?*

Methods: We first reproduced the CTH simulated craters from [11] using iSALE 2D [12-14]. Then, we expanded the parameter space to several ice thicknesses between 0-200 m with the intent to find the minimum thickness necessary for an LE to form for a given projectile size. We used projectile diameters of 200, 500 and 1000 m that produce craters ~3-18 km in diameter, which is representative of a majority observed LE on Mars [4]. All simulations are conducted at 20 cells per projectile radius (CPPR) and utilize the ANEOS equation of state for basalt for the martian rocky surface and for water ice for the surface ice. The projectiles, also basalt, impacted the martian surface at 10 km/s (slightly lower than martian typical impact velocity to account for the vertical/overhead orientation of the impact, implicit in 2D). The martian surface temperature was 210 K and the geothermal gradient was 15 K/km. We also tracked temperature, pressure and materials with massless Lagrangian tracer particles, one per cell.

We characterize as layered or radial the simulated ejecta by assessing run-out length (the extent to which the ejecta extends beyond the crater rim), the thickness of the ejecta beyond the proximal crater rim, and the potential existence of any ramparts. We qualitatively identified LE craters as those which have run-out length >2-3 crater radii with thinner ejecta further out and sometimes, possible ramparts of ice and rock. RE craters are identified when most of the ejecta is within 1-2 crater radii.

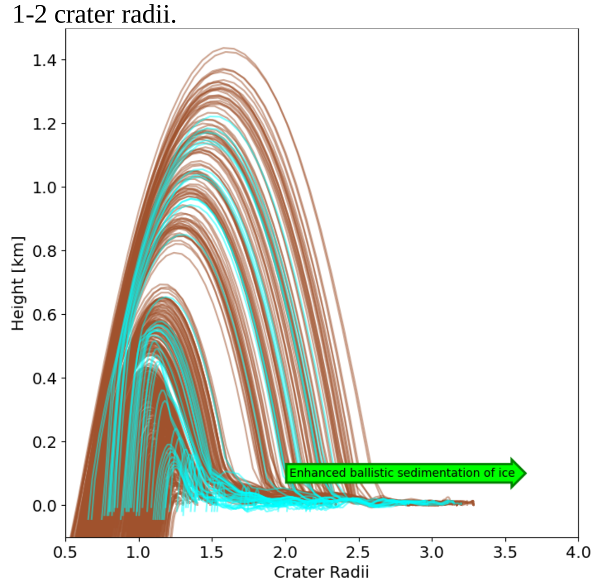

Fig. 1. Trajectory of tracer particles over time (brown/darker = basalt, blue/lighter = ice) in terms of crater radii for the simulation of a 500 m projectile with 50 m ice thickness. Non-ballistic run out of ice and rock near 3 crater radii is inferred as enhanced ballistic sedimentation.

Results and Discussion: **Fig. 1.** shows the resulting ejecta trajectories for the 500 m projectile, 50 m ice thickness case. We characterize as LE or RE as described before using the ejecta trajectories to determine run out length (e.g., **Fig. 1.**) and ejecta distributions (**Fig. 2.**) to asses ejecta thickness and the existence of any ramparts. We infer radial behavior (boxed in red, **Fig. 2.**) at zero ice thickness and observe almost immediate transition (in yellow, **Fig. 2.**) to LE (in blue, **Fig. 2.**) within examined ice thicknesses. LE

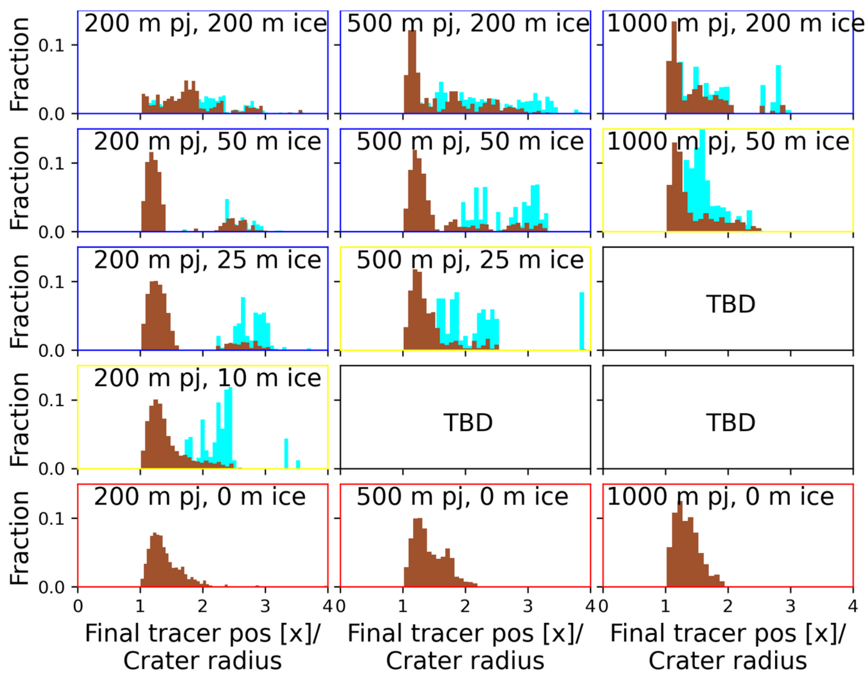

Fig. 2. Numerical investigation of impact cratering in ice layer over rock substrate. Subplot histograms show ejecta distribution (rock dark brown, ice light cyan) as functions of distance normal-ized to crater radius. Subplots are arranged with increasing projec-tile diameter on major x-axis and increasing ice thickness on major y-axis. Classification as LE, RE or transitional are denoted by the histogram border color in blue, red or yellow, respectively. TBD plots require higher resolution. Rock-only ejecta are confined to 1-2 crater radii as observed for RE craters, but ice-dominated deposits form at distances of 2-3 crater radii, characteristic of LE craters.

behavior is observed at 25 m of ice for the 200 m impactor, 50 m for the 500 m impactor and 200 m for the 1000 m impactor. However, we note that the resolution of these models is quite coarse such that for the largest impactor, ice thickness was not able to be simulated for less than 50 m and it may be that the transition for 500 and 1000 m projectiles is less than 50 m of ice.

Finally, in agreement with [11], we find non-ballistic motion of near surface ice (see annotation in **Fig**. **1**.) We interpret this behavior as enhanced ballistic sedimentation [15]. In radial crater formation, there is horizontal movement from debris flow following the impact that can form sedimentary structures. The low strength of ice at martian temperatures enhances this behavior and forms distal, lobate ejecta. As with RE on airless bodies, ballistic sedimentation obviates the need for a “base surge” from a collapsing atmospheric column such that atmospheric entrainment is not required for martian LE craters.

Conclusion: We are producing transitional-to-LE craters at 10-50 m ice thickness for martian impact conditions. Such ice thicknesses are in agreement with predicted ice accumulation at martian tropical latitudes during glaciation. Enhanced ballistic sedimentation is observed that drags ice and rock both out beyond 2-4 crater radii; this mixture leaves behind a geological remnant that can be observed today.

Future Work: We have demonstrated that ice layers as thin as several tens of meters can strongly influence ejecta behavior that, in 2D cross section, appear to be representative of LE craters. We intend to better quantify the RE-LE definition criteria and perform higher-resolution modeling to resolve the thinnest ice layer at which transition occurs.

In addition, we predict that a transition back to RE craters should occur when ice thickness is greater than a few projectile diameter, however this is not observed in the few simulations we ran with ice thickness of 800 m. Instead, we continue to see ice run-out and are presently working through this conundrum. Perhaps it is too warm on Mars or it is an artifact of the simulation. We plan to model similar cases with much colder surface temperatures (~100 K) to assess.

Acknowledgments This work was supported by NASA Grant 80NSSC19K1223. We gratefully acknowledge the developers of iSALE-2D, including G. Collins, K. Wünnemann, D. Elbeshausen, T. Davison, B. Ivanov and J. Melosh.

References: [1] Carr et al., 1977. *JGR*, 82(28), 4055– 4065. [2] Gault and Greeley, 1978. *Icarus* 34: 486–495. [3] Mouginis-Mark, 1981. *Icarus* 45: 60–76. [4] Barlow and Perez, 2003. *JGR* 108(E8). [5] Komatsu et al. 2007. *JGR* 112(E6). [6] Black and Stewart, 2008. *JGR* 113(E02015). [7] Kirchoff and Grimm., 2018. *JGR: Planets*, 123(1), 131–144. [8] Kirchoff et al., 2022. *LPSC* Abstract #2545. [9] Carr and Head, 2015. *GRL*, 42, 726–732. [10] Head et al., 2005. *Nature* 434:346-351. [11] Senft and Stewart, 2010. *Met. and Pl. Sci.*, 43(12), 1993–2013. [12] Amsden et al., 1980. *Los Alamos National Laboratories Report*, LA-8095:101p. [13] Collins et al., 2004. *Met. and Pl. Sci.*, 39:217–231. [14] Wünnemann et al., 2006. *Icarus*, 180:514–527. [15] Melosh. *Impact Cratering. A geologic process.* 1984.