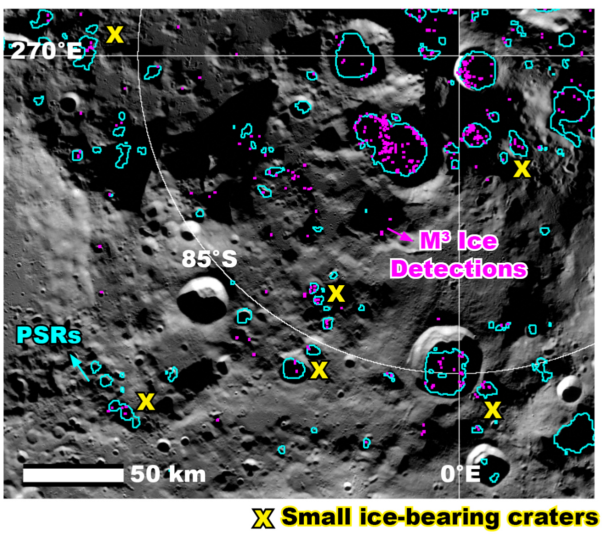
YOUNG OR OLD? INVESTIGATING THE ORIGIN AND AGE OF WATER ICE IN SIMPLE LUNAR POLAR CRATERS USING NUMERICAL MODELING. Ross W. K. Potter[1,2] and Ariel N. Deutsch[3], [1]Clarivate, 160 Blackfriars Road, London, SE1 8EZ, [2]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA 02912 (ross_potter@brown.edu), [2]NASA Ames Research Center, Mountain View, CA, USA 94035.

Introduction: Observations of water ice at the lunar poles [e.g., 1-8] provide tantalizing prospects for explorative science. This ice is expected to be largely cold-trapped in the subsurface [1-5]; however, detections of ice exposed at the surface [6–8] have also been made (**Fig. 1**). This raises the question of the origin, and consequent age, of such ice: if surface ice was delivered after the formation of their host cold traps (generally, ≤ 3.5 Ga simple impact craters), then the cold trap ages provide upper limits on the ice age; surface ice could therefore be 'young' (≤ 3.5 Gyr). Alternatively, ice could be 'old' if it existed prior to the formation of its host crater; surface ice exposures in smaller craters may then be remnants of ancient ices exposed during the impact cratering process.



Here we are interested in determining how near-surface ice is redistributed by small impact events at the lunar poles. We numerically model these events into ice-rich targets to analyze the loss and redistribution of pre-existing ice layers in order to study the conditions under which these layers can be excavated to, and preserved at, the lunar surface. This work has important implications for the stratigraphies of ice-bearing craters, and thus, the ages and sources of surface ice observed on the Moon today. It will also provide important insight into the influence of ice layers in the formation of simple craters, building upon the Shackleton crater investigation of [9].

Fig. 1. Distribution of surface ice detections [8] at the lunar south pole. Examples of small (D <10 km) craters that host ice exposures are denoted by an X. PSRs: Permanently shadowed regions. (LOLA WAC image.)

Methods: The iSALE shock physics code [10-12] was used to numerically model the formation of simple lunar impact craters with a diameter ≤ 15 km. Typical lunar impact velocities of 10 and 20 km/s were used; impactor diameters were varied between 0.5 and 2 km. Simulations were carried out in a two-dimensional half-space, with surface gravity set to 1.63 m/s^2. A semi-analytical equation of state for dunite [13] represented the impactor. The target crust was represented by an equation of state and strength model for gabbroic anorthosite [14–17]. A Tillotson equation of state for wet tuff, based on a Nevada tuff with a water content of 14.4 wt.% [9,18] was used as an ice layer proxy. This layer was interspersed within the anorthosite at various depths (e.g., 0.5 km, 1 km) and with various thicknesses (up to 1 km - representing an upper boundary of 'gigaton' thick ice deposits [19]). Surface temperature was 100 K; the ice layer proxy was a constant 125 K.

Results: Simulations illustrate the effect of an ice layer buried at depth on simple crater formation.

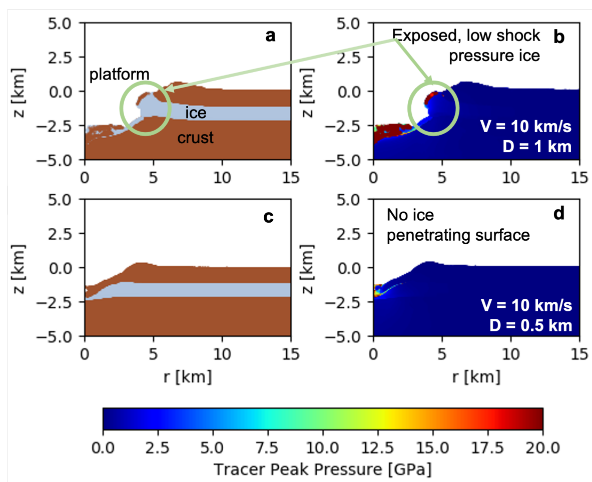


Fig. 2. Material (a,c) and ice peak shock pressure (b,d) distribution for two impact scenarios (velocity, *V*, of 10 km/s; diameter, *D*, of 1 and 0.5 km). The ice layer was originally at a depth of 1 km, with a thickness of 1 km.

Figure 2 illustrates impacts with a velocity of 10 km/s and diameters of 1 km (a,b) and 0.5 km (c,d) into a target with a 1 km thick ice layer buried 1 km beneath the surface. In the more energetic impact, ice has been exposed on the crater walls (a,b) – some of this ice is shocked to a low peak pressure. In the less energetic impact (c,d), no ice was exposed on the surface, though it was brought closer to the surface. The more energetic impact has also resulted in the formation of a, mainly ice, platform on the crater wall.

Discussion: The models demonstrate that water-saturated material (i.e., ice) originally at depth can be both exposed at the crater surface and not significantly shocked (i.e., melted/vaporized). This suggests that buried ice layers could survive a cratering event (i.e., remain solid) and be found near the crater floor. However, this is heavily dependent on the impact and target parameters, as briefly shown here. Ice must be at a great enough depth to not be vaporized (or else submitted to high peak shock pressures) and not too deep to prevent excavation or expose during crater formation. Given the size range of these ice-bearing craters (≤ 15 km), the ideal parameter condition range for this outcome is likely small.

The presence of an ice platform along the crater wall will also be dependent on impact energy and ice depth/thickness, but nonetheless demonstrates that an ice layer could affect crater formation.

The ages of exposed lunar surface ice have important implications for the source of the ice, given that different delivery mechanisms have operated at different times and intensities throughout lunar history. This work, therefore, suggests that some lunar ice deposits could be 'old' - ice exposures in smaller craters are the remnants of ancient ices, exposed during the impact cratering process. This would be consistent with Monte Carlo ice deposition modeling [19] and regolith gardening processes [20] which predict most ice is from relatively ancient, episodic deliveries.

Conclusions: The stratigraphies of lunar polar craters provide an important record of ice accumulation through time. However, this record must be read carefully, as it is complicated by discontinuities from various loss processes and by larger episodes of ice and ejecta emplacement. Understanding how small impacts play a role in modifying this record is essential for interpreting crater stratigraphies. This work focusing on the origin of ice within lunar craters will also provide important insight into interpreting future ground-based measurements of polar crater stratigraphies, as NASAs Volatiles Investigating Polar Exploration Rover (VIPER) [21] is preparing to explore and drill at the lunar poles.

References: [1] Feldman, W. C. et al. (2000) *JGRP, 105,* 4175–4195. [2] Mitrofanov, I. G. (2010) *Science, 330,* 483–486. [3] Colaprete, A. et al. (2010) *Science, 330,* 463–468. [4] Kokhanov, A. A. et al. (2015) *SSR, 49,* 295–302. [5] Rubanenko, L. et al. (2019) *Nat Geo, 12,* 597–601. [6] Hayne, P. O. et al. (2015) *Icarus, 255,* 58–69. [7] Fisher, E. A. et al. (2017) *Icarus, 292,* 74–85. [8] Li, S. et al. (2018) *PNAS, 115,* 8907–8912. [9] Halim, S. H. et al. (2021) *Icarus*, 354, 113992. [10] Amsden, A. A. et al. (1980) Los Alamos National Laboratory Report LA-8095. [11] Collins, G. S. et al. (2004) *MAPS*, 39, 217-231. [12] Wünnemann, K. et al. (2006) *Icarus*, 180, 514-527. [13] Benz, W. et al. (1989) *Icarus*, 81, 113-131. [14] Thompson, S. L. and Lauson, H. S. (1972) Sandia National Laboratory Report SC-RR-71 0714. [15] Stesky, R. M. et al. (1974) *Tectonophys*., 23 177-203. [16] Shimada, M. A. et al. (1983) *Tectonophys*., 96, 159-172. [17] Azmon, E. (1967) NSL 67-224, 16pp. [18] Allen, R. T. (1967). General Dynamics Report #GA MD-7834. [19] Cannon, K. M. et al. (2020) *GRL, 47,* e2020GL088920. [20] Costello, E. S. et al. (2020) *JGRP, 125,* e2019JE006172. [21] Colaprete, A. et al. (2020) *LPSC 51,* 2241.