STRATIGRAPHY OF ICE AND EJECTA DEPOSITS AT THE LUNAR POLES: UPDATES AND NEW INSIGHTS.

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Introduction: Many lunar cold traps appear to host a small amount of water-ice frost on the surface [1–3], which may be a recent transient phenomenon [4]. Some authors have argued for thicker deposits buried at depth under dry regolith, and newer studies suggest a possible link between subsurface ice and terrain features observed at the surface (roughness, crater morphometry, etc.) [5–7]. Understanding ice volumes and how ice is distributed at depth is significant for reconstructing the history of volatile delivery to the poles, and for modeling potential water resources for future human exploration.

Two overlooked factors in studies of lunar ice are the ejecta emplaced by large craters at the lunar poles, and the stochastic nature of ice deposition that may have been dominated by rare large impacts of hydrated asteroids. The ejecta deposits of polar craters would have been laid down in an alternating fashion with ice deposition events, creating a complex stratigraphy on a variety of spatial scales. Here, we report on recent work [8] using crater counting and computer modeling to investigate the large-scale ice stratigraphies expected to have formed at the lunar poles.

Methods:

Crater counting. We extended the crater counting of Deutsch et al. [9] for the lunar south pole to also include the north pole. Forty-three additional large craters were selected that have >100 km^2 of low slope (<10°) area on their floors, and are located above 80° north latitude. Crater counting was performed on a LOLA hillshade basemap [10] with 20 m horizontal resolution, with a minimum counted crater size of 200 m. The model ages were then fed into the stratigraphy modeling described below in order to place craters accurately in time.

Ice sources. In order to model both ejecta and ice deposition, we need an idea of the amount of water delivered to the lunar poles over time. In this work we consider two major sources: impact delivery from carbonaceous asteroids, and volcanic outgassing. For impacts, we divided the impactor population into five size classes based on different methods for calculating impact fluxes, and different scaling laws to estimate impactor sizes from crater sizes. Smaller impactors were treated as a bulk population due to their large numbers, but crucially, larger impactors were treated individually with water fractions and impact velocities assigned one-by-one. For volcanism, we used updated estimates from Head et al. [11], building on earlier work by Needham and Kring [12] that made a different set of assumptions about the volume of deposits and the spacing of volcanic eruptions. Ice contributions from solar wind were ignored because they are expected to contribute orders of magnitude less than other sources [13].

Stratigraphy modeling. To study the competing effects of ice deposition and crater ejecta, we created a computer model to build up stratigraphies. The model operates on a 2D grid, and runs from 4.25 Ga to present with a timestep of 10 Myr. At each timestep, a layer of ice is deposited corresponding to the time-dependent delivery rates from impacts and volcanism. The ejecta from any craters of that age are also emplaced over the grid in the correct locations. We assume the total cold trap areas for each pole [14] have stayed more or less constant over time, with each new crater destroying some existing cold trap area but creating new cold traps as well. This allows us to calculate ice thickness based on the delivered mass, and avoids issues of trying to reconstruct the complete topographic and thermal history of the poles over >4 Gyr. We employed a Monte Carlo approach with 10,000 simulations per pole, due to the stochastic nature of ice deposition, and the uncertainties in crater ages from crater counting.

It makes sense to look at the resulting stratigraphies for craters that host present-day cold traps, or those that post-date the true polar wander from [15], and to clip the columns based on our modeled ages of when those cold traps likely formed and could start accumulating ice.

Results and Discussion: Fig. 1 shows resulting stratigraphic columns for different locations in the same model run (left), and different model runs for the same location (right). Some of the key observations from the model ensemble include:

1. The age when a cold trap forms and begins accumulating ice is the major factor controlling ice retention and the total volume of ice in a cold trap.

2. Thick layers of ice we term “gigaton deposits” may be present at depth, but in many cases, these are buried by 10s or 100s of meters of dry regolith and are not expected to be observed by remote sensing techniques.

3. Stochasticity (due to different modeled impact histories, and uncertainties in crater ages) imparts dramatically different ice layering between runs.

4. Most modeled strata end up with a thinner, ice-rich gardened mantle in the upper 10s of meters that may be consistent with observed shallowing of polar craters and surface roughness effects [5–7].

5. The vast majority of ice is deposited early: on average, 96% before 3.75 Ga in the model ensemble.

6. Very rare outlier model runs with recent large impacts led to Mercury-like deposits with thick near-surface ice layers (Fig. 1, rightmost panel).

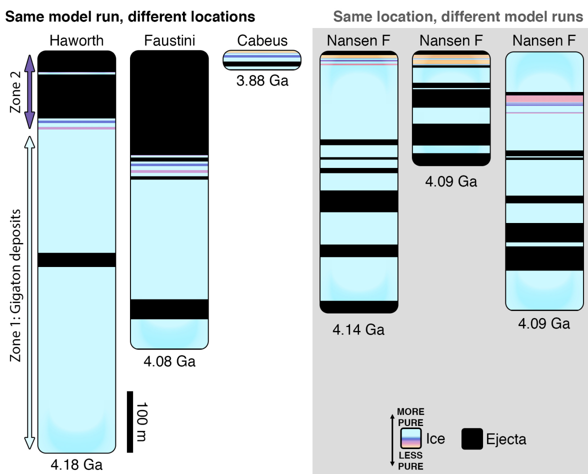

Fig. 1. Stratigraphy of ice (color scale) and ejecta (black) at multiple different cold traps, showing the effects of location (left) and stochasticity (right).

One parameter that remains poorly estimated is the loss rate of ice, particularly from violent events like ballistic sedimentation. We also relied on scaling current loss rates [4] back in time based on the impact flux, but this may not be accurate. Further constraining loss processes is likely the best way to improve estimates of total ice volumes and ice concentrations in polar cold trap deposits.

Ice Textures: The stratigraphic columns in Fig. 1 imply thick, massive-textured ice deposits, but ice may not be present in coherent layers due to the effects of impact gardening, ice deposition on grain surfaces, and sintering (as occurs in cometary ices). In addition to massive ice, and frost, other textural relations may be expected (Fig. 2) based on the complexity of particles observed in Apollo regolith samples, and on the physical processes operating in the cold traps. We are working to understand the prevalence of these different forms, and how polar processes may cause transformations between them.

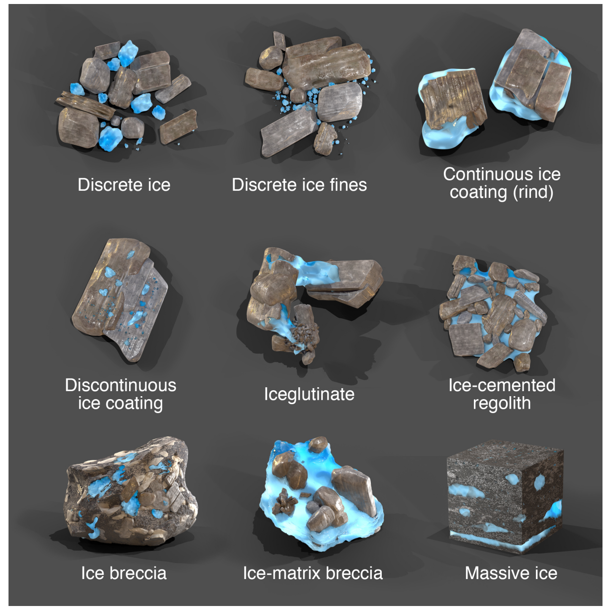

Fig. 2. Possible ice and silicate textural relations that may be observed in lunar cold trap environments.

Conclusions and Future Work: The ice observed by shortwave spectroscopy [1–3] may only scratch the surface of what could be buried underground at the lunar poles, due to a 4+ billion-year history of repeated ice deposition, burial, and loss. The Moon may not be fundamentally different than Mercury in terms of its volatiles, and we may instead be biased by remote sensing that is mostly limited to the upper meter.

After looking at both poles at a coarse scale [8], we are now integrating the stochastic deposition processes of ice and ejecta into smaller-scale 3D impact gardening models [16] relevant for a single cold trap. These models were originally designed to look at how ice was worked into the regolith and eroded after a single deposition event, but are now being extended to handle many recurring events.

References: [1] Hayne P. O. et al. (2015) *Icarus*, *255*, 58. [2] Fisher E. A. et al. (2017) *Icarus*, *292*, 74. [3] Li S. et al. (2018) *PNAS*, *115*, 8907. [4] Farrell W. M. et al. (2019) *GRL, 46,* 8680-8688. [5] Kokhanov A. A. et al. (2015) *Sol. Sys. Res., 49*, 295-302. [6] Rubanenko L. et al. (2019) *Nat. Geo.*, *12*, 597. [7] Deutsch A. N. et al., *in prep*. [8] Cannon K. M. et al. (2020) *GRL, 46*, e2020GL088920. [9] Deutsch A. N. et al. (2020) *Icarus*, *336*, 113455. [10] Smith D. E. et al. (2010) *GRL*, *37*, L18204. [11] Head J. W. et al. (2020) *GRL, 47*, e2020GL089509. [12] Needham D. H. and Kring D. A. (2017) *EPSL*, *478*, 175. [13] Lucey P. G. et al. (2020) *LPSC LI,* #2319 [14] Williams J.-P. et al. (2019) *J. Geophys. Res., 124*, 2505-2521. [15] Siegler M. et al. (2016) *Nature, 531*, 480-484. [16] Cannon K. M. and D. T. Britt (2020) *Icarus, 347*, 113778.