REVISITING ICE STRATIGRAPHIES AT THE LUNAR POLES. K. M. Cannon[1,2] and A. N. Deutsch[3], [1]Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401. cannon@mines.edu. [2]Space Resources Program, Colorado School of Mines. [3]NASA Ames Research Center, Moffett Field, CA 94035.

Introduction: In previous work [1], we described how stochastic delivery of water to the lunar poles and impact ejecta blanketing should lead to a layered stratigraphy of ice deposits. Many of the ideas and modeling methods from that work still have broad applicability: the probabilistic approach to ice deposition, the dominance of hydrated asteroids as a water source compared to volcanism and comets, and the potential for significant amounts of ice sequestered several meters beneath the surface. We also pointed out the cumulative tens to hundreds of meters-thick "layers" of ice that fall out of the simple accounting of water sources may not exist; obliquity excursions [2] and true polar wander [3] could have changed the polar thermal environment over time and therefore the t=0 when ice began accumulating in earnest. Several new developments have come out since our previous work:

(1) Ballistic hopping is no longer favored as a mechanism to transport water to the poles [4,5], but collisional atmospheres remain viable [6]. The main implication is that a threshold mass of volatiles is needed to form a collisional atmosphere, and any event releasing less water would likely lead to most of that water leaving the lunar gravitational system. We used ballistic hopping in the previous work and this likely led to overestimates of ice thicknesses because no such cutoff was incorporated.

(2) The Cassini state transition and obliquity evolution of the Moon are now better constrained [7]. The transition and massive obliquity excursion likely occurred early, but as Schorghofer [8] has highlighted, it would have taken considerable time for the solar declination to slowly recede to present-day values. We can then imagine a time with no permanent cold traps at the poles and their gradual ingrowth over time. In our modeling, this has the effect of changing t=0 for ice deposition in a location-dependent manner.

Here, we explore the implications of (1) and (2) by updating the previous modeling work.

Methods: We model ice deposition via hydrated asteroids, overturn of the regolith column via impact gardening [9], and ice erosion at the surface [10] on a 3-dimensional grid that covers most of the polar region with a horizontal resolution of 250 m and a vertical resolution of 0.1 m. A ray-tracing procedure was used to estimate the locations of permanent surface cold traps (<110 K) and subsurface cold traps (<145 K) based on the solar declination as a function of time in [8] (Fig. 1). These are approximations using the maximum angular elevation of the sun (instead of the true ephemerides), and we do not account for changes in topography with time that would affect lighting conditions and therefore temperature (i.e., new craters forming, topographic diffusion).

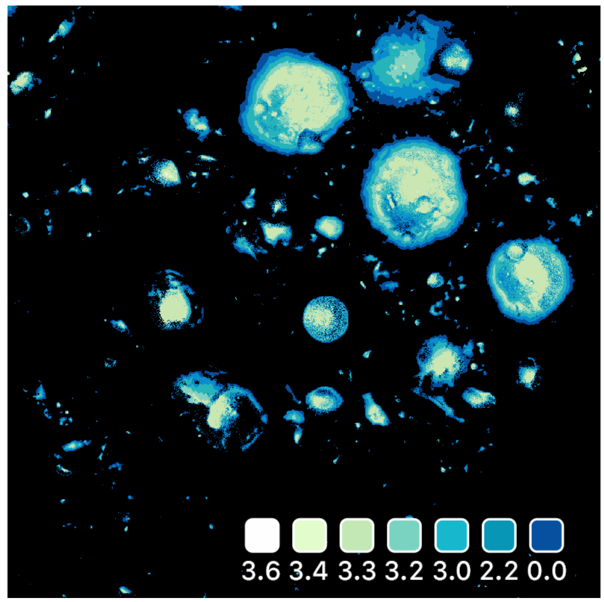

Fig 1. Predicted maps of permanent surface cold traps (<110 K) as a function of time (color coded, Ga) using solar declination values from [8]. The cold traps expand with time toward present-day boundaries.

Previously we assumed all cold-trapped ice would sit on top of the regolith, but a collisional atmosphere should diffuse into porous regolith and allow ice deposition directly into the shallow subsurface. This effect [11] has not been treated in detail for the Moon. Here we use a simplified approach that partitions ice deposited at each location evenly between the upper 10 cm of porous regolith (if <145 K and with sufficient pore space) and on top of the regolith (if <110 K). If there is already ice on top of the regolith, we assume all new ice is deposited above.

Our previous work [1] focused on large polar craters that deposit a blanket of dry insulating material, and models of ballistic sedimentation [12] have also highlighted the potential for these impacts to disrupt existing ice. However, we find only 1 of the 67 large craters we estimated ages for–Amundsen C–postdates the likely emergence of permanent cold traps based on solar declination values from [8]. Therefore, we suggest ballistic sedimentation was not an important process for disrupting ice in today's polar cold traps because their ice likely was not emplaced before the relevant large craters formed.

Results: Figure 2 shows how much ice from hydrated asteroids can be cold trapped (cumulatively) for different t=0 values. As expected, if a cold trap forms later it will accumulate less ice, and there is a dramatic difference when we consider cold traps forming based on a decrease in solar declination vs. forming with the crater itself.

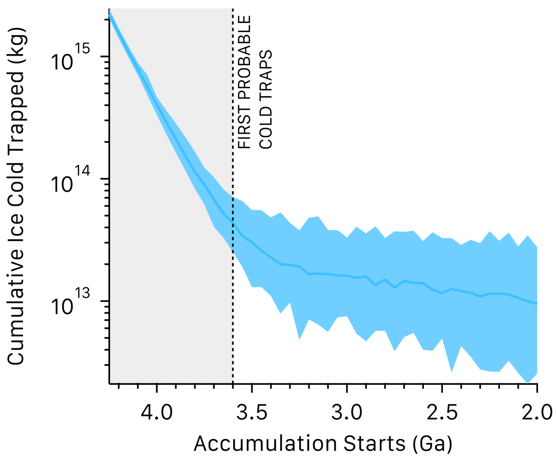

Fig. 2. Estimated total ice accumulated at the poles (assuming 26% of H_2O in a transient atmosphere is trapped [6]) as a function of model starting age. Most of the ice was likely deposited within the gray shaded region when today's cold traps may not have been around to collect it.

Figure 3 shows final ice concentrations for a single representative model run. Results are more consistent with remote sensing observations of the lunar poles: no coherent layers at depth are formed and low average ice abundances are consistent with neutron data, but pockets of higher concentrations are buried at depth.

Conclusions: Deposits of nearly pure ice tens to hundreds of meters-thick are no longer supported based on improved understanding of cold trap ages and ice deposition mechanisms. This brings models more in line with constraints from radar and neutron data and suggests an alternative explanation for differences between Mercury's polar ice and the Moon's (i.e., changes in solar declination). The models presented here will be further improved by adding volcanically derived ice, accounting for the ejecta deposits of smaller craters (<20 km) that postdate the earliest cold traps, and addressing true polar wander scenarios.

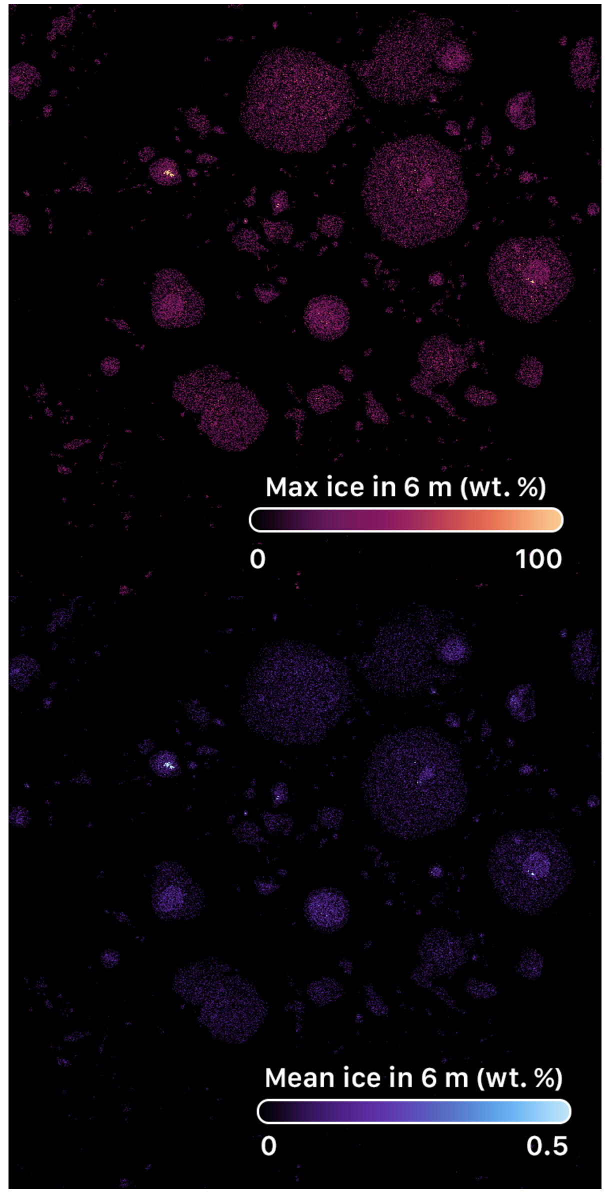

Fig. 3. Model results for a single run showing final ice concentrations integrated over the upper 6 m.

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