MODELING THE EFFECTS OF BASIN IMPACTS AND BALLISTIC SEDIMENTATION ON ICE IN LUNAR COLD TRAPS.

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Introduction: Understanding the sources, transport, deposition, and distribution of volatile materials and their cycles are important elements of polar exploration on the Moon [1, 2]. Within permanently shadowed regions (PSRs), stratigraphic columns may record the history of ice delivery to the Moon, potentially in alternating layers of ancient ice and ejecta deposition events. This rich history could hold the key to understanding the volatile delivery mechanisms within the inner Solar System. In order to predict and interpret the stratigraphy of polar ice, we began with the framework of a Monte Carlo model introduced by [3] and added geological processes that may affect the delivery, removal, and preservation of ice. The updated model scales the effects of impact gardening with age, updates volcanic outgassing with new estimates of transient atmosphere deposition [4], and includes basin-sized impactors and comets in impactor ice delivery. We also model the effects of ballistic sedimentation [5] on polar ice deposits [6]. We explore the effects of these processes on PSR stratigraphic columns and find that ballistic sedimentation may significantly influence deep ice reservoirs.

Methods: Our updated model, Moon Polar Ice and Ejecta Stratigraphy (MoonPIES), tracks the deposition and removal of ice and ejecta from 4.25 Ga to the present in 10 Myr time steps. The model outputs a stratigraphy column with layers of ice and ejecta for each cold trap. Ejecta are primarily sourced from proximal polar craters, with timing of delivery randomized within their crater-count model age uncertainties. Ice is sourced from icy impactors with size and abundance governed by the crater chronology function [7], volcanic outgassing [8], and solar wind H^+ deposition [9, 10]. Impact gardening and ballistic sedimentation remove ice from the top of each column [5, 11]. The model assumes a static polar orientation over the 4.25 Ga timespan such that each cold trap is stable from its formation to the present.

Ice delivery updates. We update the treatment of impact-delivered ice by randomizing the water content of the impactor by the likelihood of being of asteroidal or cometary in origin [12]. We also add the ability for individual basin-forming events to deliver ice with the same probabilities as other impactors. We allow solar wind H^+ deposition to form ice at a rate estimated by [9] and [10]. Volcanically-derived ice delivery is modeled similarly to [3], with an updated deposition rate [4].

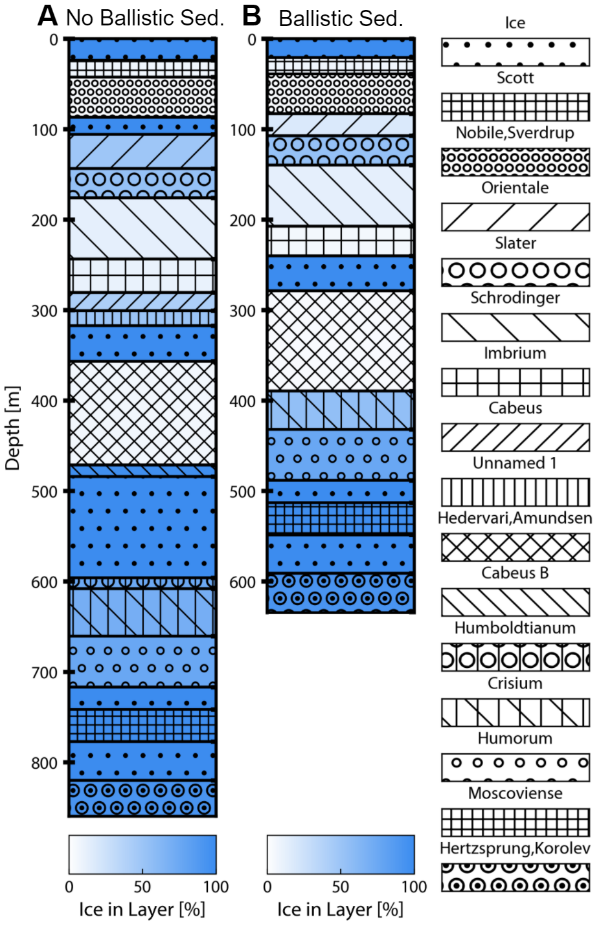

Figure 1: MoonPIES stratigraphy columns for the same run of Faustini cold trap, **A)** with ballistic sedimentation and **B)** without ballistic sedimentation. Ejecta layers are delivered in the same sequence and thickness in both runs, but when ballistic sedimentation is included in the model, several deep ice layers (formed early) are lost.

Ice removal update. The MoonPIES model updates the treatment of impact gardening consistent with new work presented in [11]. We also model the ice lost during ballistic sedimentation events whereby ejecta from a primary crater mixes local material as it is ballistically emplaced [5]. Ballistic sedimentation requires primary crater ejecta to impact with sufficient velocity and energy density to mechanically disrupt and mix with a planetary surface. Ballistic sedimentation effects were observed at the Ries crater [13] to distances of 3 crater radii and modeled to 4 crater radii in this work and others [14]. In our model, polar complex craters and basins can cause ballistic sedimentation, but basins dominate due to the higher velocity and kinetic energy of their ejecta.

Results and Discussion: We find that ballistic sedimentation has a significant effect on lunar cold trap stratigraphy. The representative example in Figure 1 shows that without ballistic sedimentation, ejecta layers preserve large subsurface ice reservoirs, but when we account for ballistic sedimentation a significant fraction of the deep ice layers may be lost. Since MoonPIES is a Monte Carlo model, the order and thickness of the ejecta and ice layers may vary from run to run, but the addition of ballistic sedimentation to any given run reduced the total modeled ice content for that run.

The timing of basin formation greatly affects ice preservation and removal in the MoonPIES model. Figure 2 summarizes the average effects of ice delivery, preservation, and removal in each lunar geologic era. Ballistic sedimentation is elevated during the lunar basin-forming epoch (Pre-Nectarian to the end of the Early Imbrian), which is also when the majority of ice is delivered in the model. In all eras, volcanic and solar wind sources of ice are orders of magnitude less than removal processes (impact gardening and ballistic sedimentation) and have little to no influence on the modeled ice stratigraphy. Therefore, our model suggests that the majority of ice retained at depth on geologic timescales is derived from impactors (comets and volatile-rich carbonaceous asteroids).

Conclusions: Basin impacts and impact gardening are critical to understanding stratigraphy at the lunar poles. Our updated model suggests that ballistic sedimentation may disrupt the deep ice reservoirs modeled by [3]. Of the sources of ice modeled here, impact-delivered ice appears to be most significant, as suggested previously [15]. Ongoing work to interpret variance between our Monte Carlo model runs will further constrain the effects of ballistic sedimentation on ice retention near the lunar poles.

Acknowledgements: We thank the CLSE, LPI, USRA, and NASA SSERVI for supporting this work.

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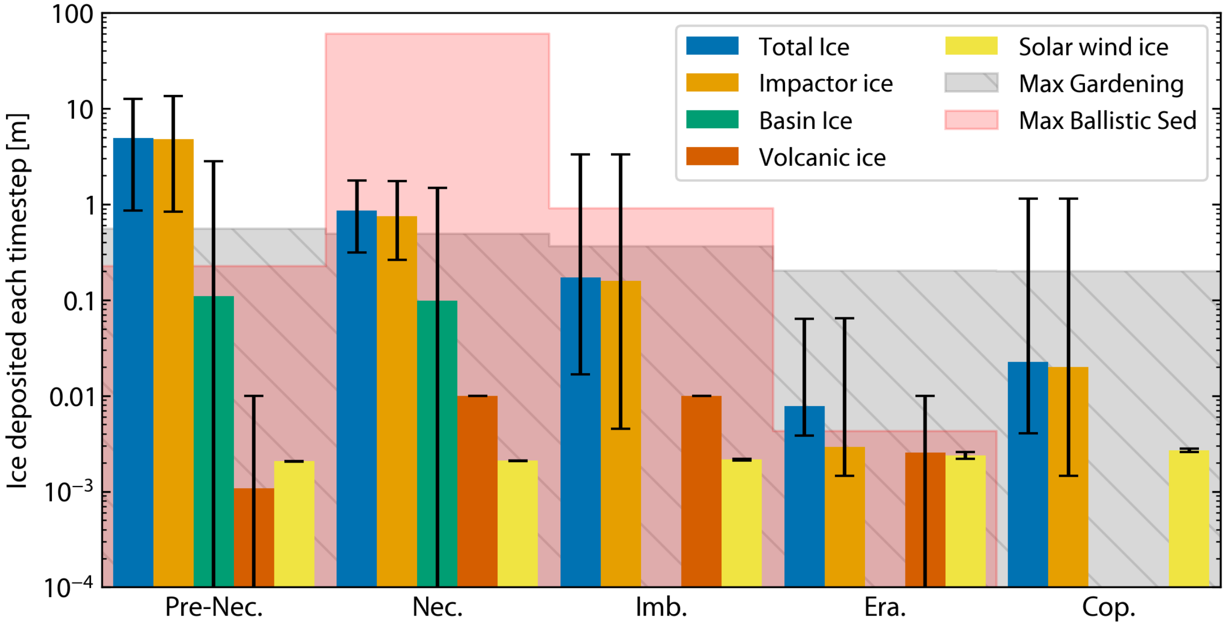

Figure 2: Average ice deposition and removal (meters, log scale) per 10 Myr timestep by lunar geologic era for one run in the Faustini cold trap. Bars represent mean ice thickness, and whiskers are the min and max ice deposited during the era. Shaded regions represent ice removal depths by impact gardening (grey) and ballistic sedimentation (pink).