Stratigraphy of Ice and Ejecta Deposits at the Lunar Poles

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Abstract Water ice has been delivered to the lunar poles from different sources over billions of years, but this accumulation was punctuated by large impacts that excavated dry regolith from depth and emplaced it in layers over the poles. Here, we model the resulting stratigraphies of ice and ejecta deposits in the lunar polar regions. Large polar craters were age dated, and their ejecta distributions calculated with standard scaling relations. We then created a Monte Carlo model for ice deposition and ejecta emplacement. Typical model runs showed that deposits in older cold traps (>4 Ga) are divided into two zones: buried ice-rich gigaton deposits and younger more gardened mantles. The latter are consistent with small crater morpometry measurements, but the existence of substantial ice buried at great depths is more difficult to confirm. Rare outlier model runs included Mercury-like cases with significant deposition events in recent history (<200 Ma).

Plain Language Summary The polar regions of Earth's Moon have topographic depressions that are never directly exposed to the Sun, so they are cold enough for deposits of ice to exist. Water can get into these regions by water-bearing asteroids colliding with the Moon, or from lunar volcanoes erupting gases that travel to the poles. At the same time, large impact craters that form at the poles eject an enormous amount of soil and rock that could bury existing ice. It is not well understood how these two processes work together to build up deposits that may have alternating layers of ice-rich and ice-poor soil. In this study, we used computer simulations to predict what these layered deposits may look like. We found it is likely that large amounts of relatively pure ice are buried at depth in the oldest deposits, covered with thinner layers hosting less ice.

1. Introduction

Following early theoretical predictions by Watson et al. (1961) and Arnold (1979), water ice has been found at the upper surface of the Moon's polar regions (Fisher et al., 2017; Hayne et al., 2015; Li et al., 2018; Lucey et al., 2014), and H2O and other cold-trapped volatiles have also been inferred in the shallow subsurface using a variety of techniques (Colaprete et al., 2010; Feldman et al., 1998; Rubanenko et al., 2019; Schultz et al., 2010; Yang et al., 2019). However, ice concentrations and particularly the stratigraphy of ice-rich and ice-poor regolith remain poorly understood (Lawrence, 2017). Surface ice detected by the Lyman-Alpha Mapping Project has been interpreted as thin transient frosts (Farrell et al., 2019; Hayne et al., 2015), but detections from Li et al. (2018) using the Moon Mineralogy Mapper instrument could represent deposits thicker than mere frost. Most studies have interpreted measurements from the Lunar Crater Observation and Sensing Satellite (LCROSS), neutron spectroscopy, and radar as low concentrations of shallow subsurface ice (Campbell & Campbell, 2006; Colaprete et al., 2010; Teodoro et al., 2014; Thomson et al., 2012), although others have interpreted radar signatures (Spudis et al., 2013) and unusually shallow polar craters (Kokhanov et al., 2015; Rubanenko et al., 2019) to favor thicker Mercury-like (i.e., meter-thick) ice layers buried under or mixed within regolith. These differing interpretations present challenges for selecting instruments to further study polar volatiles and for resource prospecting and extraction efforts.

Impact cratering has been the dominant process affecting the lunar poles, but the effects of large polar craters on nearby ice deposits have not been previously addressed. Impact effects have been considered for micrometeoroids (e.g., Farrell et al., 2019) and small impactors (Cannon & Britt, 2020; Costello et al., 2020; Crider & Vondrak, 2003; Hurley et al., 2012). The large polar craters (>20 km diameter) each formed at a distinct point in lunar history (Deutsch et al., 2020; Tye et al., 2015), and during crater formation, these...
impacts would have emplaced ejecta out to significant distances (e.g., McGetchin et al., 1973), affecting existing ice deposits in the surrounding terrains. These effects included mixing and burial through ballistic sedimentation (Oberbeck, 1975), potential melting and vaporization (Weiss & Head, 2016), and even possible aqueous alteration (Stopar et al., 2018). Ice could have accumulated more or less unimpeded by large crater-forming events after the sharp decline in the impact rate from ~3.5 to 3.0 Ga, but with a greatly reduced supply of impact-delivered water.

2. Previous Estimates of Water Ice Delivery

Previous studies have addressed part of the problem of estimating how much water makes its way to cold traps in the polar regions of the Moon or Mercury and the resulting ice deposit thicknesses. For example, Arnold (1979) originally estimated deposit densities of ~5–50 g/cm² (~50–500 mm thick). Prem et al. (2015) calculated deposit densities of up to 6.49 × 10⁶ kg/km² (~7 mm thick) 72 h after the impact of a 2-km pure ice comet on the Moon. Ernst et al. (2018) calculated that the large impactor that created Hokusai crater on Mercury could have contributed >10¹³ kg of water to the poles. Ong et al. (2010) integrated over the entire asteroidal impactor population and calculated 2.7 × 10¹³ kg of water per Ga could survive in lunar cold traps, but this used present-day impact rates.

Our ice deposition model improves on several simplifications or poorly estimated parameters in previous studies. The first major improvement we make is in modeling impactor populations. In previous studies, impactor populations that deliver water were usually treated in bulk, using averaged properties. We subdivide the impactor population into five size regimes (see Supporting Information S1) and treat large impactors (>1.5 km diameter) on an individual basis, where only 24% are hydrated C-types (Jedicke et al., 2018; Rivkin, 2012), and impact velocities are individually assigned (see the supporting information). Additionally, bulk density values used for C-type asteroids are usually far too high. Ong et al. (2010) used 1,700 kg/m³, and Lucey et al. (2020) used 2,500 kg/m³. The mean bulk density—determined by gravitational effects and albedo/thermal modeling—is ~1,300 kg/m³ for C-type asteroids with diameters <100 km (Carry, 2012), which we adopt here.

The second major improvement is accounting for permanent cold trap locations, seasonal trapping, and micro cold traps in estimating the fraction of water molecules that end up in the large ice deposits we are interested in. Permanently shadowed regions (PSRs) are often conflated with cold traps, but these are not necessarily the same because energy re-radiated from illuminated slopes can create regions in PSRs that are too warm for water ice to survive on geologic timescales (Hayne & Aharonson, 2015; Rubanenko & Aharonson, 2017). Here, we use the Diviner polar temperature data from Williams et al. (2019), which give 5,300 km² of permanent cold trap area (<110 K maximum annual temperature) for the north pole and 13,000 km² for the south pole. These values are much smaller than the PSR areas of 12,866 and 16,055 km² (Mazarico et al., 2011). The area of seasonal cold traps implied from Williams et al. (2019) is 17,500 km² for the north pole and 24,300 km² for the south. Hayne et al. (2020) recently calculated the fractional area of cold traps at all size scales as a function of latitude. We used these three sets of values to modify the migration model from Kloos et al. (2019), which was previously based on shadowing instead of temperature. The results from this new analysis (see the supporting information) give 8.1% of H₂O molecules becoming trapped in the Diviner-defined permanent cold traps (2.7% in the north pole and 5.4% in the south). This is smaller than previous estimates, for example, 20–50% from Butler (1997), 21.5% from Ong et al. (2010), 21.7% from Kloos et al. (2019), but is in the range of 5.2–13.4% from Schorghofer (2014). In effect, the micro cold traps and seasonal cold traps create a vast peripheral holding pen (Figure S1) where H₂O molecules dwell and can be removed by destructive processes (Farrell et al., 2019) before they can reach the large cold traps at higher latitudes. This is an enhancement of the geographic shielding effect demonstrated by Moores (2016).

3. Stratigraphy Simulations

We constructed a Monte Carlo model to explore the types of stratigraphies built up by the interplay between ice delivery and ejecta deposited from large polar craters. The model captures four major features: (1) ice delivered by hydrated asteroids and volcanic outgassing; (2) ejecta emplaced by the large craters that we age-dated; (3) a simplified estimate of ice loss; and (4) a proxy for smaller-scale gardening. Our model is
dissimilar to those explored by Cannon et al. (2020), Costello et al. (2020), or Hurley et al. (2012), which operated at much smaller scales.

Each lunar pole was modeled as a two-dimensional, 800 x 800 km grid in polar stereographic projection, centered at the pole. Models were run from 4.25 Ga to present, with a timestep of 10 Myr. We ran 10,000 instances of the model for each pole to build up a rigorous statistical snapshot of typical stratigraphies, as well as outlier scenarios. The parameters that change from one run to the next are (1) the number, timing, hydration status, and impact velocities of impactors that deliver water (i.e., the specific water delivery history, see the supporting information) and (2) the ages when ejecta are emplaced, based on randomly varying the large crater model ages within their error bars (Tables S1 and S2).

The ice mass deposited at each time step was converted to volume (assuming a bulk density of 934 kg/m³) and then to thickness by dividing by the large cold trap area of each pole (from Diviner). We recorded a vector of ice deposition events for each pole (given in meters per 10 Myr timestep) and the ejecta thicknesses spatially as a function of time and location on the grid. Then, we analyzed results from locations that are known to be present-day cold traps (Williams et al., 2019) inside the large craters we age-dated. We constructed stratigraphic columns by clipping the ice deposition vector to begin at the cold trap model age and combined this with the ejecta history at that location. We focused on locations that were also cold traps at the paleopole of Siegler et al. (2016), or those young enough that they likely post-date the episode of true polar wander from Siegler et al. (2016). In this way, we avoid the issue of having to know when every location on the grid was and was not cold enough to trap ice over the Moon’s history.

3.1. Ice Delivery

For impacts, we considered the roles of hydrated asteroids only, due to revised cometary impact fluxes (Morbidelli et al., 2018), and inefficient cometary water retention (~6.5% vs. ~16.5% for asteroids) caused by higher mean impact velocities (Ong et al., 2010). Asteroid impactors were divided into five size regimes (see the supporting information) based on different methods for calculating their fluxes, different size-frequency distributions, and different crater scaling laws (Brown et al., 2002; Grün et al., 2011; Mazrouei et al., 2019; Neukum et al., 2001). Impactors smaller than 1.5 km diameter were treated as a bulk population with 2.4% water by mass (24% hydrated C-types with 10% water) and 16.5% water retention (Ong et al., 2010), because of the enormous number of these impactors. However, crucially, impactors larger than this were modeled individually in that only some were hydrated and had those impact velocities favoring maximum water retention (Ong et al., 2010; Svetsov & Shuvalov, 2015; see the supporting information). The small number statistics of these larger asteroids gives rise to different model outcomes and necessitates the use of Monte Carlo techniques.

In addition to impacts, volcanic activity is suspected to be an important pathway for the transport of volatiles to the lunar surface (Milliken & Li, 2017; Needham & Kring, 2017; Saal et al., 2008; Wilson & Head, 1981). We applied new eruption frequency estimates from Head et al. (2020) to calculate the delivery of volcanically outgassed water to the poles (the supporting information). Water formed from interactions between the regolith and solar wind was ignored in this work because it likely contributes many orders of magnitude less water than asteroids and volcanism (Hurley et al., 2017; Lucey et al., 2020) and may be outweighed by loss processes including UV photolysis and solar wind sputtering at the very surface (Farrell et al., 2019).

3.2. Ejecta Emplacement

To model the timing of ejecta emplacement, we used previously calculated absolute model ages of large south pole crater floors between 80°S and 90°S (Table S1; Deutsch et al., 2020; Tye et al., 2015). Based on these same crater counting methods (the supporting information), we dated 43 new large crater floors at the north pole between 80° and 90°N (Table S2) using the CraterStats II program (Michael & Neukum, 2010). We also updated the model age of Cabeus crater at the south pole from 3.5 Ga (Deutsch et al., 2020) to 3.88 Ga based on improved counts. To calculate ejecta thickness (t) as a function of distance (r) from the crater center, we used the scaling relation from McGetchin et al. (1973) which is similar to later estimates by Haskin et al. (2003), Petro and Pieters (2006), and Fassett et al. (2011):
where $R$ is the crater radius (all units in meters). For medial to distal ejecta, this thickness will become dominated by local materials (Oberbeck, 1975); therefore, we only modeled ejecta within $4R$ distance from the crater center in order to focus on proximal ejecta and avoid issues related to the curvature of the Moon and the Coriolis effect.

### 3.3. Ice Loss and Impact Gardening

Lunar ice loss processes are still not well understood, including both background erosive processes (Farrell et al., 2019), and also more stochastic, violent events (e.g., ballistic sedimentation). Therefore, we adopted a simple approach to implement ice loss in the model. Within our $10^7$-year timestep, the results of Costello et al. (2018) suggest the upper ~10 cm of regolith is well mixed, and the upper ~40 cm is overturned at least once for present day impact fluxes. We therefore assume up to 10 cm thickness equivalent of ice is lost from the surface every timestep (due mostly to micrometeoroids; Farrell et al., 2019), unless there is at least a 40-cm-thick layer of dry regolith cover that prevents ice from being brought up to the surface.

In addition to outright loss, ice can also be diluted with dry regolith through impact gardening. Instead of directly modeling this dilution, we calculated how long a given parcel of ice was exposed within the upper meter of the surface and what the impact flux was during that exposure (see the supporting information). Together, these represent a proxy for impact gardening that leads to the dilution of ice.

### 3.4. Model Assumptions

We assumed the total cold trap area at the poles has remained relatively constant at present-day values over the duration of the model runs. This implies a type of cold trap equilibrium similar to the concept of crater equilibrium, such that topographic changes from each large crater create new cold trap area roughly equal to the preexisting cold traps they superimpose or remove. This is not an ideal assumption, but reconstructing the complete topographic and thermal history over the lunar poles for >4 billion years is not straightforward.

We did not explicitly include the effects of transient atmospheres in transporting volatiles to the poles. These effects (Needham & Kring, 2017; Prem et al., 2015, 2019; Stewart et al., 2011) modestly enhance the survival of H$_2$O molecules by shielding them from photodestruction. However, the data available from these studies are not yet sufficient to determine how these effects scale with the mass of water delivered by impact or erupted from volcanism. Future modeling of transient atmospheres should be run on different impactor sizes, angles, and locations and include the effects of micro cold traps and seasonal cold traps.

Finally, we relied on complex crater scaling relations (Collins et al., 2005; Johnson et al., 2016; Prieur et al., 2017) to estimate the sizes and therefore water contents of impactor populations. Recently, there has been debate about the validity of these scaling relations (Bottke et al., 2016; Collins et al., 2020), and a new simple relation called $f24$ scaling was proposed but still faces challenges (Collins et al., 2020). Because water mass varies as the third power of impactor diameter, this is a sensitive parameter, and resolving these scaling issues could dramatically improve estimates of water delivered to the poles.

### 4. Results

#### 4.1. Effects of Cold Trap Age

The age when a cold trap began accumulating ice in the model was the major determining factor for both the net amount of ice and the resulting architecture of the deposits. Table 1 presents statistics from the model ensemble for five present-day cold traps and shows that the mean ice thickness decreased sharply as a function of age. We found for the entire 4.25 Ga duration of the model, a median of 49% of the total ice was deposited within the first 100 Myr, and 96% within the first 500 Myr (Table 1). This is because of the exponential decline in the flux of hydrated impactors over time. Figure 1 shows stratigraphic columns for four of the locations from Table 1, with representative model runs identified using principle components analysis. In the oldest deposits, the stratigraphies of ejecta and ice can be broadly divided into two zones (Figure 1): (1) a lower substratum with up to hundreds of meters of relatively pure ice and (2) an overlying zone that was thinner with more heavily gardened ice and more dry ejecta. For zone (1), if this type of deposit filled even a smaller 100 km$^2$ cold trap (e.g., that in Rozhdestvenskiy crater), the total amount of ice would exceed $10^9$ metric tons;
hence, we call these “gigaton deposits.” The gigaton deposits are mostly absent in Cabeus due to its younger age (Figure 1). We refer to zone (2) as a “gardened mantle,” which is discussed further below.

4.2. Location Effects

The amount of ejecta deposited by the large craters in this study was highly location-dependent across each pole and differed between poles. In Figure 1, the stratigraphic columns differ significantly in terms of the number of ejecta layers, their thicknesses, and their relative depths in the column. The closely adjacent Haworth and Faustini craters highlight these differences. Figure 2 shows calculated ejecta isopach maps for the north and south pole, separated into ejecta exterior to the craters, and interior to them (only from

| Metric | Mean | Minimum | Maximum | St. dev. |
|--------|------|---------|---------|----------|
| Net ice in Haworth crater (4.18 Ga) (m) | 295 | 153 | 596 | 55 |
| Net ice in Nansen F crater (4.12 Ga) (m) | 228 | 82 | 526 | 60 |
| Net ice in Faustini crater (4.1 Ga) (m) | 156 | 45 | 372 | 43 |
| Net ice in Cabeus crater (3.88 Ga) (m) | 14 | 0 | 153 | 20 |
| Net ice in Shackleton crater (3.15 Ga) (m) | 0.36 | 0 | 61 | 3 |
| Fraction of ice deposited before 4.15 Ga (%) | 49 | 31 | 72 | 5.4 |
| Fraction of ice deposited before 3.75 Ga (%) | 96 | 78 | 99 | 2.1 |
| Thickness of ice deposited after 200 Ma (m) | 0.031 | 0.018 | 60 | 1.4 |
| Thickness of ice deposited after 10 Ma (m) | 0.00086 | 0.00084 | 7.5 | 0.15 |
| Ratio of impact ice to volcanic ice (unitless) | 400 | 270 | 620 | 46 |

Note. The “fraction of ice” metrics are given for the entire model duration (4.25 Ga to present). Net ice incorporates loss processes.
later-formed surrounding impacts). The exterior ejecta distribution was identical in all model runs, while the interior distributions varied depending on the crater sequencing, and ranged as high as 900 m thick in some locations.

### 4.3. Stochastic Effects

Imposing stochastic hydrated impactor properties and varying the crater ages within their errors led to significant variance in ice deposition history (Figures S2 and S3) and the resulting stratigraphies (Figure 1). Table 1 shows there was a significant range in the total amount of ice delivered between model runs, as well as the timing of ice delivery. Varying the crater ages also led to different layering within the deposits. Figure 1 (gray shaded area) shows stratigraphic columns for three different model runs for Nansen F crater at the north pole, which differed in terms of the number and sequence of ejecta horizons, and the relative dilution of the ice deposits as a result. Combined, the uncertainties in crater formation ages and the delivery of water by rare, large impact events make it difficult to estimate the absolute amount of ice deposited in a given cold trap, and the relative amount of ice between cold traps of similar estimated ages. However, the trends observed for much younger cold traps like Shackleton were robust across the model ensemble (Table 1).

### 4.4. Outlier Scenarios

The majority of model runs showed very little ice deposited in recent history (Table 1), but a small number of outliers produced tens of meters of thick pure ice near the surface (Figure 1, right-most column; Figure S4).

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**Figure 2.** The amount of ejecta deposited from the large craters age-dated as part of this study. Left: Cumulative ejecta deposited outside of craters (same for all model runs). Right: Ejecta deposited inside these craters after they formed, from representative model runs. Note the logarithmic scales range between 2 and 1,000 m.
These scenarios could be a proxy for what happened on Mercury, whose ice deposits (Chabot et al., 2014; Deutsch et al., 2016; Harmon et al., 2011; Lawrence et al., 2013; Neumann et al., 2013) suggest a young deposition event that could have supplied most if not all the exposed surface volatile deposits (Deutsch et al., 2019; Ernst et al., 2018). This scenario was quite rare in our model ensemble: only 28 runs out of 10,000 (0.28%) had >10 m of ice deposited in the final 200 Myr. The discrepancy between lunar and Hermean polar deposits (Lawrence, 2017) could be explained partly by the rarity of Mercury-like scenarios in our model ensemble.

5. Discussion
5.1. Gardened Mantle
The gardened mantle that developed in the majority of our model stratigraphies (Figure 1) implies a substantial thickness (>10 m) of ice-bearing regolith near the surface of lunar cold traps. This might seem at odds with remote sensing observations suggesting low amounts of ice (usually 0–5%) in the upper few meters of regolith (e.g., Colaprete et al., 2010; Teodoro et al., 2014). However, Kokhanov et al. (2015), followed by Rubeneko et al. (2019), used morphometry measurements of small polar craters and suggested significant ice-rich deposits of up to 50 m thick, particularly at the south pole (Rubeneko et al., 2019). As Cannon and Britt (2020) showed, impact gardening should lead to a desiccated ice-poor zone in the upper ~50 cm of regolith, which could explain why neutron spectroscopy measurements generally show low hydrogen concentrations inside cold traps (e.g., Teodoro et al., 2014). We also suggest here the south-north disparity observed by Rubenenko et al. (2019) could be affected by small-number statistics: If most of the ice in the gardened mantle came from a handful of hydrated asteroid or comet impacts, more of these impacts occurring in the southern hemisphere could skew the deposition pattern to the south pole.

5.2. Gigaton Deposits
The stunning volume of ice implied by the gigaton deposits found in the oldest cold traps in our model (Figure 1) is quite provocative. There are several reasons why gigaton deposits may never have formed in the first place. First, the retention and migration of water from impacts may not be realistically captured by various models (e.g., Ong et al., 2010; Stewart et al., 2011). If water retention is overestimated, the thickest ice horizons may have only been meters or tens of meters thick. Second, the canonical crater scaling relations used to extract impactor sizes could be seriously in error. If impactor sizes are being systematically overestimated, then so is water delivery. As a test, we reran the entire model ensemble using the $f_{24}$ scaling from Collins et al. (2020) and found 8.6 times less ice deposited than with the standard scaling laws. Finally, cold trapping may be a self-limiting process, as ice deposits could reach heights where they become more illuminated, or ice could collapse from gravitational settling into warmer surrounding regions.

If gigaton deposits did form, different mechanisms could remove them later. The ballistic sedimentation and ejecta heating described qualitatively here could have significantly eroded underlying ice-rich deposits. Changes in the spin-axis pole including a possible Cassini-state transition (Siegler et al., 2015, 2016) could have warmed the deposits and removed the ice. Very few areas were cold traps both before and after the particular true polar wander path proposed by Siegler et al. (2016). Notable exceptions include Haworth, Shoemaker, Faustini, and Nansen F, which also have the kinds of ancient model ages required for gigaton deposits to form (Tables S1 and S2).

5.3. Implications for Future Exploration
The stratigraphies modeled in this work have significant implications for how to study and possibly harvest polar volatiles in the future. Ice detected using UV and shortwave infrared spectroscopy (Fisher et al., 2017; Hayne et al., 2015; Lucey et al., 2014; Qiao et al., 2019; Zuber et al., 2012) could be young, transient frosts (Farrell et al., 2019). Orbital radar instruments are in theory ideal for probing the upper stratigraphy of ice and ejecta in cold traps, but they face possibly insurmountable challenges due to the ambiguities of subsurface ice versus roughness and blocks (Fa & Cai, 2013; Fa & Eke, 2018). In situ investigations involving drilling and particularly trenching are promising approaches to properly investigate cold trap deposits at modest depths (Cannon et al., 2020), and the upcoming Volatiles Investigating Polar Exploration Rover (VIPER) mission (Colaprete et al., 2019) will be the first chance to test some of our model results (Figure 1).
Ground-penetrating radar, as employed successfully on Chang’e-3 and 4 (e.g., Li et al., 2020) could be used as a complement to drilling and trenching on future lunar surface missions.

A tremendous amount would be learned from a deep (>10 m) drilling campaign (Zacny et al., 2016) inside an ancient lunar cold trap, particularly if ice is buried as deeply in certain locations as some of our results suggest (Figure 1). We also suggest here an intriguing possibility: Ice deposited from vapor at <120 K is not crystalline ice but microporous amorphous solid water (Mayer & Pletzer, 1986; Raut et al., 2007). Porosity is low when deposition occurs at steep incidence angles (Dohnálek et al., 2003) like those expected for ballistic hopping, but porosity is high at lower deposition angles potentially achieved in collisional atmospheres. Microporous amorphous ice has an enormous specific surface area (Raut et al., 2007) and can effectively trap gas molecules. If preserved within lunar polar strata, microporous ice could comprise a unique record analogous to terrestrial ice cores.

6. Conclusions

We used a model of ejecta emplacement and stochastic ice deposition to simulate 10,000 possible stratigraphies in lunar cold trap environments. Typical model runs led to retention of >200 m of total ice in the oldest cold traps, with two distinct zones forming. The lower zone (“gigaton deposits”) consisted of thick ice-rich layers with interspersed ejecta horizons, and the upper zone (“gardened mantle”) was thinner with lower implied ice fractions. Impact-delivered ice exceeded volcanically derived ice by >400 times by mass. The majority of ice was deposited early, but a rare subset of model runs featured late, large impacts of hydrated asteroids leading to more Mercury-like, thick surface deposits. Future exploration using drilling, trenching, and ground-based remote sensing can be used to test predictions about ice deposits made here, and preserved microporous ice in these deposits could provide a robust record of past transient atmospheres around the Moon.

Data Availability Statement

GIS shapefiles for the large lunar craters are available from http://www.planetary.brown.edu/html_pages/LOLAcarters.html. The LOLA DEMs we used for crater counting are available from the NASA PDS and http://imbruum.mit.edu/BROWSE/LOLA_GDR/. MATLAB code for our model is included as part of the supporting information.

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