Assessing the Roughness Properties of Circumpolar Lunar Craters: Implications for the Timing of Water-Ice Delivery to the Moon

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Abstract The roughness properties of impact craters are valuable indicators of crater degradation and can provide insight into crater ages. We evaluate the roughness of lunar craters from different geologic eras, confirming that young, Copernican craters are distinctly rougher than older craters. We evaluate the potential age of small (less than ~15 km) craters that are thought to host surface ice by quantifying the roughness inside these craters, as well as outside. Interior roughness may be subdued by slope processes or the presence of volatiles. The distribution of ice-bearing craters is skewed toward roughness values higher than those of pre-Imbrian craters, although no ice-bearing craters are within the Copernican-only domain in roughness space. All of the 15 rough, permanently shadowed craters that are found within the Copernican-only domain lack water-ice detections, suggesting that either ice has not been delivered to these young craters or that it has since been destroyed.

Plain Language Summary When a planetary surface is struck by an impactor, the preexisting surface is disturbed as rocks and boulders scatter from the high-energy collision. Over time, the surface texture becomes smoother as these rocks and boulders are broken up into smaller pieces and begin to diffuse away. Surface texture is thus a powerful tool for evaluating the degradation of impact craters, given that young, fresh craters tend to be rougher than old craters due to the presence of rocks and boulders on the recently disturbed surface. Here we quantify the surface texture of lunar craters of different geologic eras and establish a relationship between the roughness and age of craters. We evaluate the roughness of small craters that host near-polar surface ice and find a population of craters likely to be post-Nectarian in age. However, the youngest polar craters lack surface ice detections.

1. Introduction

The lunar poles provide a fascinating thermal environment capable of cold trapping water ice on geologic timescales (Schorghofer & Aharonson, 2014; Siegler et al., 2016; Vasavada et al., 1999; Williams et al., 2017). Water ice has been reported to be present on permanently shadowed surfaces, as detected from diagnostic near-infrared absorption features of water ice in reflectance spectra acquired by the Moon Mineralogy Mapper (M3) instrument (Li, Lucey, et al., 2018). While there have been various observations indicating the presence of water ice at the lunar surface (Fisher et al., 2017; Hayne et al., 2015; Li, Lucey, et al., 2018), it is still not clear when this ice was delivered. The timing of volatiles deposition provides important constraints on the origin of lunar ice because different delivery mechanisms have been active at different times throughout lunar history (e.g., Lawrence, 2017; Siegler et al., 2016). For example, impact bombardment and volcanic outgassing are capable of delivering water to the lunar surface, but both were more active early on in lunar history and have significantly declined toward the present (e.g., Head & Wilson, 2017; Hiesinger et al., 2011; Needham & Kring, 2017; Nesvorny et al., 2017; Pokorný et al., 2019). Interactions between the solar wind and the lunar regolith can also form water on the surface, and this process is still very active today (Crider & Vondrak, 2002; Jones et al., 2018).

To date, the origin of polar volatiles remains a major outstanding question in lunar science, but the age of the ice can provide important constraints. One approach to describing the age of the reported ice detections (Li, Lucey, et al., 2018; from here on referred to as “the ice”) is to use relative dating to analyze the stratigraphic
record of the ice and its host craters. We previously took this approach, using crater density statistics to estimate the ages of ice-bearing craters at the south pole of the Moon (Deutsch et al., 2020). The derived ages of the host craters provide an upper limit for the ages of the ice contained within the craters. While all of the craters that we dated have estimated model ages >2.8 Ga, some ice-bearing craters were too small to allow for robust cratering statistics and were excluded from the age-dating analysis (Deutsch et al., 2020). Interestingly, some of these small (<10 km) craters have morphologies suggestive of relatively young ages, on the basis of crisp crater rim crests. Ice in young craters is particularly interesting because it suggests that there is some recent and perhaps ongoing mechanism that is delivering or redistributing water to polar cold traps. Therefore, understanding if these small, ice-bearing craters are indeed young is essential in understanding the age and source of volatiles on the Moon.

Here we take a new approach to understand the ages of these small polar cold traps: analyzing the roughness properties of small ice-bearing (Li, Lucey, et al., 2018) craters. It is understood that impact crater properties evolve with time due to a variety of geologic and space-weathering processes; young, pristine craters can be characterized by sharper rim crest morphologies and greater depth-to-diameter ratios than old, degraded craters (Agarwal et al., 2019; Basilevsky, 1976; Fassett & Thomson, 2014; Ofield & Pohn, 1970; Pike, 1977; Pohn & Ofield, 1970). Younger craters are also associated with lower surface porosities (Mandt et al., 2016) and higher rock abundances, which tend to decrease with age (Ghent et al., 2014; Li, Basilevsky, et al., 2018; Mazrouei et al., 2019). Additionally, the topographic roughness of a crater and its ejecta evolves with time and can help provide insight into the age of the crater (Kreslavsky et al., 2013; Neumann et al., 2015).

Topographic roughness is a measurement of the local deviation from the mean topography, providing a measurement of surface texture, and is a powerful tool for evaluating surface evolution over geologic time (Kreslavsky & Head, 2000; Kreslavsky et al., 2013; Neumann et al., 2015; Rosenberg et al., 2011). Neumann et al. (2015) demonstrated that Copernican craters typically have high surface roughness at the small spatial scales (~dm–m) of multibeam laser spots. More recently, Wang et al. (2019) analyzed various lunar impact craters that span in stratigraphic age from the Pre-Nectarian through the Copernican eras, and found that the youngest craters could be identified on the basis of greater roughness, as well as greater rock abundances and higher soil temperatures. They showed that these properties tend to decrease toward equilibrium with crater age (Wang et al., 2019).

Here, we seek to understand whether any craters that host surface ice on the Moon are geologically young, using roughness as a proxy for crater age. We first analyze the roughness properties of a variety of circum-polar craters from all geologic eras to establish the dependence of crater roughness on crater age. We then analyze the roughness properties of small (less than ~15 km) ice-bearing craters that may be geologically young (Deutsch et al., 2020) and compare them to the roughness properties of different-aged lunar craters. Understanding the timing of water delivery to the Moon is a critical step in understanding the nature of the lunar volatile cycle and how it is evolving with time.

2. Methods and Results

We analyze the roughness of the lunar surface using the Lunar Orbiter Laser Altimeter (LOLA; Smith et al., 2010, 2017) Digital Roughness Maps (LDRM_40S_1000M; LDRM_40N_1000M; http://imbrium.mit.edu/DATA/LOLA_GDR/). In these data products, surface roughness was derived from the root-mean-square (RMS) variation in the surface elevation of the five adjacent spots returned from a single laser pulse acquired by LOLA (Neumann et al., 2015; Smith et al., 2017). For each group of returned spots, the local slope was removed and the roughness, $R$, was estimated from the residual heights:

$$R=\sqrt{\frac{1}{n-\nu}\sum_{i=1}^{n}z_i^2},$$

In Equation 1, $n$ is the number of LOLA spots (five), $\nu$ is the number of degrees of freedom (three) used to find the surface height and slope, and $z$ is the height residual for a given spot. The RMS height represents an unbiased estimate of surface roughness of a random topographic field at the center of each LOLA spot (Neumann et al., 2015; Smith et al., 2017).
As explained in detail in the documentation of the LDRM (http://imbrium.mit.edu/DATA/LOLA_GDR/), the data account for changes in spacecraft altitude during data acquisition, residual uncorrelated noise of the instrument range measurements, and drift in system parameters over the course of the LRO mission that causes deviations from a flat measurement. The five-spot LOLA data were median-averaged at a pixel resolution of 1,000 m for the lunar surface between ±40° to each pole. The separation between the five-spot footprints is ~15–25 m. The 1-km scale analyzed here could be refined in future studies of small regions.

2.1. The Roughness of Lunar Craters as an Indicator of Age

We analyze the roughness of over 400 impact craters located between ±40°N and ±90°N (Table S1 in the supporting information). These craters, identified using the Lunar and Planetary Institute (LPI) lunar crater database (Losiak et al., 2009), have previously been catalogued into lunar geologic eras. We find the mean roughness value for the interior of each crater and for rings extending 2 km from the crater rim. We find that, at a distance of 2 km, the mean roughness outside of a crater is relatively similar to the mean roughness within a crater (Figure 1). The roughness becomes increasingly less distinct with distance from the crater (Figure 1).

The distinctness of roughness properties decreases not only with distance from the crater (Figure 1) but also with crater age (Figure 2). Figure 2a shows that Copernican craters have distinctly rougher interiors than older craters, consistent with previous work (Wang et al., 2019). This is also consistent with work that demonstrates that younger craters have higher circular polarization ratios (CPR) suggestive of higher surface roughness (Fa & Eke, 2018; Fassett et al., 2018). The interior roughness of different-aged craters is generally more distinct than the exterior roughness, as external units tend to reach equilibrium more quickly. However, the exterior units of Copernican-aged craters are also distinctly rougher (at a distance of 2 km from their rims) than the exterior units of older craters (Figure 2b).

The major differences in roughness domains exist between Copernican craters and craters of older eras (Figure 2). However, there are still statistically significant differences (p value of 3.3e–9 according to the Kolmogorov-Smirnov [KS] statistical test) in surface roughness between the oldest lunar craters (pre-Imbrian) and craters formed within the Imbrian and Eratosthenian periods (Figure 2).

We note that while geologically young craters have distinct roughness properties (Figure 2), as well as thermophysical (Ghent et al., 2014; Li, Basilevsky, et al., 2018; Mazrouei et al., 2019; Wang et al., 2019) and morphological properties (Agarwal et al., 2019; Fassett & Thomson, 2014; Pike, 1977), the roughness of a crater cannot independently establish its age. Instrument noise (Neumann et al., 2015; Smith et al., 2017), the natural variability and nonuniform degradation of individual craters (Head, 1975), and differences in target properties (Cintala et al., 1977) result in roughness variations between individual craters of similar stratigraphic age, and even statistical overlap between craters of different geologic eras (Wang et al., 2019). However, surface roughness remains an important tool in evaluating crater degradation and age (Kreslavsky & Head, 2000; Kreslavsky et al., 2013; Neumann et al., 2015; Rosenburg et al., 2011; Wang et al., 2019), specifically for the youngest, most pristine craters, which we are interested in here.

In addition to quantifying the roughness properties of lunar craters of different geologic eras, we also analyze the roughness properties with respect to crater size. We find that the roughness of craters does not vary with crater size in a statistically significant trend, either for the interiors or exteriors of craters (Figure S1). Therefore, even though the craters included in the LPI database (Losiak et al., 2009) are all larger than the small ice-bearing craters that we are interested in here (typically <15 km), it is appropriate to directly compare the roughness properties of craters from both groups (section 2.2).

2.2. The Roughness of Small Ice-Bearing Craters on the Moon

Using reported ice detections from analyses of diagnostic vibrations of water ice (Li, Lucey, et al., 2018), we identify 82 small (less than ~15 km) ice-bearing craters that are located between ±80° and ±90° (Table S2).
If all ice on the Moon was deposited early on in lunar history, we would expect ice to be present only in old, smooth craters. We compare the roughness of ice-bearing craters to the roughness of old craters of Nectarian and Pre-Nectarian age (Figure 3). Although the histograms of both populations peak at similar roughness values ($R \approx 0.43 \text{ m}$), the distribution of the ice-bearing craters is skewed toward higher interior roughness values. The K-S statistical test indicates that the difference between the interior roughness-frequency distribution is statistically significant with high confidence ($p$ value $= 0.002$). This indicates that the population of ice-bearing craters contains some rougher craters that are likely to be post-Nectarian.

Importantly, surface roughness within a crater may be lowered by either mass wasting (e.g., Fassett & Thomson, 2014; Zuber et al., 2012) or the presence of frozen volatiles (Kreslavsky & Head, 2000; Putzig et al., 2014). Additionally, at the spatial resolution of the LDRM, our roughness measurements are likely sampling more of the sloping crater walls for the relatively smaller ice-bearing craters than for the different-aged craters from the LPI crater database, and crater walls are relatively smoother than other impact crater units (Wang et al., 2019; Zuber et al., 2012). Furthermore, smaller impact craters may degrade and become smoother more quickly than larger craters of the same formation age (Bart & Melosh, 2010a, 2010b; Basilevsky et al., 2018; Mahanti et al., 2018). Due to these multiple variations between the small, ice-bearing craters and the larger craters analyzed, the roughness values that we find for the interiors of ice-bearing craters are likely to be lower than the roughness values of similarly aged craters that lack ice. The ice-bearing craters that have higher interior roughness values than Nectarian or Pre-Nectarian craters (Figure 3a) are therefore highly suggestive of post-Nectarian ages given that they are likely to have been

Figure 2. The mean roughness (a) within and (b) surrounding impact craters (Table S1) of different geologic eras. The box plots show the spread of data for each geologic era, increasing in age to the right: Copernican (C; <0.8 Gyr), Eratosthenian (E; 0.8–3.2 Gyr), Upper Imbrian (UI; 3.2–3.8 Gyr), Lower Imbrian (LI; 3.8–3.85 Gyr), Nectarian (N; 3.85–3.92 Gyr), and Pre-Nectarian (PN; >3.92 Gyr). Absolute age ranges for each era are from Stöffler and Ryder (2001). For each era, the box denotes the innermost 50% of the analyzed crater population, the red line within each box denotes the median, and the dashed lines extending from the box denote the entire data range, from minimum to maximum. Histograms of the mean (c) interior and (d) exterior roughness values of pre-Imbrian (Pre-Nectarian and Nectarian) craters in semitransparent yellow, Imbrian-Eratosthenian craters in semitransparent red, and Copernican craters in semitransparent green.
subdued by these geologic processes or by the presence of surface ice (Kreslavsky & Head, 2000; Moon et al., 2019; Putzig et al., 2014). It is possible that some additional craters are also post-Nectarian, but that their roughness properties have been altered by surface ice such that they appear smoother and thus older. Because the interior roughness properties of ice-bearing craters may be subdued by the presence of volatiles (Kreslavsky & Head, 2000; Moon et al., 2019; Putzig et al., 2014), we also analyze the roughness outside of ice-bearing craters, for an exterior ring extending 2 km from the rim (Figure 3b). We find that although the surface roughness at a distance of 2 km from relatively large craters (~10–100 km in diameter) is a reasonable representation of crater roughness (Figure 1) and appears to vary with crater age (Figure 2), it is not a reliable measurement of degradation for relatively small impact craters (~1–15 km) at the resolution of the analyzed LDRM data. The roughness data have a pixel resolution of 1,000 m (Neumann et al., 2015; Smith et al., 2017); therefore, the mean surface roughness values calculated for the exterior portions of the small impact craters rely on only a few individual roughness values. While expanding the analyzed area surrounding the crater would improve the number of values incorporated in calculating the mean, we find that the surface roughness becomes increasingly less distinct with distance from the crater and is not a good proxy for the crater’s degradation state (Figure 1).

2.3. Distinctly Rough Polar Craters That Lack Ice

We find that none of the small craters analyzed here that are identified as ice-bearing (Li, Lucey, et al., 2018) have roughness properties that belong to a Copernican-only domain in the roughness space (Figure 4). Interestingly though, we identify 15 polar craters between ±75° and ±90° that do not have positive detections of water ice (Li, Lucey, et al., 2018) but do have enhanced roughness values suggestive of

Figure 3. Histograms of the mean (a) interior and (b) exterior roughness values of 82 small ice-bearing craters (Li, Lucey, et al., 2018) in both polar regions and 206 craters of Nectarian and Pre-Nectarian age. Histograms of the mean interior roughness values of 15 craters lacking positive water-ice detections (Li, Lucey, et al., 2018) and (c) 206 pre-Imbrian craters and (d) 20 Copernican craters.
Copernican ages (Table S3). All of these 15 craters have permanently shadowed surfaces, suggesting they may be thermally stable for the cold trapping of water ice (Mazarico et al., 2011). The roughness values of these 15 craters are statistically distinct from Pre-Imbrian craters (Figures 3b and 3c) and lie within the Copernican-only domain (Figures 3b, 3c, and 4).

3. The Age of Lunar Surface Ice

Overall, the statistical difference between the roughness-frequency distribution of pre-Imbrian and ice-bearing craters (Figures 3a and 3b) suggests that some ice-bearing craters are post-Nectarian in age. The ages of the host craters provide an upper constraint on the age of the surface ice they contain, and it is possible that the small post-Nectarian craters identified here host ice that was delivered relatively recently. In fact, it has been suggested that perhaps all of the surface ice observed at the lunar poles is geologically young; analysis of the icy regolith detected by the Lyman Alpha Mapping Project (LAMP) ultraviolet (UV) instrument suggests ice was deposited very recently (Farrell et al., 2019). Specifically, the ongoing rates of plasma sputtering and meteoric impact vaporization and ejection on the Moon suggest that the ice present at the surface or near-surface of regolith particles (as sensed by LAMP to a depth of <1 μm) must be <2,000 years old (Farrell et al., 2019). Relatively young surface ice can be delivered to the Moon from micrometeorite bombarding (Ong et al., 2010; Pokorný et al., 2019; Szalay et al., 2019) or formed in situ from the ongoing interactions between solar wind protons and oxygen in the lunar regolith (e.g., Crider & Vondrak, 2000; Dyar et al., 2010).

Ice delivered during the Eratosthenian or Copernican eras is not predicted to be volcanic in origin, given that the bulk of lunar volcanism occurred prior to these eras (e.g., Needham & Kring, 2017). Curiously, our analysis reveals that all of the polar impact craters with roughness properties that lie distinctly within a Copernican-only domain do not have positive water-ice detections by Li, Lucey, et al. (2018). All of these 15 impact craters have permanently shadowed surfaces (http://imbrium.mit.edu/BROWSE/EXTRAS/ILLUMINATION/), but it is possible that they are not thermally stable environments for the cold trapping of surface ice (Ingersoll et al., 1992; Rubanenko et al., 2019). If these permanently shadowed surfaces are in fact stable to the cold trapping of ice, then this finding suggests that (1) perhaps water ice has not been cold trapped in the youngest polar craters on the Moon, which would imply that the most recent episodes of ice delivery occurred prior to the formation of these impact craters, or (2) ice that was delivered to these particularly rough craters has since been destroyed. However, if these permanently shadowed surfaces are not stable to the cold trapping of ice, then the youngest ice-bearing craters on the Moon appear to be Imbrian-Eratosthenian in age, on the basis of surface roughness (Figure 3) and crater density statistics (Deutsch et al., 2020).

4. Conclusion

It has been well demonstrated that the roughness properties of impact craters are valuable indicators of crater degradation states and provide important insight into the ages of craters (Figure 2) (Kreslavsky & Head, 2000; Kreslavsky et al., 2013; Neumann et al., 2015; Rosenburg et al., 2011; Wang et al., 2019). Here we find that the distribution of ice-bearing craters on the Moon is skewed toward roughness values that are higher than those of pre-Imbrian craters (Figure 3a) (p value = 0.002). It is possible that these ice-bearing craters are of relatively young ages, given that their surface textures are likely to be subdued by the presence of surface ice (Kreslavsky & Head, 2000; Moon et al., 2019; Putzig et al., 2014). We do not identify any ice-bearing craters that are within the Copernican-only domain in roughness space; in fact, all of the 15 rough polar craters (±75° to ±90°) that are found within this domain lack water-ice detections (Li, Lucey, et al., 2018). If surface ice is stable in these permanently shadowed craters, then either ice has not been delivered to these young

Figure 4. The mean interior roughness of craters analyzed. Ice-bearing craters (Li, Lucey, et al., 2018) are shown in black, and craters of different geologic eras are colored with respect to age: Copernican (red), Eratosthenian (orange), Upper Imbrian (yellow), Lower Imbrian (green), Nectarian (light blue), and Pre-Nectarian (blue). Craters that lack positive water-ice detections (Li, Lucey, et al., 2018) and lie distinctly within the Copernican-only domain of roughness space are denoted by red X’s.
craters since their formation, or it has since been destroyed. If these craters, however, are not thermally stable environments for surface ice, then the youngest ice-bearing craters on the Moon appear to be Imbrian–Eratosthenian in age, on the basis of surface roughness (Figure 3) and crater density statistics (Deutsch et al., 2020).

Determining the timing of water delivery to the Moon is a critical step in understanding the nature of the lunar volatile cycle and how it is evolving with time. The rough, ice-bearing craters identified here, as well as even smaller cold traps (Hayne et al., 2018; Rubanenko &Aharonson, 2017; Rubanenko et al., 2018), are excellent exploration candidates for studying the most recent history of volatile delivery to the Moon. Determining the abundance and precise chemical composition of volatiles within younger cold traps is essential in determining the recent fluxes and sources of volatiles to the lunar surface, providing insight into how the lunar volatile system is actively evolving.

Data Availability Statement

Topographic, roughness, and shadow data analyzed in this paper are all available at the LOLA PDS Data Node (http://imbrium.mit.edu/). Individual craters analyzed here can be found in the supporting information.

References


