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THE ROUGHNESS PROPERTIES OF SMALL ICE-BEARING CRATERS AT THE SOUTH POLE OF THE MOON: IMPLICATIONS FOR ACCESSING FRESH WATER ICE IN FUTURE SURFACE OPERATIONS.

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Introduction: The lunar poles provide a fascinating thermal environment capable of cold-trapping water ice on geologic timescales [1]. While there have been many observations indicating the presence of water ice at the lunar surface [e.g., 2–4], it is still not clear when this ice was delivered to the Moon. The timing of volatile deposition provides important constraints on the origin of lunar ice because different delivery mechanisms have been active at different times throughout lunar history.

We previously found that some small (<10 km) craters at the south pole of the Moon have morphologies suggestive of relatively young ages, on the basis of crisp crater rims [5]. These craters are too small to date with robust cratering statistics [5], but the possibility of ice in young craters is intriguing 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 craters. It is well understood that impact crater properties (e.g., morphology, rock abundance, and roughness) evolve with time due to a variety of geologic and space-weathering processes [6–11]. 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 [e.g., 11–14].

In this study we analyze the roughness of southern lunar craters (40°S–90°S) from all geologic eras, and determine how the roughness of small (<10 km) ice-bearing craters compare. We discuss the implications of the ages of ice-bearing south polar craters, and potential strategies for accessing fresh ice on the Moon.

Methods and Results: We analyze the roughness of the lunar surface using the Lunar Orbiter Laser Altimeter (LOLA) Digital Roughness Map (pixel resolution of 1000 m; http://imbrium.mit.edu/DATA/LOLA_GDR /) [11, 15]. In this data product, surface roughness was derived from the root mean square variation in the surface elevation of the five adjacent spots returned from a single laser pulse acquired by LOLA [11, 15]:

$$R = \sqrt{\frac{1}{n-\nu}\sum_{i=1}^{n} {z_i}^2} \qquad (1).$$

In Eq. 1, n is the number of LOLA spots (five), ν 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 roughness of lunar craters. We analyze the roughness of over 200 impact craters located between 40°S and 90°S (work is ongoing to analyze the north polar region). These craters, identified using the LPI lunar crater database [16], have previously been catalogued into lunar geologic eras. We find the mean roughness value within and around each crater, for an exterior ring extending 2 km from the crater rim. We find that Copernican and Eratosthenian craters have distinctly rougher interiors than older craters (Fig. 1). The distinctness of roughness properties tends to decrease toward equilibrium with crater age, consistent with previous work [10]. Copernican-aged craters also clearly have rougher surroundings (at 2 km from their rims) than older craters do (Fig. 1). But overall, the interior roughness of different-aged craters is generally more distinct than the exterior roughness, as external units tend to reach equilibrium more quickly [e.g., 10].

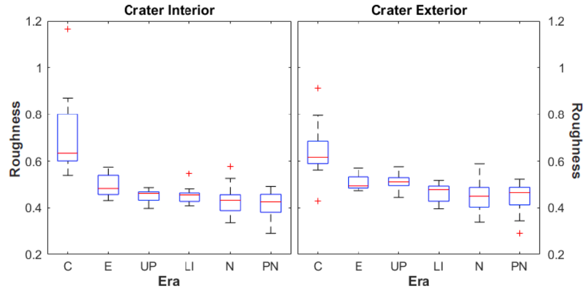

Fig. 1. The mean roughness within (left) and surrounding (right) impact craters of different geologic eras.

We also find that the interior roughness of craters shows some variation with crater size (Fig. 2). In general, larger craters tend to be relatively rougher than smaller craters formed within the same era. This size-dependency is strongest for Copernican and Eratosthenian craters, but relatively weak for older craters, which have been exposed to more extensive weathering.

The craters included in the LPI database [16] are >10 km in diameter; however, the small ice-bearing craters that we are interested in here are <10 km. In order to compare the roughness of small ice-bearing craters to the roughness properties of different-aged craters, we solve for the best linear fit between crater roughness and crater diameter for each geologic era (Fig. 2).

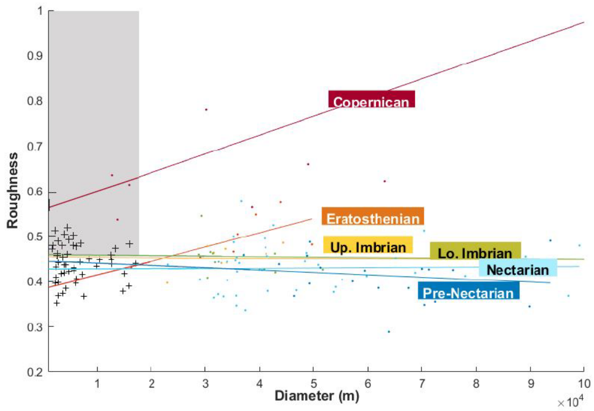

Fig. 2. Best fit lines between the roughness and diameters of impact craters from different geologic eras. The mean roughness of small ice-bearing craters are plotted in black crosses. Those that are rougher than average Eratosthenian–Pre-Nectarian craters are shaded in grey.

The roughness of small ice-bearing craters. We identify ice-bearing craters <10 km in diameter in the south polar region of the Moon from previous analyses of diagnostic vibrations of water ice [4]. We compare the interior roughness properties within the craters to those estimated for similarly sized craters of different geologic eras from the regression lines in Fig. 2. We find a population of small ice-bearing craters that has enhanced roughness values suggestive of young (Copernican) ages (shaded in Fig. 2).

The presence of surface ice within these small craters is expected to subdue the interior roughness properties of the craters [17]. Thus, it is likely that the roughness values we find for ice-bearing craters are lower than similarly aged craters that lack ice. The enhanced roughness values for craters shaded in Fig. 2 are therefore highly suggestive of young (Copernican) ages. It is also possible that some additional craters not in the shaded region are also young, but their roughness properties have been altered by surface ice such that they appear smoother and thus older.

Young ice on the Moon? The elevated roughness within and surrounding some small ice-bearing craters (Fig. 2) suggests that these host craters may be geologically fresh, implying that a young source of volatiles must be considered as an origin of surface ice.

Young lunar craters occupied by surface ice is consistent with previous work analyzing the presence of ice in micro-cold traps [18–20]. These ~1–10 m cold traps represent the smallest, most easily erodible ice deposits, and therefore the presence of ice within them may be suggestive of young volatiles [20].

Additionally, analysis of the icy regolith detected by the Lyman Alpha Mapping Project UV instrument also suggests that the icy regolith of the Moon is geologically young given the ongoing fluxes of plasma sputtering and meteoric impact vaporization and ejection [21].

Implications for future surface operations: These small ice-bearing craters are excellent exploration candidates for studying the recent history of volatile delivery to the Moon. Determining the abundance and precise chemical composition of volatiles within young 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. The youngest ice-bearing cold traps on the Moon provide ideal *in situ* laboratories for such studies.

Overall, the craters identified here, as well as even smaller cold traps [18–20], may offer targets that are more easily accessible than large permanently shadowed cold traps canonically considered for polar surface operations. These small cold traps should be considered for analyzing and extracting ice, as NASA, international partners, and commercial partners prepare for future missions to the Moon.

Conclusions: 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. Here we find that the enhanced roughness of some small (<10 km) ice-bearing craters is suggestive of Copernican-aged craters hosting surface water ice on the Moon. These small cold traps may be more accessible to future robotic and human exploration than larger, permanently shadowed cold traps. We recommend that the small craters we identify be considered in future operations to understand the history of lunar volatiles, as well as the total ice inventory on the Moon for economic endeavors.

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