MODELING THE PRODUCTION AND DESTRUCTION OF COLD TRAPS AT THE HUMAN SCALE OF ARTEMIS EXPLORATION.

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Introduction: The Artemis missions, like the Apollo missions before them, will explore the lunar surface at a human scale of hundreds of meters or less. These relatively small spatial scales are not yet well understood, and are complicated by a long and active history of impact bombardment. Repeated impacts shape and reshape the lunar surface and control the availability, accessibility, and coherence of lunar volatiles. At the human scale, the search for volatiles requires understanding these impact processes, which are not visible at larger scales in the polar regions.

Cold traps are locations shielded from sunlight where volatiles accumulate and can vary in size from centimeter-scale "micro cold traps" [1] to many kilometers-scale permanently shadowed regions (PSRs). Cold traps are located within the topographic lows of craters; thus, to understand the production and evolution of craters is to understand the evolution of cold traps.

Theoretical tools provide critical insight into the evolution of the lunar surface and volatiles at human scales and shed light on the surface evolution which has become invisible through overlapping or are below remote sensing resolution. To model the production, longevity, and destruction timescale of human-scale cold traps, we use a crater accumulation and impact gardening model, which has successfully reproduced the mixing of space weathering products observed in the Apollo cores [2, 3].

We interpret the timescale between crater equilibrium and geometric saturation to understand the average production, longevity, and destruction of cold traps. We follow the terminology presented in Minton et al. [4], where "geometric saturation" is defined to occur when a surface has reached maximum packing of a power law distribution of circular features on a two-dimensional surface, and "equilibrium" occurs when craters form at the same rate that craters are removed (by craters and by other degradation processes). Geometric saturation represents certain and complete destruction of a micro cold trap. The difference between equilibrium and saturation represents a maximum lifetime for any given cold trap crater, where equilibrium guarantees a crater has formed and saturation guarantees its obliteration.

Our model constrains the lifetime of cold traps and can be used to develop expectations concerning the discoverability of lunar volatiles at scales relevant to exploration by humans and rovers.

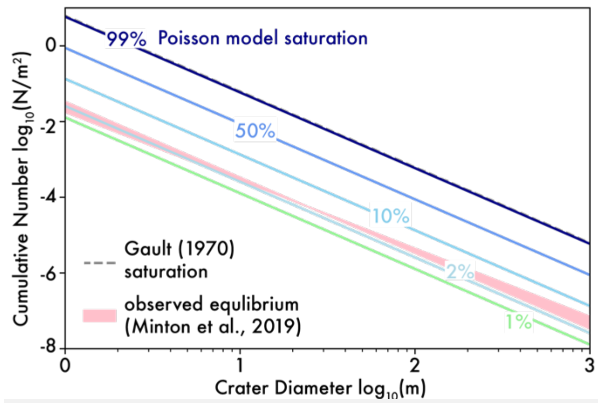

Figure 1. We model equilibrium as it approaches geometric saturation (99%). Equilibrium always occurs before saturation. Observed crater equilibrium on the mare occurs at around 2% of geometric saturation [4] but in some highlands locations occurs at 10% [e.g., 5].

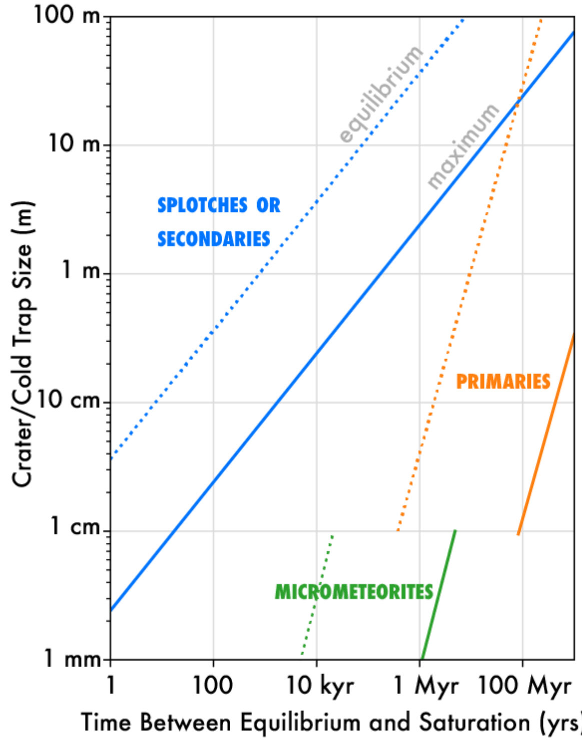

Figure 2. The time to equilibrium (2% of saturation) and the time interval difference between equilibrium and saturation (labeled 'maximum') are plotted for micrometeorites, primary impacts, and secondary impacts. Crater size represents a proxy of micro-cold trap size because cold traps are found within the topographic low of crater bowls.

Model: We use a statistical model of crater accumulation and geometric saturation (**Figure 1,** [2,6]). The model describes the probability that a sample point is interacted with by an impact crater provided an impact flux (number of impacts of a given energy per unit area and time) and a timescale. Per [4], we define a minimum equilibrium to occur at 2% of geometric saturation and geometric saturation to occur at 99% model probability (i.e., 99% probability that any given sample point has been inside of a crater at least once).

To understand the longevity of cold traps, we take the difference in time between crater equilibrium and geometric saturation for each crater size. This time interval represents the lifetime of a crater between its equilibrium and certain and complete obliteration by a crater of equal or greater size at saturation (**Figure 2**).

We model three impactor populations which produce craters: micrometeorite impacts (<1 cm), large primary impacts (>1 cm), and secondary impacts of all sizes. We model a flux of secondary impacts [2], which is consistent with the production of albedo anomalous "splotches" observed in NAC temporal pairs that are interpreted as secondaries [7]. We model a primary impact flux following lunar-scaled bolide flux [8] and a micrometeorite flux following [9]. Our model is valid for crater accumulation over the last one billion years.

Results: We plot generic geometric saturation (**Figure 1**) and model results for the difference between equilibrium and saturation timescales of micrometeorites, primaries, and secondaries **(Figure 2**). Secondaries are more abundant than primaries at the < 100 m scale and therefore reach both equilibrium and saturation before primaries.

Cold trap lifetime scales with size. Large cold traps last exponentially longer than small cold traps. Cold trap craters > 100 m in diameter last as long or longer than 1 Gyr. Cold trap craters between 1 and 10 m in diameter last between 1 and 100 Myr. Cold trap craters which are smaller than the decimeters scale, last less than a thousand years. Any volatiles within the cold traps must be younger than these age ranges.

Just as secondary impact cratering dominates vertical impact gardening [2, 3], secondaries also dominate crater equilibrium and saturation at sub-kilometer scales. Because most small craters can be assumed to be secondary craters, most micro-cold traps are within secondary craters. Secondary cratering dominates both the production and destruction of micro cold traps.

Discussion: Our model results (**Figure 2**) demonstrate that micro cold traps within > 10 m craters like those VIPER will explore are relatively long-lived (>100 Myr), and the larger the crater, the longer it takes to obliterate cold traps. From our model, we can reason that 100 m cold traps which formed 1 Gyr ago, are still present today and can have captured the last 1 Gyr of lunar volatile history.

In contrast, micro-cold traps at the decimeter and smaller scale are extremely ephemeral, lasting less than one thousand years. Cold traps at the meter scale last only on the order of tens of thousands of years last only on the order of about a million years under the flux of primary impacts which have sufficient energy to generate impact melts from silicate rocks. Therefore, it is unlikely that significant volatile accumulation could occur in the smallest micro-cold traps. If volatiles accumulate, they will be physically and possibly thermally destabilized by impacts and gardened to and away from the surface over a short time. The uppermost surface of all cold traps, even relatively ancient large cold traps, has been disturbed at smaller scales.

This extreme ephemerality of small cold traps, the intense mixing seen by the surface, and the implicit short lifetime of surface volatiles is consistent with the expected young age of LAMP-observed surface ice [10]. However, because secondary impacts dominate saturation and because secondary impacts impact with lower energy than primary impacts, they may not efficiently devolatilize a surface [2, 3]. Crater equilibrium may represent a state where volatiles have been sequestered at the bottom of cold trap craters which have not yet been obliterated by saturation.

Conclusion: In conclusion, we find that meter and smaller scale micro-cold traps are extremely ephemeral; however, larger cold traps at the tens to hundreds of meters scale are exponentially more long-lasting and may represent locations where the volatile history of the Moon is well preserved, and significant volatile accumulation has been able to occur. Thus, any given 100 m crater cold trap within the Artemis explorations zone represents a candidate for investigating volatiles, and older 100 m craters may have been cold traps for geologic timescales.

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