Understanding the 3D Stratigraphy of Icy Regolith Deposits at the Lunar South Pole

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1. Introduction

Theoretical predictions (Watson et al., 1961; Arnold, 1979), models (e.g., Ong et al., 2010; Hurley et al., 2012; Prem et al., 2015), and observations (e.g., Feldman et al., 1998; Colaprete et al., 2010; Hayne et al., 2015; Fisher et al., 2017; Li et al., 2018; Rubanenko et al., 2019) all point to the presence of water ice and other volatiles at the surface and in the subsurface at the lunar poles. The abundance and three-dimensional stratigraphy of this polar ice is not well understood, but has important implications for the history of water delivered to the Earth-Moon system through time. Polar ice deposits likely have complex distributions, and could extend tens or even hundreds of meters below ground. Models developed by Cannon and Britt (2020) and Cannon et al. (under revision) predict the following:

1. Only rare events–impacts of large hydrated asteroids (or comets) and voluminous volcanic episodes–could have deposited ice layers that were thick enough such that ice was worked down into the subsurface by gardening before it was eroded.

2. Large polar craters emplaced ejecta deposits out to significant distances that buried surrounding ice, and likely disrupted and heated its upper reaches. Once buried by a diffusive regolith barrier, ice could be protected from further losses at the surface.

3. These two effects operating in tandem *should have built up stratigraphies of ice-rich and ice-poor regolith* at a range of vertical spatial scales, with lateral variation across the poles due to the sharp falloff of ejecta thickness with distance.

4. The age when a cold trap formed, and the timing of deposition events determines when this stratigraphy began accumulating, and the thermal environment (i.e., topography) sets the "accommodation space". Thus, all things being equal, the older cold traps (~3.8 Ga or older) should have accumulated much more ice.

Currently available data from remote sensing are unable to test these predictions and resolve in detail the structure and potential layering of icy deposits at the poles. The VIPER mission offers the next opportunity to do so with controlled "bites" through regolith strata, but drilling can only provide a one-dimensional view. Interpolating between cores taken even a short distance apart is not generally possible, as the Apollo coring experiments showed (Heiken et al., 1991). The Artemis III human crew can thus expand on the success of VIPER by exposing subsurface icy strata in three dimensions, sampling these exposures, and deploying instruments to interrogate these deposits at even greater vertical depths. By creating "roadcuts" into cold-trap regolith, samples can be intelligently selected, and spatially-resolved measurements can be made. These investigations will also serve a dual purpose of proving potential water *reserves*, advancing from the current status as *identified resources*.

2. Science Questions

There are many key lunar volatile questions that remain unanswered after decades of orbital study and modeling work. These include:

A. What is the relative importance of each of the proposed sources for polar volatiles (asteroids, volcanism, solar wind, etc.), and how have these changed over time?

B. What is the spatial distribution, concentration, and chemistry of volatile deposits, and how deep below the surface do these materials extend? Why is there an apparent disconnect in many locations between surface ice detected by shortwave spectroscopy, and subsurface ice inferred from neutron spectroscopy?

C. Have volatiles chemically reacted with each other and with anhydrous silicate minerals after being deposited? Is there evidence for transient liquid water and water-rock reaction products?

3. Science Objectives

The relevant science objectives that can be addressed by Artemis III include:

I. Determine the presence, abundance, and chemistry of volatiles in different thermal environments, including those where ice is thermally stable at the surface, stable at depth, and not stable at any depth.

II. Determine whether layering exists within ice-bearing deposits, and if so, the nature of the stratigraphy down to at least 1 meter depth directly, and up to 100 meter depth indirectly.

III. Thoroughly characterize the environment and materials where volatiles are located, including temperatures and the physical properties of the regolith.

4. Enabling Activities

For Artemis III astronauts to meet these science objectives, we envision a coordinated campaign involving direct human manipulation and sampling during EVA, human-deployed remote sensing instruments including ground-penetrating radar in and around cold-trap environments, and robots that can pre-deploy to excavate exposures into the regolith and/or assist with measurements and sampling. These tasks can be accomplished in micro cold traps that are likely to be present at any landing site, or ideally in larger shallow cold traps that are specifically targeted as part of landing site selection. Human-robot partnerships will alleviate some of the constraints from EVA suits on the duration astronauts can spend in cold-trap environments.

5. Conclusions

Having the Artemis III crew simply make surface measurements, or acquire quick grab samples from permanently shadowed regions *will not mark a significant improvement over orbital remote sensing and the VIPER mission*. To truly advance lunar polar volatile research, the Artemis III crew should work with robots, hand tools, and deployed instruments to expose and interrogate the 3D stratigraphy of icy regolith deposits, including ground-based remote sensing measurements such as GPR that extend 10s to 100s of meters deep. These measurements and the resulting sample suite will produce game-changing science to better understand all aspects of the volatile story on the Moon, and other bodies including Mercury and Ceres. They will also make fundamental contributions to NASA's emerging ISRU strategy that aims to have a pilot ice processing plant by 2028.

6. References

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