Science Strategy for Understanding Regolith Development and Space Weathering with Artemis III

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Background: Understanding the Moon requires understanding the lunar regolith. Defined as the layer of fragmental debris above a more coherent substrate, all returned lunar samples have come from the regolith (no bedrock has been investigated in situ), and most of our remote data is sensing only the regolith as well. A landing site near the lunar south pole provides important opportunities to acquire new knowledge of the Moon by learning from the polar regolith. Near the south pole, there are a number of science opportunities to investigate regolith development and regolith processes (space weathering, ballistic sedimentation, regolith gardening) that should be prioritized for Artemis III. Most investigations are not landing site specific, though a landing site on the Shackleton–de Gerlache ridge would provide an extra opportunity to sample a ray of Tycho crater. A summary of recommendations is presented here, for background and references see Denevi and Robinson (2020; https://www.hou.usra.edu/meetings/lunarsurface2020/pdf/5122.pdf).

Space Weathering: A polar landing site presents the opportunity to understand the relative roles of the solar wind and micrometeoroids in space weathering, the largest open question related to this phenomenon that is common to airless bodies across the Solar System. Because the curvature of the Moon reduces the effective solar wind flux at high latitudes (flux scales with the cosine of latitude), polar regions are the perfect place to determine how regolith matures when the effects of the solar wind are minimized and to resolve a conflict between remote sensing observations and studies of lunar samples. *Any* returned sample of "typical" mature regolith from a polar region will provide new insights into the nature of space weathering, including regolith collected in the first contingency sample. Further samples to address this question should be collected from locations that experience a different solar wind flux due to topography, such as a regolith from the poleward- and equatorward-facing slopes of an Eratosthenian (or older) crater, and regolith from regions of persistent and permanent shadow. Regolith samples collected from the ejecta of Copernican craters would be especially valuable in understanding rates of polar space weathering if accompanied by samples of the craters' impact melt or rocks from the rim suitable for cosmic ray exposure dating.

An additional test of space weathering would be possible if a landing site was selected on or near the ray of Tycho crater that crosses the ridge between de Gerlache and Shackleton craters (Denevi and Robinson, 2020). Samples collected from this site, where the regolith has been disturbed by the ray and near the rims of Tycho secondaries would enable a direct comparison of how highland material has matured since its exposure at the same time at the two extremes of the lunar space weathering environments (the polar regolith, and the light mantle at the ~equatorial Apollo 17 landing site). Further, cosmic ray exposure ages of rocks collected from the rims of Tycho secondaries, or impact glass within the ray regolith (equivalent to the Apollo 12 brown ropy glass attributed to Copernicus) would provide a test of the ~100 My estimate for the age of the Tycho impact.

Ballistic Sedimentation: Recent observations have provided a new understanding of the great distances over which impact crater ejecta can affect the surface, but there have been fewer advances in understanding the fraction of primary material deposited at these distances vs. local disturbed material. Any polar site will provide new information on the distal transport of material. All of the Apollo and Luna sample return sites were close to a mare–highlands boundary; most were within several tens of km. Only Apollo 16 was ~220 km from a mare deposit, but it still contains basaltic fragments. A polar landing site will be >500 km from any mare deposit, and will thus provide a chance to better understand how impact events have transported material to great distances throughout the Moon's history. Sampling within the Tycho ray would also provide a direct comparison to the older Copernicus ray visited at the Apollo 12 landing and thus new information on the process of ballistic sedimentation, particularly if material from within and outside of the ray are sampled.

Regolith Mixing and Stratigraphy: Coring and trenching is an excellent way to investigate the local history of the polar regolith. Layers derived from discrete ejecta emplacement events can be observed within Apollo core samples, recording the unique impact history of that location. At the example of the Shackleton–de Gerlache ridge, sampling the regolith with depth would provide a history of the Tycho, Shackleton, and de Gerlache impact events, and the more recent shallower reworking of these materials. The ancient highlands regolith also contains fossil regoliths (paleoregolith) that could provide a history of changes in the solar wind, or major events such as from solar flares or cosmic rays. A trench dug either from a relatively flat area or by digging into a crater wall would expose layering. Subtle differences in these layers could be discerned with multispectral imaging to document this stratigraphy and aid in selecting samples from each layer to bag and return. Coring or trenching should be designed with a goal to sample to depths greater than those achieved by the Apollo deep drill cores (<3 m). For example, the age of Shackleton crater is estimated to be ~2.5 Gy, and models of regolith mixing suggest that the upper several meters of its ejecta will have been mixed by impact gardening. Coring or trenching to greater depths near this crater (or any large crater) could provide relatively undisturbed ejecta from that impact event and would provide a greater chance of discovering ancient fossil regoliths.

Coring and/or trenching should be complemented with ground penetrating radar (GPR) measurements, which would be the first such measurements of the highlands regolith that is produced by a longer and more intense period of bombardment. Apollo cores are highly variable even within a single site, and no layers could be definitively linked from core-to-core. Thus to understand the relationship of layers to specific impact events or the broader geologic context of a landing site, GPR is essential. The pairing of core/trench samples from depth and GPR measurements of subsurface regolith stratigraphy would reveal new insights into regolith development and evolution, and provide critical context to the samples. However, GPR measurements would be most useful if collected from a rover or crew vehicle.

Summary: We cannot overemphasize the importance of a complete investigation of the polar regolith in illuminated terrain, persistently shadowed terrain, and permanently shadowed terrain. Such an investigation will allow substantial progress in our understanding of the significance of key processes in the formation and evolution of regolith (sputtering, micrometeoroid impacts, solar wind implantation, gardening, ballistic sedimentation, etc.), will provide context to the provenance of all samples collected from the region, and will inform future engineering decisions. A carefully planned regolith investigation will thus enable a wealth of future exploration and science advancements.