PROGRESS TOWARD THE INITIAL USGS RESOURCE ASSESSMENT OF LUNAR REGOLITH.

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Introduction: In situ resource utilization (ISRU) is widely regarded as an essential technology for enabling a sustained human presence beyond the Earth [1-3]. Establishing ISRU on the lunar surface is a major goal for NASA's *Artemis* program [4] and an explicit priority of the U.S. Office of Science and Technology Policy [5]. The United States Geological Survey (USGS) is the U.S. Federal agency tasked with assessing natural resources within and beyond the Nation's boundaries [6,7]. Over the past several years, the USGS has investigated extending its mineral resource assessment methodology to the asteroids [8] and the Moon [9,10].

We examined applying the established USGS methods to (1) solar energy, (2) regolith, and (3) water ice on the Moon. We concluded that solar energy was too deterministic a problem to benefit from the statistical methods of a formal resource assessment. Most of the uncertainty comes from a single source: the slopes at the scale of a lander. In contrast, water ice deposits on the Moon are still too poorly understood to assess using the USGS methodology; the issue is that the USGS methods begin with a qualitative model of the geologic processes that create the deposit [11]. Given that it is unclear if the source of the lunar ice is impacts, volcanism, and/or the solar wind, we cannot complete the first step in the assessment for ice. While other methods that are divorced from geologic processes could be applied, this is too great a deviation from the established USGS methods for us to pursue. Instead, we await data from in situ measurements of the lunar ice before we attempt a formal USGS resource assessment of lunar ice.

Lunar regolith, on the other hand, appeared to be well-suited for conducting a traditional USGS mineral resource assessment, albeit with some modest adjustments to the methodology. Here we report on progress toward the first such assessment. Lunar regolith has many potential uses [12]; for our first assessment we focus on bulk regolith used for simple construction and/or shielding.

Summary of the USGS Resource Assessment Methodology: While the USGS has been tasked with assessing geologic resources since its inception in 1879, modern quantitative assessments rely on a methodology that has been developed and refined over the past few decades [11]. The purpose of these assessments is to provide unbiased, reliable, quantitative information that decisionmakers can easily understand. As such, the final output is deceptively simple, providing three values for the amount of the resource: a reasonable lower bound, the most likely amount, and a plausible upper bound. To produce these values, a number of different probability distribution functions are combined using Monte Carlo methods. The difficult aspect of this work is in deriving scientifically rigorous mathematical models for the expected number, size, and grade of the deposits. Further analysis is then used to identify the geographic tracts where the deposits could exist and place economic and technological constraints on extraction/recovery of the resource. However, all of this is predicated on a good understanding of the geologic processes that create the deposits.

Descriptive Model for Lunar Regolith: There are sufficient data to have developed a robust understanding of the geologic processes that formed the lunar regolith [e.g., 13] Regolith has been investigated with remote observations from the UV through radar wavelengths as well as from in situ observations and returned samples. The 1- to 2-m deep *Apollo* 15, 16, 17 drill cores, with contextual geologic and geophysical data, are particularly informative. Repeated impacts by asteroids and comets shatter the bedrock, creating breccias with clasts that have been subjected to highly variable levels of shock and heating. While some material is transported great distances across the surface of the Moon, the bulk of the regolith is formed by comminution of local rocks. In the time between the larger impacts the surface is modified by micrometeorite impacts and radiation. These processes act to variable depths, resulting in varied alteration with depth. The detailed nature of the regolith is thus strongly affected by the age and lithology of the underlying geologic units. Compared to terrestrial soils, lunar regolith is notable for being extremely poorly sorted with no alteration by aqueous or biologic processes [13].

Spatial and Deposit Density Models: On Earth, the processes that produce economically viable deposits have typically only acted in limited areas that can be delineated as tracts in a "spatial model." However, impacts are ubiquitous on the Moon, so regolith is found everywhere. As such, the concept of the spatial model needs to be adjusted in this case. Similarly, the terrestrial mining concept of discrete deposits does not immediately translate to bulk regolith which forms a global blanket over the Moon. However, there are significant spatial variations in the properties of the regolith that do need to be captured in some manner. We combine the concept of these two types of models by considering the nature of the regolith within each of the geologic units in the renovated global geologic maps of the Moon [14]. These units delineate the significant changes in age and lithology on the Moon that affect nature of the regolith and can each be considered a discrete regolith "deposit."

Grade-Tonnage Model: The USGS resource assessment methodology relies on probability distribution functions for the size (tonnage) and concentration (grade) of deposits. Given the distributed and relatively uniform nature of the lunar regolith, we combine these concepts into a single parameter: the thickness of the regolith for each geologic unit. For our initial assessment we are primarily relying on the published global Diviner map of H-parameter that translates surface temperature variations into the rate at which the regolith compacts with depth [15]. This compaction rate can be extrapolated to estimate regolith depth. We will spot-check these estimates with results from long wavelength (70 cm) radar that can penetrate the regolith to the underlying bedrock [16] and the morphology of small craters, which can show a distinct bench at the boundary between the regolith and bedrock [17, 18].

Since lunar regolith is expected to grade into fractured bedrock/megabreccia, our most significant source of uncertainty is in defining the "base" of the regolith. However it is the finer and looser regolith near the surface that is expected to be the most useful material. The H-parameter provides good constraints on this uppermost part of the regolith.

However, some more sophisticated ISRU concepts require specific grain sizes (e.g., cannot utilize particles larger than pebble-sized) or require specific minerals to catalyze reactions. Thermal data alone cannot provide this information and more complex analyses including infrared spectroscopy and radar imaging at multiple wavelengths and polarizations will be needed. However, this more complete analysis of regolith properties is beyond the scope of this initial assessment.

Monte Carlo Modeling: For each geologic unit, we will use GIS software to query the data on regolith depth. Given the ~250 m/pixel resolution of the Diviner H-parameter map, there is ample data to derive statistically meaningful probability distribution functions for all units. We need to also quantitatively account for the inherent noise in the data and uncertainties in their interpretation. These probability distribution functions will then be entered into a Monte Carlo modeling application, such as the one used for the feasibility study for asteroid resource assessments [7]. The output will be a probability distribution function for the amount of regolith per unit area expected for each mapped geologic unit on the Moon.

Economic/Technical Constraints: Not all the regolith included in this raw assessment will be necessarily accessible for ISRU. For example, there may be trafficability (e.g., slope) or rock abundance limits for the regolith collector. There may be limits on the distance the collectors can move and the depth to which they can dig. There may be specific minerals (e.g., FeO, TiO_2 and oxygen rich ilmenite) that are especially beneficial for the specific ISRU process in question [19]. These additional constraints can be applied to assess the amount of resource that can be exploited with different ISRU technologies. However, such analyses are largely beyond the scope of this initial assessment.

Schedule and Future Plans: Our goal is to submit our initial assessment for review before the end of FY20 (i.e., September 30, 2020) as a USGS Circular. A draft report will be presented for community scrutiny at the 2020 Solar System Resources Roundtable held annually at the Colorado School of Mines. We plan to follow-up this initial assessment with more in-depth studies to create assessments tailored to specific lunar regolith ISRU concepts that are of greatest interest to NASA and other decisionmakers. More specifically, we expect that the next tier of assessments will add information on grain size and mineralogy that are important to specific ISRU processes such as 3D printing and oxygen extraction. If the ISRU concepts are sufficiently mature, we will include appropriate engineering constraints. All this effort lays the groundwork for completing an assessment of water ice once the relevant geologic processes are revealed by a future landed mission.

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