FIRST STEPS TOWARD A USGS ASSESSMENT OF LUNAR REGOLITH AS A RESOURCE. L. Keszthelyi, L. Gaddis, L. R. Ostrach, K. Bennett and C. Fortezzo, U.S. Geological Survey Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001 (laz@usgs.gov).

Introduction: Last year we examined applying the established USGS resource assessments methods to the Moon, considering solar energy, regolith, and water ice [1]. We concluded that solar energy was probably too deterministic a problem to benefit from the statistical methods typically used by the USGS; conversely, water ice deposits on the Moon were too poorly understood to assess quantitatively. Regolith, on the other hand, appeared to be in the sweet spot for such assessment. Here we report on our first steps toward conducting such an assessment.

For this study, we consider the fine component of the regolith, sometimes called lunar "soil" to be the resource of interest. Many *in situ* resource utilization (ISRU) concepts rely on pouring such material into a hopper at the start of the processing facility [2-5]. While boulders and cobbles can be crushed into finer materials, we assume that this additional step is undesirable.

Summary of the USGS Resource Assessment Methodology: While the USGS has been in the business of 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 [6]. 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 work is in deriving scientifically rigorous mathematical models for the expected number, size, and grade of the deposits. Further analysis is 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: The lunar regolith is primarily the product of eons of impacts [7]. The regolith has been investigated with remote observations from the UV through radar wavelengths as well in situ observations and returned samples [e.g., 8]. As such, we have a robust understanding of the relevant geologic processes. 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 micrometeoroid 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 sediments, lunar regolith is notable for being extremely poorly sorted with no alteration by aqueous and biologic processes [7].

Spatial and Deposit Density Models: On Earth, the processes that produce resources 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. Our plan is to combine these two models by considering the nature of the regolith within each of the geologic units in the renovated global geologic maps of the Moon [9]. These units should delineate the significant changes in age and lithology on the Moon that affect nature of the regolith. However, it is possible that the geologic map has more spatial detail than we can use at this point and some judicious joining of similar map units may be necessary.

Grade-Tonnage Model: The USGS methodology relies on probability distribution functions for the size (tonnage) and concentration (grade) of the resource within a deposit. We translate "tonnage" to the depth of the regolith. Two of the most useful data sets for estimating the thickness of the regolith layer are (1) long wavelength (70 cm) radar which can penetrate the regolith to the underlying bedrock [10] and (2) the morphology of small craters which can show a distinct bench at the boundary between the regolith and bedrock [11]. The Earth-based radar data is only available for the near-side of the Moon so we will have to infer the depth of the regolith on the far-side. We expect to find a statistically meaningful relationship between estimated regolith depth and the age and lithology of the mapped geologic unit.

For basic uses of bulk regolith, the proportion of the regolith that is fines/soil fits the concept of "grade." Thermal inertia is one of the best techniques for measuring the near-surface rock abundance [12]. From there, the regolith is expected to become coarser with depth following a standard pattern. For this initial assessment we plan to rely on published global DIVINER results [12].

Monte Carlo Modeling: For each geologic unit we will use GIS software to query the data on regolith depth and rock abundance. There should be sufficient data to derive statistically meaningful probability distribution functions for all but the smallest units (which we may need to combine with other nearby/similar 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 an existing Monte Carlo modeling application, such as the one used for the feasibility study for asteroid resource assessments [13]. The output will be a probability distribution function for the amount of regolith 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., ilmenite) that are especially beneficial for the specific ISRU process in question. These additional constraints can be applied to the spatial, tonnage, and grade models to assess the amount of resource that can be exploited with different ISRU technologies.

However, for the initial assessment we plan to ignore these considerations so we can quickly produce a useful product for decisionmakers charting the path for future lunar exploration. We (USGS) are working with NASA to identify the best way to proceed but are suggesting that we publish the initial assessment in 2021 and follow with refinements every few years. Adding information on chemistry and mineralogy from gamma ray and visible-infrared spectroscopy is a top priority.

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