RESOURCE EXPLORATION AND ASSESSMENTS AS LUNAR SURFACE SCIENCE.

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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].

Surface science conducted by human crews near the lunar south pole would play a crucial role in all the steps that bring ISRU from concept studies to full production. Such work would be enabled by foundational geospatial data sets including geologic and mineral maps based on orbital data [6-9]. Here we focus on quantitative assessment of resources, something essential for a mining process to move beyond initial "prospecting" to "exploration" that supports full-scale "extraction." The purpose of these assessments is to provide unbiased, reliable, quantitative information that decisionmakers can easily understand. This type of assessment is not the natural outcome of hypothesis-driven science; instead, it is applied science that is often provided by government as part of a policy to promote commercial activities.

USGS Resource Assessments on Earth and Beyond: The United States Geological Survey (USGS) is the U.S. Federal agency tasked with assessing natural resources within and beyond the Nation's boundaries [10,11]. While the USGS has worked on assessments of 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 [12]. 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, the relevant probability density functions are combined using Monte Carlo methods. The difficult aspect of this work is in deriving scientifically rigorous statistical 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.

A Tale of Three Lunar Resources: Recently, the USGS has investigated extending its mineral resource assessment methodology to the asteroids [13] and the Moon [14]. We examined applying the established USGS methods to (1) solar energy, (2) regolith, and (3) water ice on the Moon.

Solar Energy. We found that the USGS mineral resource assessment methodology was a poor fit for solar energy resources. Not only is the resource not geologic in nature, but the problem is also too deterministic 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. While knowledge of the topography of the Moon can always be improved, it should be very well understood in any regions where human surface activities are taking place.

Water. We found that water ice deposits on the Moon are still too poorly understood to assess using the USGS methodology. The issue is that the USGS begins with a qualitative model of the geologic processes that create the deposit [12]. 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.

Regolith. We found that the lunar regolith is well-suited for conducting a traditional USGS mineral resource assessment, albeit with some modest adjustments to the methodology. Based on this finding, we recently started an initial assessment [15]. While regolith has many potential uses [e.g., 16], this first assessment is focused only on bulk regolith for construction and/or shielding. The basic descriptive model of lunar regolith has been drafted largely based on published review studies. The spatial model is derived from the newly unified and renovated global geologic map [17] on the understanding that the properties of the regolith are mostly a function of the age and lithology of the underlying basement rocks. The concepts of grade and tonnage have been combined into a single parameter, the thickness of the upper, relatively unconsolidated part of the regolith. This thickness is estimated using the H-parameter calculated from Diviner data by Hayne et al. [18]. The uncertainties will be combined in a statistically rigorous way to produce the final assessment. The assessment should be submitted for publication before the end of the year. This work also lays the foundations for assessing more complex uses of regolith, such as oxygen extraction, with the addition of mineralogic and grain-size information.

What Should Human Crews Do to Assess Lunar Resources in the 2024-2028 Timeframe?

Ground-truth Orbital Data Sets. The polar regions are especially challenging for remote sensing measurements of reflected sunlight or thermal emission. These remote observations are sometimes pushing beyond where we can confidently rely on ground-truth from Apollo. This makes new ground-truth data on mineralogy and thermophysical properties especially valuable. Robotic explorers, including NASA's *Volatiles Investigating Polar Exploration Rover* (*VIPER*), should provide key ground-truth measurements, but the volume of such data is likely to be quite sparse when the initial crews return to the Moon under the *Artemis* Project.

The types of data and surface science activities needed to confirm remote measurements of the regolith are not dissimilar to what was done on Apollo. Human crews should collect a representative suite of rocks and soils for detailed petrologic and geochemical analysis, conduct basic geophysical surveys, and obtain core samples to understand vertical variations. It would be helpful to also have close-range remote sensing data to tie to the orbital data. Portable VNIR and thermal IR spectrometers are now much more practical for astronauts to use than during Apollo.

For water ice, it is essential to establish a robust relationship between the remote sensing data and volatile abundance and compositions. While this relationship must be based on the underlying physics of the orbital measurements, with sufficient ground-truth data, it can be empirically tuned. This semi-empirical approach, leveraging Apollo and other lunar samples, allows very robust mineral identifications from remote spectral measurements. It would be ideal to return cores to Earth that have not been thermally disturbed so the *in situ* state of the volatiles could be observed in the laboratory. Given the level of difficulty in returning similar samples from a comet [19], this may prove to be impractical. It may instead be necessary to return a series of smaller sealed samples, each from a known narrow depth interval. This need emphasizes the importance of the ongoing development of tools and procedures [e.g., 20] to collect samples from at least the margins of permanently shadowed regions (PSRs).

Systematic High-Spatial Resolution Surveys. Before initiating large-scale ISRU processing, experience has proven that developing a detailed three-dimensional view of the "ore" deposit has a very high return on investment. For regolith, this should be relatively simple since it is a generally uniform surface mantling material. Significant changes are only expected near younger craters and steeper slopes. However, to understand inhomogeneities on the scale of an excavator scoop, it would be best to dig a network of trenches that expose the regolith in cross section. The astronauts on the Apollo missions demonstrated the feasibility of digging such trenches into the upper, relatively unconsolidated, part of the regolith. We encourage efforts to determine how much of the characterization of trenches (i.e., documenting vertical and lateral variations in grain size, mineralogy, density, and cohesiveness) should be done by *in situ* examination with microscopic imagers and other instruments versus by analysis of returned samples.

For water ice, trenching may prove impractical if the ice-rich regolith is mechanically strong. A systematic drilling campaign that obtains a statistically robust description of the vertical and lateral heterogeneities in the composition and concentration of frozen volatiles is a good alternative. The *VIPER* mission should develop most of the relevant technologies, but it is likely that dozens, if not hundreds, of additional drill sites will be required. Given the hostile environment of the PSRs and the tedious nature of drilling, this activity may be an excellent candidate for tele-operated robotics.

Discovery-driven Resource Exploration. We feel it is important to emphasize that our current knowledge of lunar resources is rudimentary (or worse for water-ice); therefore, discoveries that require significant revision of our strategy for resource exploration (and extraction) are likely. While it is tautologically impossible to plan for specific unexpected discoveries, flexibility in procedures and "excess" capability in tools are essential. We strongly support ongoing efforts to take maximum advantage of human crews' ability to respond to the unexpected. We agree with the view that the unexpected is likely to drive the most exciting surface science to be done by human crews on the Moon.

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