PROGRESS AT THE UNITED STATES GEOLOGICAL SURVEY TOWARD QUANTITATIVE RESOURCE ASSESSMENTS OF LUNAR RESOURCES.

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Introduction: Even without a formalized lunar resources program, the U.S. Geological Survey (USGS) is taking deliberate steps toward quantitative lunar resource assessments. This effort has relied heavily on leveraging existing projects and new collaborations. Despite some added challenges, a benefit of this approach has been to build a broader community in developing common standards and methods.

Methodology: A general methodology for quantitative lunar resource assessments based on the USGS "three-part" model [1] was presented at the 2019 Space Resources Roundtable (SRR) [2] and more fully described in a USGS circular [3]. The circular also suggests a generic lunar resource classification scheme, which was presented at the SRR in 2023 [4], simplifying and blending multiple classifications widely used on Earth. Three types of lunar resources were considered, related to energy (solar), minerals (bulk regolith), and water (polar ice). Solar energy can be considered a "reserve" since many current lunar missions harvest sunlight to produce electricity as a commodity. In contrast, lunar ice is classified as a "speculative" resource that is currently unrecoverable [3]. Neither of these types of resources presents an urgent need for a quantitative resource assessment. We therefore have focused on lunar regolith for our initial quantitative assessment.

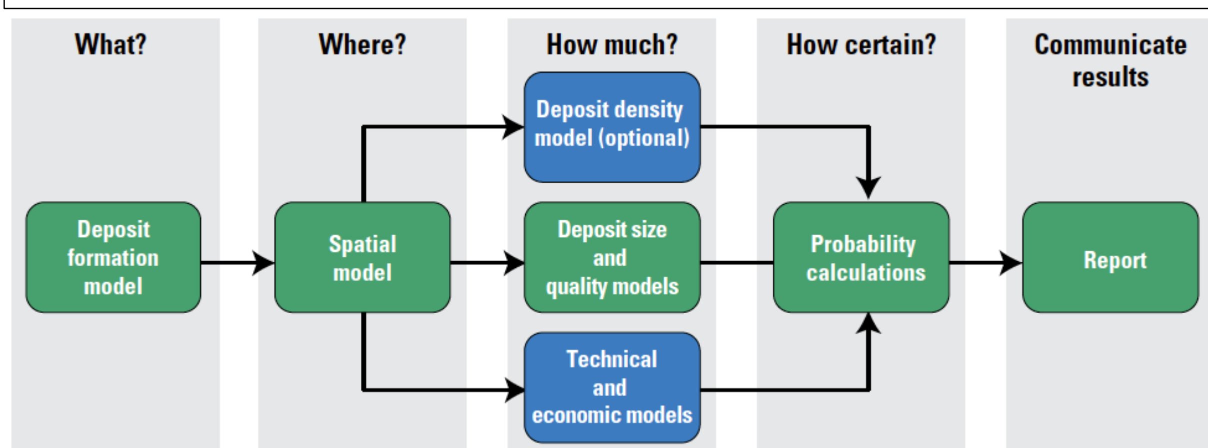
Resource Models: Figure 1 summarizes the generic workflow for such an assessment. The initial steps are the descriptive and spatial models.

Descriptive Models. Quantitative assessments start with a qualitative "descriptive" model for a given type of deposit. These models serve multiple purposes but perhaps the most basic is to establish what type of deposit is, and is not, being considered within a particular assessment. A clear delineation is essential to avoid mixing different types of deposits with different characteristics. Conducting statistics on an ill-defined mixture of different populations is an invitation to meaningless results.

An important consideration in separating different types of deposits is the desire to identify materials suitable to some specific process that would convert the resource into one or more commodities. Regolith has many potential uses, such as bulk aggregate for construction of landing pads, roadways, habitats, and shielding. However, one of the more mature in situ resource utilization (ISRU) technologies is the production of oxygen through hydrogen reduction, which takes place most efficiently when the titanium-bearing mineral ilmenite is present [5]. On the Moon, ilmenite is primarily found in some specific volcanic rocks.

Preliminary descriptive models for different types of titanium-rich lava flows and pyroclastic deposits were presented in 2023 at the SRR by our colleagues at the European Space Resources Innovation Center (ESRIC) in Luxembourg [6]. We are now collaborating to publish the next iteration of these models for mare materials and pyroclastic deposits in peer-reviewed journals.

Figure 1. Diagram of generic methodology for quantitative assessment of lunar resources after [3]. The first step is to clearly describe the type of deposit that is being assessed. Then defining the regions where this type of deposit is plausible is delineated in the form of permissive tracts. This is followed by obtaining statistics on key characteristics of the deposits. Monte Carlo modeling combines these statistics to calculate the probability distribution of parameters of most interest to decisionmakers. The results are published in a report that is intended to be readily understood by readers with varied technical knowledge.



Spatial Models. The next step in the quantitative assessment methodology is to produce maps of the localities where the specified type of deposit may be plausibly found. ESRIC [6] presented an initial set of spatial models for titanium-rich volcanic regolith in 2023.

As we are refining these spatial models, we have realized that the accessible lunar regolith is more similar to a continuous deposit (like surficial sand) than buried discrete ore bodies (like copper porphyry deposits). While buried resources may eventually be of interest, early lunar resource utilization is likely to target surface exposures. We have sufficient knowledge and data to identify the locations that are likely to have high-titanium regolith without having to employ traditional deposit density models. Furthermore, the concept of deposit size and quality (grade and tonnage) needs to be adjusted to focus on spatial variability in the resource.

Future Work: Our immediate focus is on extending methods used for continuous deposits to the lunar regolith. At the USGS, we are extending our recent scientific investigations of lunar pyroclastics [7] to consider parameters relevant to their utilization. In particular, we plan to publish information on parameters such as the concentration of iron-bearing glass and titanium (Fig. 2). Many lunar pyroclastic deposits are large enough to derive statistics on the variability of glass and ilmenite content at multiple scales. From this, we may be able to extrapolate (with significant uncertainties) to the scale of an ISRU project. This will allow the geologic certainty of the presence of resources within these deposits to be quantified.

In order to apply these results to an actual mission, it will be necessary to develop quantitative models for the engineering requirements of specific ISRU systems. These will need to be expressed in terms that can be measured using orbital remote sensing data (e.g., slope). Then the results can be statistically combined to produce maps of the suitability of specific pyroclastic deposits for specific ISRU applications – with quantified uncertainties. These uncertainties can be translated into a metric for risk, the parameter that is likely to be of greatest interest, especially for mission managers.

Current data are likely adequate for an assessment to support an ISRU demonstration mission for extracting O_2 from Ti-rich regolith. However, it is plausible that commercial-scale ISRU will require more *in situ* exploration. Methods being developed to analyze data from NASA's Volatile Investigating Polar Exploration Rover (VIPER) may be relevant to such future exploration.

An open question is where the role of government ends in assessing the risks for ISRU. For a government-funded demonstration mission, it seems the onus is on the government to assess risk as part of selecting between competing proposals. Our expectation is that the USGS will help develop methods and standards for doing end-to-end quantitative resource assessments while missions are largely funded by NASA. However, as the lunar economy matures, the government's role should diminish. If we use mining on Earth as a model, government will focus on assessing geologic certainty for some types of deposits while the risk associated with converting the resource into a commodity will shift to commercial entities.

References: [1] Singer D. A. (2007) *USGS OFR 2007-1434*. [2] Keszthelyi L. et al. (2019) *Space Res. Roundtable XX*. [3] Keszthelyi L. et al. (2023) *USGS Circular* 1507. [4] Keszthelyi L. and J. Coyan (2023) *Space Res. Roundtable XXIII*. [5] Crawford I. A. (2015) *Prog. Phys. Geogr., 39*, 137-167. [6] Calzada Diaz A. (2023) *Space Res. Roundtable XXIII*. [7] Pigue L. et al. (2023) J. Geophy. Res., 128 https://doi.org/10.1029/2023JE007861.

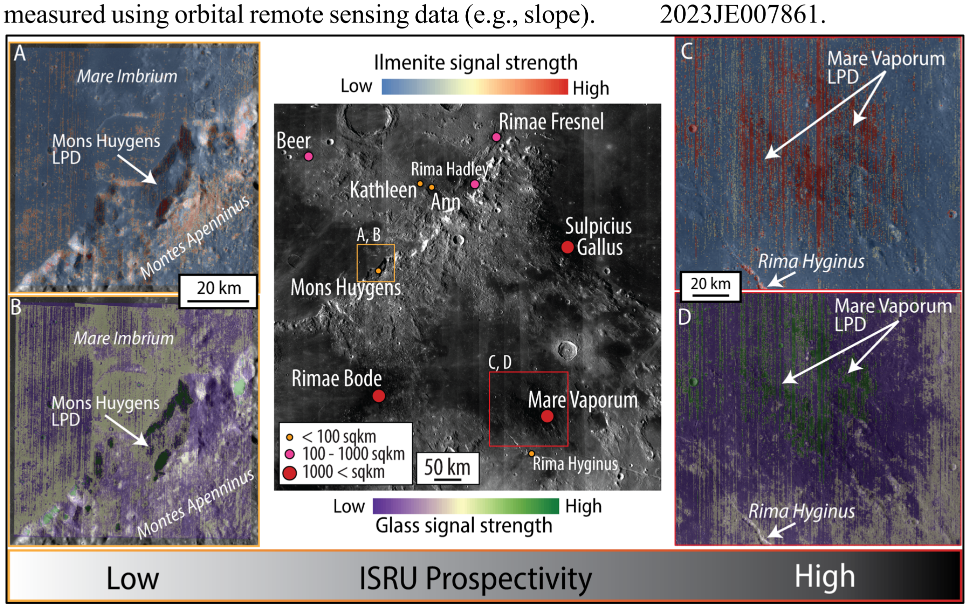


Figure 2: Case study investigating parameters for lunar pyroclastic deposit prospectivity. Center image shows the Montes Apenninus region, with known pyroclastic deposits indicated by areal extent. Two selected pyroclastic deposits are shown in ilmenite (top) and iron-bearing glass (bottom). Mons Huygens (A,B) would have low future resource potential with a small areal extent and low ilmenite and glass content. Mare Vaporum (C,D) would have high prospectivity for the given parameters.