PTMSS
Planetary & Terrestrial Mining Sciences Symposium

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Prospecting

REFINING THE CONCEPT OF USGS LUNAR RESOURCE ASSESSMENTS. L. Keszthelyi[1], T. S. J. Gabriel[1], L. R. Ostrach[1] and T. Crafford[2], [1]U.S. Geological Survey Astrogeology Science Center, Flagstaff, AZ 86001 (laz@usgs.gov), [2]U.S. Geological Survey, Mineral Resources Program, Reston, VA 20192.

Introduction: Over the past few years, the U.S. Geological Survey (USGS) has conducted a low-level effort to prepare for conducting assessments of lunar resources. The emphasis has been on determining how the established Earth-based USGS methodologies need to be adjusted for application to the Moon. While the timing of a formal assessment remains unclear, significant progress has been made [1-3]. Here we report on a number of refinements to our 2019 presentation at the Space Resources Roundtable and Planetary & Terrestrial Mining Sciences Symposium.

The Role of USGS Resource Assessments: USGS resource assessments are designed to provide reliable and actionable information to a wide range of decisionmakers. While the USGS does not directly set government policies, USGS data regularly underpins decisions made by a variety of Federal agencies as well as local governments. The established reputation for providing reliable information in formats that are intelligible and relevant to non-scientists means that USGS resource assessments are also used by a wide variety of non-governmental decisionmakers. This includes commercial/private investors who wish to evaluate resource extraction/development opportunities. The U.S. Federal government, including the USGS, is generally prohibited from providing information that supports a specific private endeavor. Instead, the aim is to provide information that is relevant to an entire industry or sector of industry. USGS lunar resource assessments will follow this same philosophy. While such assessments may prove useful to commercial/private lunar activities, the focus will be on providing essential information for setting or implementing Federal policies (e.g., NASA plans for sustainable human exploration of the Moon).

What is a USGS Resource Assessment? The USGS assessment distills all the available scientific information into a few parameters that allow reasoned decision-making [4]. In practice, the minimum set of information consists of (1) the geographic extent of the region where the resource can be found, (2) the amount of the resource that has a 50% chance of being in that area, and (3) a measure of uncertainty in that amount. The uncertainty is generally easiest to convey as the top and bottom of a confidence interval (often 90 or 95%). In some circumstances, knowing the middle value and the range that can be reasonably expected is all a decision maker requires to take action. However, the assessment also includes details on the methodology and input data to allow subject matter experts to delve deeper. The USGS resource assessment methodology utilizes Monte Carlo statistical programs to rigorously incorporate the different sources of uncertainty. The inputs are three types of statistical models: deposit-density (number of deposits per unit area), deposit grade and tonnage (quality and size of deposits), and tract (subsection of the study area where a deposit is possible). All of these models are underpinned by a detailed understanding of the processes that create the deposits and the report is rigorously peer reviewed [4].

What are the Resources? Water (ice) extracted from the lunar poles is currently of greatest interest, but it is important to recall that there are other valuable resources to be found on the Moon. These directly align with the resources that the USGS studies on Earth: water, energy, and minerals. The only major departure from experience on Earth is that the water on the Moon is in the solid phase and is therefore more akin to a mineral deposit than to groundwater. Our initial evaluation led us to focus on lunar regolith as the most appropriate lunar resource for a formal USGS assessment [3]. However, in the following we summarize how it has become clear that the USGS resource assessment methodologies have broader applicability.

Energy Resources: For activities on the Moon, the primary *in situ* source of energy is sunlight. The concept of deposit "tonnage" (i.e., quantity) translates to the fraction of time insolated but some systems are also sensitive to the duration of gaps in insolation. Deposit "grade" (i.e., quality/concentration) translates to the energy flux (W/m^2), a parameter that is essentially constant if solar arrays can be tilted and rotated. The only significant source of uncertainty is topography on the scale of the lander. While there are many different high-quality topographic data sets for the Moon, only stereo-derived digital terrain maps from the *Lunar Reconnaissance Orbiter* Camera (LROC) Narrow Angle Camera (NAC) are at close to the scale of landers [5]. However, at meter-scales, uncertainties in the slopes (a derivative of the elevations) are often significant and challenging to quantify. The USGS remains the premier organization in rigorous quantitative assessment of topographic and other foundational geospatial data. Therefore, the USGS and NASA are now collaborating to establish "foundational" data sets for the Moon over the next few years, which is anticipated to include quantifying uncertainties in topography down to the scale of landers.

There has also been discussion of extracting heavy isotopes of helium from the lunar surface to utilize in fusion power generation [6]. Since the industrial-scale generation of fusion power has not been demonstrated, an assessment of this energy resource does not appear to be urgent. However, we note that the material of interest is derived from the solar wind and implanted in the ubiquitous lunar regolith and is expected to form a broad and relatively homogenous deposit [6].

Minerals: The USGS mineral resources methodology has been honed over the past several decades [4] and we find that it can be readily translated to lunar mineral resources [2]. However, the geologic processes that produced the resource deposits are radically different from those on Earth, so some adjustments are needed. On Earth, liquid water plays a key role in the development of the vast majority of mineral resource deposits. This includes hydrothermal systems (e.g., porphyry copper deposits) and sedimentary processes (e.g., placer deposits). In contrast, there is no evidence that liquid water played a geologically significant role on the Moon. Instead, meteorite impacts, interaction with the solar wind, exospheric processes, and volcanism are key players [7]. These processes act over broad areas so lunar resource assessments need to seek a generalized view of a "deposit."

Regolith. The pulverized rock that covers the entire lunar surface can be used as an aggregate in building simple structures like berms or habitat shielding; or it can be agglutinated to form more durable concrete-like materials for landing pads or walls [8]. The ubiquitous regolith can also be fed into chemical processors to extract oxygen and other compounds [8]. We have found that regolith is best considered as a single global deposit, albeit with some variations in properties. There are three main variables: (1) depth, (2) grain-size and (3) mineralogy. Depth varies by a factor of a few, but is meters deep in all locations other than on steep slopes [9]. Since the typical 5-10 m depth of the regolith exceeds excavation capabilities being considered at this time, regolith depth is not a particularly important consideration for near-term ISRU. However, boulders and coarse fragments may pose a significant challenge for excavation and processing. Their presence in the upper tens of centimeters can be determined from orbital thermal and radar measurements that have been correlated with large boulders seen in high-resolution imaging. These data show that >10-cm-diameter "rocks" cover <1% of the lunar surface except in the vicinity of young craters that penetrate through the regolith to competent bedrock [9].

For most construction uses, the mineralogy of the regolith is also irrelevant, but the presence of Ti- or Fe-bearing minerals can aid some more energy-efficient methods of oxygen extraction. Lunar pyroclastic deposits are considered especially desirable feedstock for some of these methods [8]. Orbital remote sensing, ground-truthed with *Apollo* samples, has enabled the mapping of such pyroclastic materials [10] but additional *in situ* studies would add valuable information to enable their usage for ISRU.

Ice. Lunar ice deposits are of special interest because the water can be used for life support systems or converted into rocket fuel. These deposits are the most similar to mineral deposits on Earth because they are found in isolated shadowed patches where temperatures are low enough for ice to be stable for geologically significant time. Orbital data have confirmed the presence of near-surface hydrogen in many of these cold traps, but ground-truth data are limited. The LCROSS impact experiment found 5.6 wt.% H_2O with a 1σ uncertainty of ±2.9% [11]. Therefore, major questions remain about the source of the volatiles, when the deposits formed, and their evolution. The most likely sources are exogenic (meteoritic materials and solar wind) or endogenic (volcanic gases) [7]. The relative proportions of the input from these sources are essential for understanding when the bulk of the deposits formed and thus where they are likely.

The upcoming VIPER mission is essential for addressing these knowledge gaps. A formal USGS assessment of lunar ice deposits should be possible once the fundamental science questions are answered, permitting more confident interpretation of orbital remote sensing data on a regional scale. VIPER will also pave the way for site-specific exploration needed to ascertain ice distribution at the scale of an ice extraction enterprise. The vertical and lateral distribution of ice (and contaminants) at that scale will be defined by the local impact cratering history. This again mirrors experience with mineral resources on Earth: the USGS can provide a rigorous assessment of the resource on a regional scale, but this will not obviate the need for more detailed local studies to make industrial-scale resource utilization a reality.

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Abstract for PTMSS

Insights on Geological Deposit Modelling on Lunar Water and Volatile Deposits

Fundamental in developing ISRU is the requirement to know where to look for water and volatile deposits on the lunar surface and why. Watts, Griffis, and McOuat Ltd. ("WGM") thought its Water Works Group ("WWG") has used well established sedimentary geological modeling techniques and applied them to the unique nature of the Moon to develop detailed geological models. The results are theoretical breakthroughs in understanding how, where, and why water and volatile deposition occurs. Some key findings include deposition occurring on the sides of PSR craters rather than the bottoms and clear zonation of different volatile species resulting in natural separation and concentration. Theoretical findings will be reviewed based on studies of orbital data with specific examples of prospecting targets analyzed.

An Overview of the Lunar Water ISRU Measurement Study (LWIMS).

J. E. Kleinhenz[2], A. C. McAdam[1], A. Colaprete[3], D.W. Beaty[4], P. Clark[4], B. A. Cohen[1], J. E. Gruener[5], J. M. Schuler[6], and K. E. Young[1]. [1]NASA Goddard Space Flight Center Greenbelt, MD 20771, [2]NASA Glenn Research Center 21000 Brook Park Rd Cleveland, OH 44135, [3]NASA Ames Research Center Moffett Field, CA 94035, [4]NASA Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, CA 91109, [5]NASA Johnson Space Center Houston, TX 77058 [6]NASA Kennedy Space Center, FL 32899

Introduction: NASA announced plans for the Artemis program, which would send crewed missions to the Moon by 2024 and achieve a sustainable lunar presence by 2028 [1]. To carry out sustained crewed surface operations, In-Situ Resource Utilization (ISRU), which would use lunar resources to produce mission consumables, will be critical. Water-bearing materials have been identified at both lunar poles and are often associated with Permanently Shadowed Regions (PSRs). These constitute a geological resource that may or may not be convertible to reserves with additional exploration. This water could provide both fuel and oxygen for refueling vehicles as well as life support consumables. However, the nature and extent of this resource is not well understood. Detection of water alone is not adequate for ISRU planning. For this reason, NASA chartered the Lunar Water ISRU Measurement Study (LWIMS). The goal of this study was to assess and define the type, amount, and fidelity of the measurements needed to select mining locations for lunar water ISRU and to define resource-related requirements for ISRU hardware development and architectures (mining operations, hardware emplacement, concept of operations).

The full findings of LWIMS were released in October 2020 [2]. An overview of the approach and findings will be presented here.

Definition of a "Reserve": The goal of the recommended exploration/measurement plan was to provide enough information on lunar water-bearing materials to select a site and design hardware for a 'pilot' scale ISRU system, currently targeting the production of 1 mT of O_2 in 2028 time frame. However, scaleability to 10mT of O_2 would be the target for supporting Artemis human operations in the 2030s. Initial architecture studies [3] suggest that water concentrations below 2 wt% are not a viable ISRU target for the baselined technologies. These production, or tonnage, goals provide a key piece of information to define an ISRU reserve.

It is important to qualify the use of the term 'reserve' in the context of extraterrestrial application. There is still debate regarding the definition of a reserve for extraterrestrial application and if/how it is unique from the terrestrial case. The concept of reserve, in that it can be presumed to lead to future success, is unchanged. However, the metric for success in the terrestrial definition is financial, while in the extraterrestrial case is more nuanced. There are broader objectives than cost and/or profit, such as supporting a human life or enabling further exploration. Likewise there is not a consistent agreement on how to financially account for extraterrestrial exploration costs, risks, etc. Circumstances will change over time and the terrestrial and extraterrestrial definitions will converge. The LWIMS approach was to define a 'reference' reserve, that refers to the current state of lunar exploration and knowledge.

Current Knowledge State: Potential lunar water sources that have been identified include surface frost, shallow bulk water, deep bulk water, and pyroclastic deposits. Among these, shallow bulk water has been identified as the primary ISRU target based on current reserve definition parameters. Assets that have detected this type of water include neutron spectroscopy (e.g., Lunar Reconnaissance Orbiter (LRO), Lunar Prospector, radar (e.g., LRO, Chandrayaan-1), and one unique 'surface' detection; namely LCROSS [4]. The resolutions from these data sets are insufficient for ISRU needs where high resolution observation of a particular resource is required. These prior efforts had science objectives in mind when choosing their instruments and vantage points. While science and ISRU have common measurement needs that will support one another [5], distinct data sets are required for each. Figure 1 graphically shows this overlap. While the critical commonalities should be highlighted for mission selection and data processing, LWIMS focused on the particular ISRU interests.

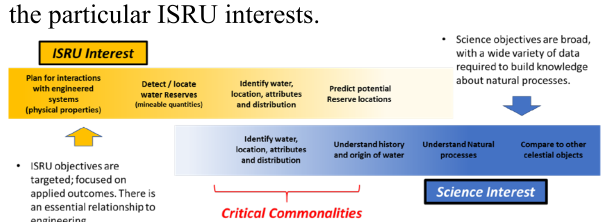

Figure 1: *The overlap and differences between ISRU measurements objectives and those that more science focused.*

Findings: The findings lay out a measurement plan structure Fig. 2, which consists of three main elements: advance and continue important orbital observations, support continued development of detailed resource models, and carry out a campaign of landed exploration missions of 3 different types.

The modeling capability is at the center of this plan; taking in all orbital and landing measurements to build a 'water favorability' map. This predictive capability is key to locating potential ISRU sites for hardware emplacement and for predicting the context of the resource that is available there. Orbital measurements provide information at the regional/global scale, in contrast to the point, or local, measurements of landed assets. Properly integrating orbital data, including LCROSS, and anchoring to landed measurements is critical to identification of water-favorable sites. Landed, or surface, measurements are critical to proper interpretation of orbital data and validating the model. Surface measurements are also needed to characterize the most promising water reserve sites in terms of higher resolution water distribution and water abundance information, as well as surface properties (geotechnical factors, dust, etc.).

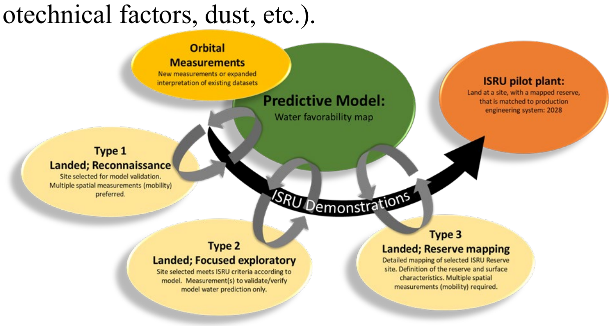

Figure 2:*Graphical representation of the LWIMS measurement plan, showing the key elements and flow.*

Three types of surface missions were defined to achieve the fidelity of data needed. Details on the measurements goals and accuracies for each are contained in [2]. The primary goal of Type 1 missions is to feed into model development and put orbital measurements in context. The landing sites may not be of high interest for ISRU implementation, but rather are chosen to obtain a broad data range. NASA's upcoming VIPER and PRIME-1 missions are Type 1 missions. These would be followed by Type 2 mission(s) that would target potential ISRU sites chosen from the predictive models, which were refined with information from the Type 1 mission(s). The goal is to validate the water prediction. With this single, focused intent, Type 2 missions could be single point measurements (no mobility), short lived and/or low cost instruments (e.g. impactors), though mobility platforms could be an option. A Type 3 mission would be sent to the most promising ISRU site; one that has been accepted as an ISRU reserve. The goal here would be full reserve characterization including detailed mapping of water concentration and lateral and depth distribution, geotechnical information, etc. Mobility would be needed to do this level of mapping.

The cadence of mission types will depend on how well the surface measurements (particularly in Type 2 or 3 approaches) agree with the predictive model. The required confidence level in the presence of a reserve in order commit to an ISRU site and pilot plant architecture will depend on the agency's risk posture, particularly considering the limited timeframe. Figure 3 shows the decisional flow diagram, where risk is qualitatively identified. The decision path, and the details of the missions implemented at each stage, depend on timeline for ISRU, availability of mission opportunities, risk posture (particularly if the mission outcomes deviate from what is anticipated), and budget availability. It should be noted that in Fig. 2, 'ISRU demonstrations' are highlighted within the path. This indicates that other flight opportunities can be leveraged to obtain the measurement information.

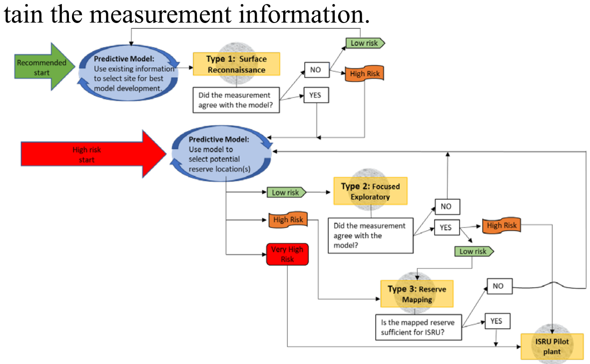

Figure 3: *The decisional flow diagram indicating the qualitative risk posture of decision points.*

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Prospecting, Extraction, and Processing of Lunar Resources utilizing Swarms of Lunar Outpost's Mobile Autonomous Prospecting Platform (MAPP) Rovers J.A. Cyrus[1], A.J. Gemer[1], and J.B. Cyrus[1], [1]Lunar Outpost, Inc. (17700 S. Golden Rd., Ste 102,Golden,CO 80401, justin@lunaroutpost.com)

Introduction: Lunar Outpost has been awarded one of the first ever contracts for the purchase of lunar resources to NASA which will help establish the legal and procedural framework for the commercialization of space resources. Due to the historical significance of the contract (and the $1 price tag) international attention has been drawn to these efforts. With the current focus being on the 50-150g acquisition with a flight scheduled prior to the 2023 deadline, it is important to envision how efficient prospecting and future extraction of resources will take place. Lunar Outpost will show how teams of 10kg class Mobile Autonomous Prospecting Platforms (MAPPs) and their larger 300kg class HL-MAPP counterparts will work together to provide a robust, cost-effective surface mobility solution to enable a sustainable cislunar architecture. A photo of a TRL 6 MAPP technology demonstrator during field testing is shown below in Fig 1.

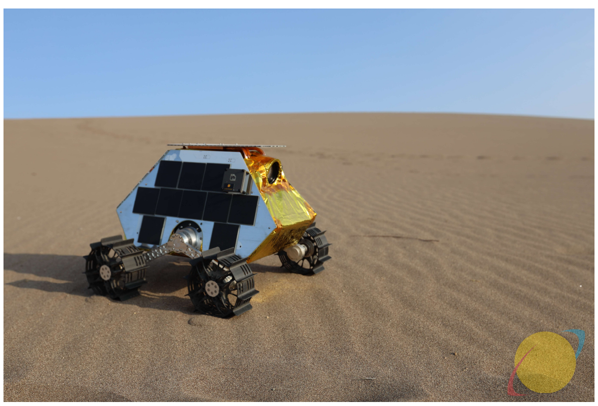

Figure 1: M1-MAPP / COLD-MAPP

Abstract: With many proposed prospecting and excavation architectures not being feasible within the next 10 years due to lack of infrastructure, technological maturity, or supporting technologies; Lunar Outpost is taking a different approach. By utilizing swarms of mobile robots, prospecting, excavation, and utilization can be expanded over time as the market grows. This allows a substantially lower upfront entry into the market while providing a viable path forward to encourage the adoption of space resources. Current MAPP capabilities include cryo-capable wheel drives; autonomous navigation, hazard avoidance, path planning, swarm robotics, and teleoperations software; and sensor capabilities including merging of vision-based navigation (VBN) and LIDAR point-cloud data for driving in high-contrast, deeply-shadowed, or dark conditions. With near-future iterations of MAPP (such as **PSR-MAPP** and **COLD-MAPP** being mission-ready in early 2022) and HL-MAPP (Heavy Lift Mobile Autonomous Platform) being able to operate for long-durations on the lunar surface, small scale production of resources will begin within the next 5 years.

With a flight schedule for the first acquisition of space resources in the next few years, Lunar Outpost is looking to quickly build on the lunar resource efforts to reach small scale prospecting, extraction, and production of usable products from the Moon. Lunar Outpost is focused on the space vehicle portion of the project and will be relying on partners to provide the material processing technologies. Lunar Outpost MAPP reserves significant interior volume for payloads that can contribute to the processing of lunar materials. These payloads may be mounted internally or externally to the body, depending on payload requirements.

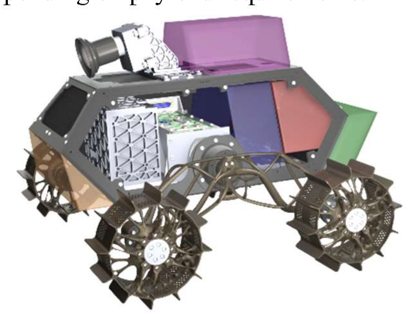

Figure 2: MAPP Payload Volumes

Swarms: A Swarm of robots is considered multiple or many robots working together to meet a shared goal or objective. Through implementation of novel swarm algorithms, Lunar Outpost will be able to efficiently prospect an area of interest in an extremely cost-effective manner. Once an 'ore' of the desired resource is identified, swarms of HL-MAPPs will be able to extract and process the resource in-place providing a resilient architecture that is readably scalable. HL-MAPP is sized to fit on a number of CLPS (Commercial Lunar Payload Services) landers allowing for near-term delivery to the lunar surface.

The scalability of the Lunar Outpost MAPP Swarm architecture is key as it is designed to help solve the 'chicken and the egg' problem that the field of Space Resources has faced for decades. The architecture also provides notable opportunities for third parties to utilize and benefit from the architecture being put in place.

MULTISPECTRAL IMAGER WITH ACTIVE ILLUMINATION FOR LUNAR MICRO-ROVER. Jayshri Sabarinathan[1,2], Aref Bakhtazad[1,2], Gordon R. Osinski[1,3*], Eric A. Pilles[1,3], Livio L. Tornabene[1,3], [1]Institute for Earth and Space Exploration, University of Western Ontario, London, ON N6A 3K7; corresponding author email: jsabarin@uwo.ca, [2]Department of Electrical and Computer Engineering, University of Western Ontario, London, ON N6A 5B9, [3]Department of Earth Sciences, University of Western Ontario, London, ON N6A 3K7

Introduction This project seeks to develop a compact multispectral imager with active illumination source (AI-MSI) which can be interfaced to a lunar micro-rover for scientific investigation of the lunar surface. The instrument's targeted goal will be to provide the ability to image the permanently shadowed regions (PSR) or other regions where there is not sufficient ambient light. This is enabled by incorporating an active light source integrated with the MSI. Additionally, it can also provide multi-spectral images at distance ranges for which there is enough ambient illumination. The advantage of this instrument is its ability to do scientific investigation on the lunar surface in both lighting conditions while providing a small form factor for Class <3kg rover. This instrument would also be available relatively quickly as a preliminary prototype of the MSI unit has been built and tested for terrestrial applications.

The importance of PSRs: The nearly perpendicular spin axis of the Moon with respect to the ecliptic plane (about 1.5°) generates areas of illumination extremes near the lunar poles due to its complicated local topography [1,2]. This causes regions with high topography to be constantly sunlit while rendering topographic lows to be permanently shadowed. The temperatures inside these permanently shadowed regions have been estimated to be low enough (around 50K) to not allow thermal escape of water molecules in the polar cold trap [3]. Hence, they have long been hypothesized to be dark, cold [4] and to possibly contain deposits of water ice and other volatiles [3,5]. These volatiles and water-ice deposits could be indigenous to the Moon itself [6] or may have been sourced from interaction with asteroids or comets passing the inner Solar System [6]. Although most shadowed regions are polar, recent studies [7] do indicate these regions could extend to latitudes as low as 58°, with at least 50 such regions being documented across both lunar hemispheres.

While sunlit regions can provide optimal conditions for landing sites and lunar outposts for future human surface missions, the permanently shadowed regions provide some exciting prospects for lunar water mining. If indeed water is found to be present in these regions, they would form a key resource for future lunar astronauts meeting drinking water needs or even as rocket fuel, if chemically broken apart. Additionally, detailed geochemical studies of these water samples can also provide new information on the source of these deposits, and by extension, give us some key insights into our understanding of processes that shaped the early Solar System and the evolution of volatiles, particularly in the Earth-Moon system (Mitchell et al., 2018). It is therefore critical to accurately define the locations and quantities of lunar polar water ice deposits, with most likely sites being the permanently shadowed regions on the Moon.

Scientific Goals and Objectives: The primary goal for the AI-MSI is to *evaluate the in-situ resource utilization (ISRU) potential of permanently shadowed regions of the lunar poles.* Four objectives have been identified in relation to this goal:

1. Characterize the composition of rocks and regolith within PSRs.
2. Characterize the texture and grain size of rocks and regolith within PSRs.
3. Identify ice within PSRs.
4. Identify water-bearing minerals in rocks and regolith.

To address these objectives, the selection of filters will have to be carefully selected to enable the detection of common lunar minerals as well as the detection of ices and water-bearing minerals. Below we identify critical spectral features necessary for their detection that will be used to determine the ideal set of filters to be used for resource detection in PSRs on the Moon.

- Olivine: Very broad absorption feature centered near 800-1300 nm
- Pyroxene: Two broad absorptions from 900-1050 nm and 1800-2300 nm [8] depending on whether it is low- or high-calcium pyroxene
- Plagioclase: Broad absorption centered at 1250-1310 nm [9]
- Ilmenite: Reflectivity upturn below 450 nm [10]
- Spinels: Wide absorption near 2000 nm, shallow absorptions near 700 and 1000 nm [11]
- Lunar glasses: Darkening and sloping of spectra towards the red [12]
- Ices: High reflectance near blue, asymmetric overtone absorption bands (800, 890 and 1030 nm), and 1300, 1500 and 2000 nm absorptions [13]

Current VIS/NIR multispectral camera: We have built and demonstrated a MSI in the Vis-NIR range for agronomy applications [14]. The prototype of the instrument has been flight-tested on UAV remote sensing for acquiring images of farm fields, as well as testing in greenhouse environments to take images at close distances – as would also be the case in Lunar rover application. The MSI utilizes a low power Qualcomm mobile processor and a patented MIPI CS2 switching scheme protocol for multispectral imaging (with the capability of up to 10Gb/s data transfer rate). This capability makes the MSI suitable for multispectral imaging for diverse applications. Different spatial resolutions, field of view and up to 7 optical spectral bands were implemented. The main multispectral camera module weight is about 500g, its dimension is 10cm × 9.4cm ×5.6cm, and consumes only 4W. Several of these units (~15) have also been built in collaboration with local agricultural services company A&L Canada Labs and currently being beta tested.

Operational Concept of the AI-MSI: The AI-MSI integrates a multi-spectral imager (MSI), an LED light source module in flash mode, and an on-board processor. The imager is uncooled silicon sensor and MSI spectrum coverage is from 350 to 1050 nm. The AI-MSI processor controls the imager, LED light source and the filter wheel, then gathers all image data, processes them and sends them to the micro-rover. The instrument will be mounted on the mast of a micro-rover at a specific height and angle The main specifications of the AI-MSI are shown in Table 1, while figures 1 and 2 show the concept model and subsystems for the instrument, respectively.

Table 1. AI-MSI main specifications.

Parameters	Values
Minimum resolution	2mm
Spatial FOV	1.35m×(0.81- 0.99m)
Spectral range	350nm to 1050nm
Imaging time for each waveband	<2 second
Power consumption	~20-50W (depends on operation mode)
Operating temperature	0 to 45oC
Non-operating temperature	–40o to 60oC
Weight	<2kg

The instrument can be used for exploration when:

- There is not enough ambient light (active light mode)
- There is enough ambient light, but the object is in shadow (active light mode).
- There is enough ambient light, and the object is not in shadow (passive light mode).

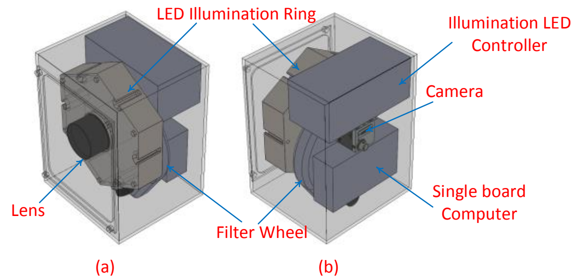

Fig. 1. Concept model of the AI-MSI instrument.

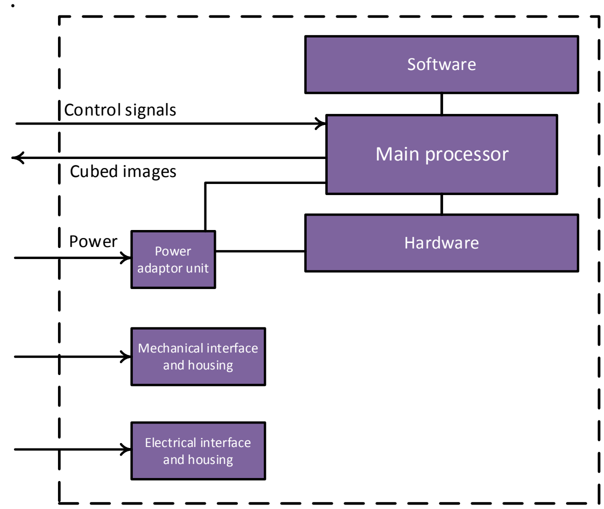

Fig. 2. A schematic of the AI-MSI subsystems.

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Determining Volatile Content and Geotechnical Properties using a Percussive Hot Cone Penetrometer and Ground Penetrating Radar P.J. van Susante[1] J. Allen[2], T.C. Eisele[3], T. Scarlett[4], and K.A. Zacny[5], [1]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, pjvansus@mtu.edu, [2]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, jstallen@mtu.edu, [3]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, tceisele@mtu.edu, [4]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, scarlett@mtu.edu, [5]Honeybee Robotics, 2408 Lincoln Avenue, Altadena, CA 91001. KA-Zacny@honeybeerobotics.com.

Introduction: With increased international interest in returning to the lunar surface and harvesting the water ice in the permanently shaded regions it is clear many uncertainties about the geotechnical properties, type and quantity of volatiles remain. Current state of the art in-situ measurements cannot uniquely determine what volatiles are present while determining geotechnical properties. No volatile release profile database exist currently. As part of the inaugural NASA Lunar Surface Technology Research (LuSTR) program [1] our approach to use a dynamic hot cone penetrometer (DHCP) in combination with ground penetrating radar (GPR) was selected for funding. The team from Michigan Technological University (MTU) and Honeybee Robotics will perform this work in two years from 2021-2023.

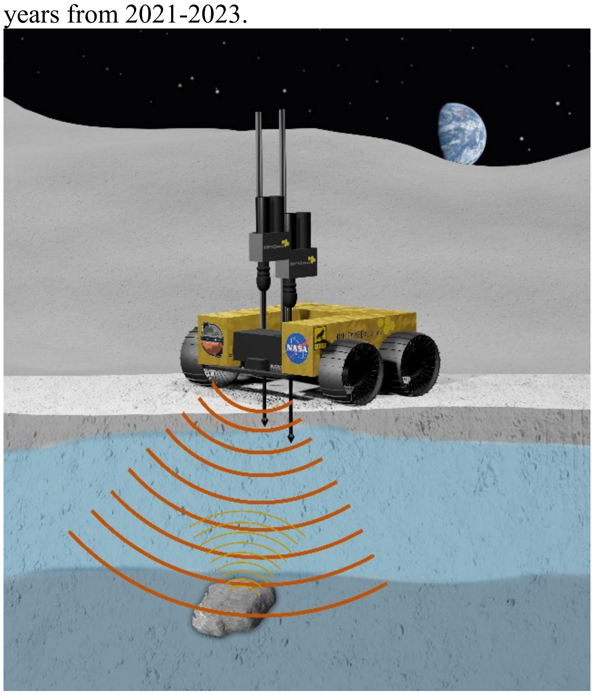

Figure 1: Rover Example showing PHCP using DSC and GPR

Planned Approach: Combine a percussive cone penetrometer with heaters and sensors and mount them on the TRIDENT drill z-stage (TRIDENT is scheduled to fly to the Moon as part of PRIME1 and VIPER). In between penetrometer locations, use GPR to determine spatial distribu-tion and layering of ice and rock. This will identi-fy, quatify volatiles in subsurfaceas well as ge-otechnical properties of the regolith.

Development Objectives: Create prototypes of the heated cone penetrometer and test effectiveness. Using differential scanning calorimetry (DSC) in two percussive cone penetrometers in combination with GPR to determine the type, concentration and vertical and lateral variation in volatiles in the lunar regolith by using thermal profiles and cycling. A dataset of thermal release profiles of cryogenically frozen regolith infused with volatiles will be a major objective.

Testing plan and deliverables: Testing will encompass DHCP testing under lab and field conditions using cryogenically frozen regolith simulant and volatiles in the lab and two field sites, one in a trench filled with different icy layers of regolith simulant to test the DHCP and GPR and another in a natural frozen basalt sand environment where we will create known underground ice and rock layers to identify with GPR. Separate frozen icy regolith simulant test layers will be created in a large freezer for testing the geotechnical property determination using the DHCP as function of ice content and percussive frequency and energy.

Impact and Infusion: The proposed research will provide a dramatic improvement in the direct in-situ measurement of ice concentration with depth at accuracy of 0.1 wt% at 10 cm vertical intervals using DSC. GPR (once calibrated by in-situ measurements) will provide continuous measurement of layers and continuity/obstacles. This will directly inform fol-low-on missions to the lunar surface and design of the ice mining and extraction equipment Since PHCP will be deployed from a modified TRIDENT-based hammering drill (designed for VIPER), it would fit within VIPER mass/power envelope and as such, it could fly on VIPER 2.0 in 2024 or later. This mission would directly in-form the goals of 2028 sustainable lunar presence with mining of polar water ice. Synergy with Astrobotic's SBIR phase II funded GPR devel-opment effort will also be possible.

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AN EVALUATION OF THE WATER ON THE ILLUMINATED MOON AS AN IN-SITU RESOURCE.
C. A. Hibbitts, K. Runyon, M. Nord, JHUAPL, 11100 Johns Hopkins R., Laurel, Md., 20723. Karl.hibbitts@jhuapl.edu;

Introduction: Water—broadly meaning either H_2O or OH, greatly varies in its physical and chemical states over the illuminated and unilluminated portions of the Moon. These variations will determine the amount of processing and energy needed to extract the water and thus greatly affect its usefulness as a 'reserve'. Water ice in Permanently Shadowed Regions (PSRs) offers a potentially viable resource, but here we briefly consider a different resource, namely the viability of water and OH retained in and on lunar grains in illuminated terrain. While water may potentially represent a 'gold mine' for enabling sustained lunar presence, its abundance and state, affecting attributes such as amount of material that must be processed and energy required, must be evaluated when considering its practical use as a resource.

Abundance: Whereas the abundance of water ice in PSRs may range as high as 10s of percent [1], the water or OH in the illuminated terrain are associated with silicate minerals that are nominally anhydrous meaning that the OH and/or H_2O will be present at much lower abundances. Terrestrial pyroxenes—and by extension lunar minerals—can incorporate up to ~ 200 ppm of OH, and feldspars can hold more, up to ~ 500 ppm of OH. At greater abundances, molecular water is the preferred state, and reaches 1.5% by mass whether in minerals or glass [e.g. 2] although this level abundance has not yet been seen in lunar materials. Some of the highest abundances are seen in lunar pyroclastic silicate glasses that reach several hundreds of ppm [3] and spectrally modeled to be as high as 0.05 wt. % [1].

There are several sources for this water that result in different forms that affect both its abundance as well as ease of extraction:

Hydroxyl formed from the implantation of solar wind protons. Solar wind keV protons will penetrate into and subsequently diffuse to ~ 50-100 nm into silicate grains to form OH in the grains' rims. [4], with the OH that is formed being more stable and will more slowly desorb from silicates even at 400K to thus accumulate over time reaching a number density of ~ $10^{17}/cm^3$ [5] though there may also be some temperature dependent diurnal variation in abundance [e.g. 6]. This surficial OH has been observed optically with an estimated abundance potentially as high as 1000 ppm [7]. However, once the solar wind source is cut-off recombinative desorption, although slow, will proceed at surface illuminated temperatures, and any grain that is buried and no longer is being rejuvenated by solar wind, will slowly deplete of OH. So, the bulk abundance of solar wind OH in the near surface is actually an unknown, but will almost certainly be less than possibly 1000 ppm observed on the optical surface.

Molecular water formed from the hydroxyl: The hydroxyl isn't the only physical state of water in the surface of the illuminated Moon. Molecular water has also recently been detected on the surface of the illuminated Moon [e.g. 8] with a spectral signature that is inferred to indicate its existence as a fluid inclusion in silicate minerals. The spectral feature at 6 microns is consistent with a few to several hundred ppm. This H_2O is believed to have formed from OH through non-equilibrium reaction in micro meteoroid impact plumes and subsequently trapped in frozen melt splashes. Thus, H_2O may be ubiquitous at the 10s to few 100s ppm in agglutinates throughout the soil. Agglutinates make up about half of mature soil.

Surface adsorbed water: Adsorbed H_2O and OH, can potentially reach an effective bulk concentration of ~ 1000 ppm in desiccated but cold soil, such as may exist in the near surface of high latitude polar terrain [9]. However, its abundance may be much lower given that a full monolayer often does not develop [10]. The thermal stability of this phase is sufficiently weak that the H_2O molecule will not persist on the surface for more than a few seconds in directly illuminated terrain [e.g. 10]. However, the rate of loss can be mitigated by diffusion through even a 10s to 100 of micron of regolith by several orders of magnitude [9] and thus, near-surface adsorbed molecular water can potentially be stable in the near-surface of cooler but still illuminated polar regions.

Required processing rates and power: With projected needs for H_2O (or O_2) ranging from ~ 1 metric ton (MT) per year for astronaut consumables, to maybe ~ 10 MT for initial propellant needs, and easily growing to 100 MT/yr or more for enabling sustained presence with multiple fights per year [11], the rates of regolith material needing to be processed, and the associated power required, can be derived (Figures 1 and 2). These concentrations of 'ore' are several orders of magnitude lower than estimated water ice abundance in PSRs and similar to that for disseminated metal deposits on Earth, and the amounts of material to be processed would be similar for a given amount of

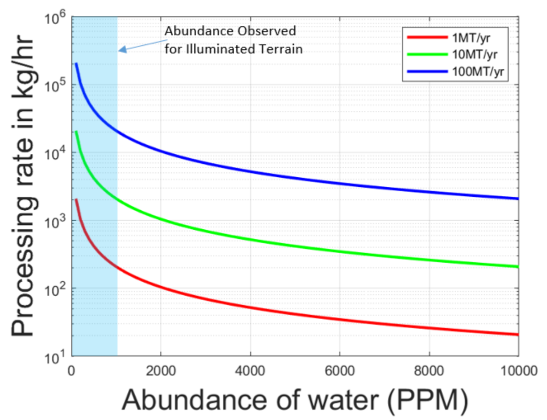

Figure 1. Approximate processing rates needed for water extraction from soil in illuminated terrain is at least 100s kg/hour and can exceed 1000s kg/hour of regolith assuming 200 days/year and 24 hours/day of processing time.

extracted ore. These rates and power required are also orders of magnitude higher than estimated for the extraction of O_2 from lunar regolith. As an example, O_2 extraction from lunar regolith leverages an O_2 concentration in the silicate minerals that is ~ 60% molar, or 11% by mass for anorthite, which is the dominant mineral in highland soils. Conservatively assuming a 45% extraction efficiency of O_2 from regolith, about 1 to 100 kg/hr is needed to provide 1 to 100 MT of O_2 per year compared to the 100s to 1000s kg/hr needed for water extracted from illuminated lunar soils.

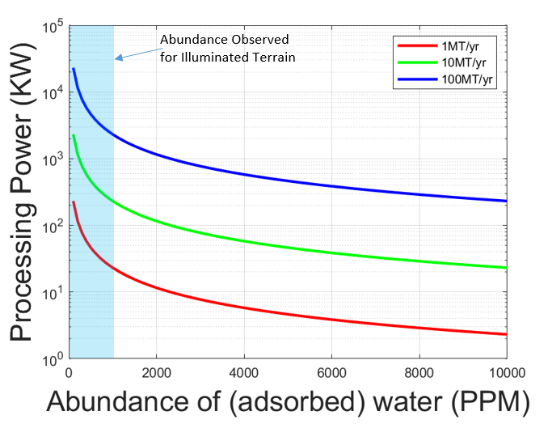

Figure 2. Even the most optimistic scenario of molecular water adsorbed onto grain surfaces requires copious amounts of energy for extraction. Assuming heating to 500K from a starting temperature of 300K and same rates as in Figure 1. If O_2 is desired, additional power would be needed for electrolysis of the water. Extraction of internal OH or water inclusions would require two to five times as much energy.

The concentration of water directly affects the amount of energy required to extract the resource as well, due to having to heat the regolith in or upon which the water is adsorbed (Figure 2). The extraction of internal OH or water inclusions is further elevated by needing more heating than that required to only desorb the surficial adsorbed water that is assumed for Figure 2. Fully removing chemisorbed water and internal OH requires heating to 600 to 750K, and liberating water trapped inside agglutinates would require the melting of the soil, T>1000 K. To put in context with respect to using the soil itself as a reserve, the power needed for both the heating (melting) and electrolysis of O_2 extracted from regolith is more than an order of magnitude lower than the ~ 20 to 200 kW per metric ton for extraction of 1000 ppm or lower abundances of adsorbed water, assuming a 45% efficiency for O_2 extraction.

Conclusions: The low abundance as well as high physical/chemical stability of water on the illuminated terrain results in a requirement for significant power consumption and large processing rates to meet the expected demands for ISRU. The predicted regolith processing rates and power requirements are 100s to many 1000s kg/hr of regolith material and 100s to many 1000s of kW to provide 1 to 100 MT of water per year.

Acknowledgments: We acknowledge the support of the NASA Lunar Surface Innovation Initiative.

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LUNAR WATER ICE AS AN OASIS OR MIRAGE: WHAT DOES THE LATEST SCIENCE TELL US?

K. M. Cannon[1], [1]Colorado School of Mines, GGE & Space Resources Program, Golden CO. cannon@mines.edu

Introduction: Water ice and other volatile species at the lunar poles are touted as a promising source of both oxygen and hydrogen for in-space propellant and life support [1-3]. However, the energy for extracting and especially electrolyzing H_2O (per mass O_2) is roughly on par with pulling oxygen directly from regolith (e.g., through molten regolith electrolysis), and operating in cold trap environments is significantly more difficult than in well-lit warmer areas. Thus, the viability of water ice as a resource is closely tied to its concentration and accessibility. If there is abundant ice located close to the surface, it may trade favorably compared to extracting O_2 from regolith. But if there is much less ice or it is mostly buried deep underground, then the trade becomes less clear.

There has been a tendency in the space resources community to latch onto specific numbers like 5.6 wt.% ice from LCROSS [4] or up to 30 wt.% from M^3 [5] without a thorough analysis of the limitations of these remote sensing techniques and the caveats involved in specific published studies. Here, I synthesize current knowledge about the nature and distribution of polar ice, drawing on recent/ongoing studies and what they may be telling us about the potential for ice as a resource.

The importance of sensing depth: Each different remote sensing technique is sensitive to a certain depth beneath the Moon's surface, depending on the region of the electromagnetic spectrum used. Fig. 1 distinguishes between "surface ice" at the optical surface, "shallow ice" within the upper meter, and "deep ice" beneath this. Instruments like LAMP, LOLA and M^3 that use reflected light can only detect ice to several μm or tens of μm beneath the surface: they cannot distinguish between a surficial frost and a deeper deposit. Neutron spectroscopy, radar, and the LCROSS experiment are able to detect shallow ice, and extend slightly into the the upper reaches of where deep ice would be if it exists.

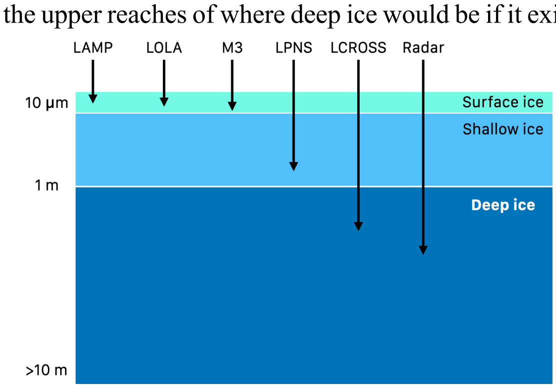

Fig. 1. Sensing depth of remote sensing techniques.

Synthesis: *Surficial ice:* Water ice has been positively detected at the very upper surface (μm to tens of μm deep) of cold traps by three different orbital instruments: LAMP, LOLA, and M^3. LAMP and LOLA measurements are both consistent with a thin patchy frost, that if it were evenly distributed would have a concentration of 0.1-2 wt.% ice [6,7]. Reports of up to 30 wt.% ice from the M^3 instrument seem to be at odds with this [5], but there are important caveats: (1) 30% is the *maximum* from over 1,500 pixels with ice detetions, with no median or mean reported, and (2) the 30% value came from fitting one ice absorption band in isolation, and when all three were fitted simultaneously, a much lower value of ~1-2% was reached which is consistent with LAMP and LOLA. In recent work, Farrell et al. [8] suggest the ice detected by these shortwave reflectance techniques is a thin transient frost <2,000 years old. Distinct terrain features (ring-mold craters, glaciers, etc.) suggestive of ice have not been observed at the surface of lunar cold traps–unlike Mars or Mercury–despite dedicated searches [9].

Shallow subsurface ice: The most definitive data for shallow ice within the upper meter come from neutron spectroscopy. The Lunar Prospector Neutron Spectrometer (LPNS) detected hydrogen at both poles of the Moon within the upper 70-100 cm [10-12]. If present in the form of H_2O and evenly distributed, the concentration would be ~0.01 wt.%, but there is strong evidence the H is clustered within cold traps [11,12], in which case concentrations range between 0.2-2 wt.% H_2O [12]. There is also strong evidence from LPNS that the upper 10 ±5 cm is particularly dry with ~0% ice [13]. Shallow ice could be present at >2 wt.% in some places if it is extremely heterogeneous laterally at the subpixel scale, but impact gardening should act to homogenize the regolith, not the converse.

Radar has also been used to probe the lunar poles. In general, radar measurements are not consistent with thick pure ice deposits within the top several meters [14,15], and have been used to put upper limits in some locations of no more than 5-10 wt.% ice [15]. A controversial set of studies interpreted circular polarization ratios as evidence for thick ice [16], but those results have been repeatedly refuted [e.g., 17].

The LCROSS experiment detected water ice and other volatiles indirectly from a plume of material ejected from a synthetic crater [4]. Originally an average of 5.6 wt.% H_2O was reported in the plume material that sampled down to several meters deep. A brand-new reanalysis of the plume [18] is consistent with little to no ice in the upper 5-6 m, but a hard (ice-cemented?) layer beneath this with significantly more ice.

Deep ice: New evidence is emerging that there could be substantial amounts of ice at the poles, but that it is buried quite deep (>5-10 m) beneath the surface. Depth/diameter ratios of small craters at the poles are suggestive of meters to tens of meters thick layered deposits of ice and regolith buried at depth [e.g., 19]. This is consistent with my own modeling studies that predict a thick layering of ice and ejecta at depth, but little ice near the surface [20].

Summarizing: There is evidence for a ~µm-thick frost at the surface of many cold traps at the poles. A small amount (<1-2 wt.%) of ice is mixed in the regolith beneath this in cold traps, likely separated by a desiccated layer of 10 ±5 cm thick. Substantial ice may be buried at depth (>5-10 m), but evidence for deep ice is indirect. This scenario can be explained by known processes operating at the poles [3,20]: ice deposited by asteroids and volcanic outgassing is cold trapped at the surface. Most events only deposit a thin layer that is quickly lost, but larger events can lay down meters or tens of meters at a time. Some of this ice can be protected by thick lag deposits of dry regolith emplaced on top of it. Impact gardening churns the regolith, and various processes (sputtering, micrometeoroids) erode ice at the surface. Initially ice is worked down into the subsurface, but as fresh ice is brought back up it is exposed to space weathering, forming a dry layer that deepens over time. The surface frost detected today could come from a small recent deposition event, or from pockets of deep ice that are exposed by impacts and re-distributed.

Ice textures: Regolith particles from returned Apollo samples are fiendishly complex. They contain many phases and fragments welded together with glass, and are coated with nano- and micro-sized clinging fines. When more components (H_2O, CO_2, etc.) are added to the system, this complexity should increase. Many different forms of ice are likely present in cold traps (Fig. 2). Without in-situ exploration and returned samples, it would not be wise to make assumptions about which forms are dominant at the lunar poles.

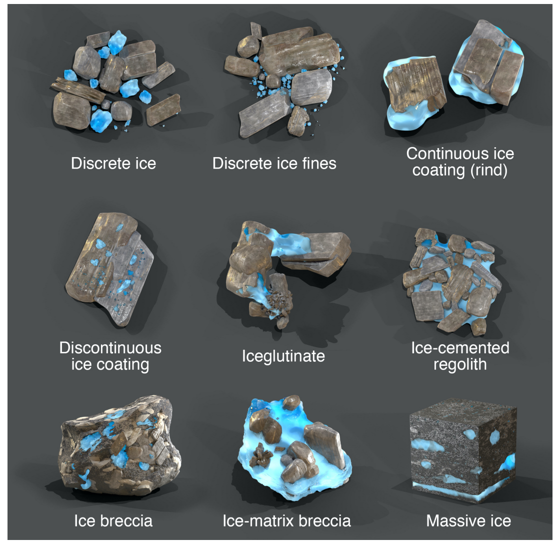

Fig. 2. Probable textures of water ice and regolith grains in lunar cold trap environments.

Implications for ice as a resource: *Prospecting:* The synthesis above suggests no high-grade ice deposits have yet been located near the surface, and easily accessible regolith is likely ice-poor (less than 1-2 wt.% ice). A viable resource may only be present if shallow ice is extremely clustered, or if deep ice is present. In both cases, prospecting is needed to locate deposits, and for deep ice a different set of techniques is needed for detection compared to existing remote sensing methods.

Extraction: Almost all extraction methods being developed today assume moderate to high ice concentrations are present at <1 m depth. If the synthesis above is more or less correct, this is a poor assumption. Architectures to extract deep ice (>5-10 m) should be studied, which likely involve a large amount of overburden removal and/or completely different extraction methods.

Trade with O_2 from regolith: The main benefits of targeting water ice rather than O_2 from regolith are access to hydrogen, and low-temperature processing built on proven technology. But with some combinations of low ice concentrations and difficulty of access, it is no longer worth it to brave the cold dark reaches where ices may be found. Deep ice remains a promising target for lunar propellant, but a different set of technologies are needed to prove its existence then be able to extract it.

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