PTMSS
Planetary & Terrestrial Mining Sciences Symposium

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Space Resources Roundtable

Hosted by the Canadian Minerals and Metals Plan Secretariat

The Canadian Minerals and Metals Plan | Le Plan canadien pour les minéraux et les métaux

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Virtual 2021

Wednesday June 9, 2021 Abstracts and Presentations

Prospecting

Asteroids/Simulants

Simulants

Roundtable 2

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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.

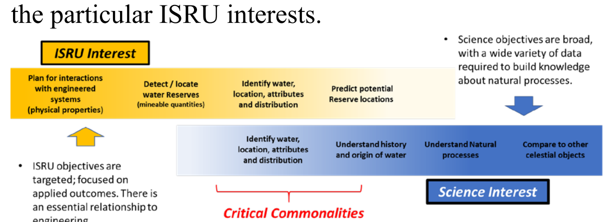

Figure 1: *The overlap and differences between ISRU measurements objectives and those that more science focused.*

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.).

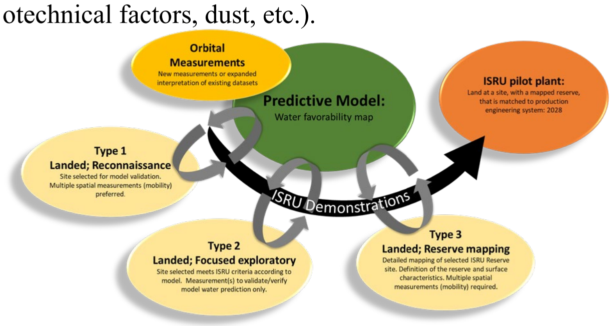

Figure 2:*Graphical representation of the LWIMS measurement plan, showing the key elements and flow.*

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.

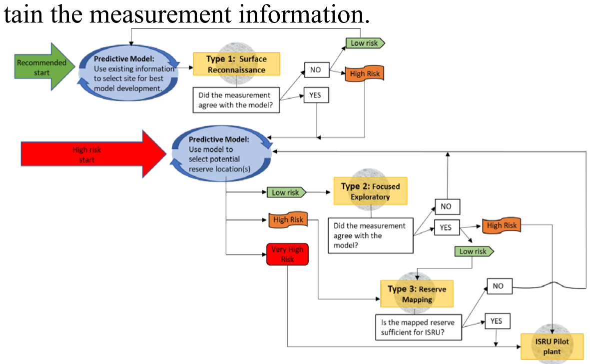

Figure 3: *The decisional flow diagram indicating the qualitative risk posture of decision points.*

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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.

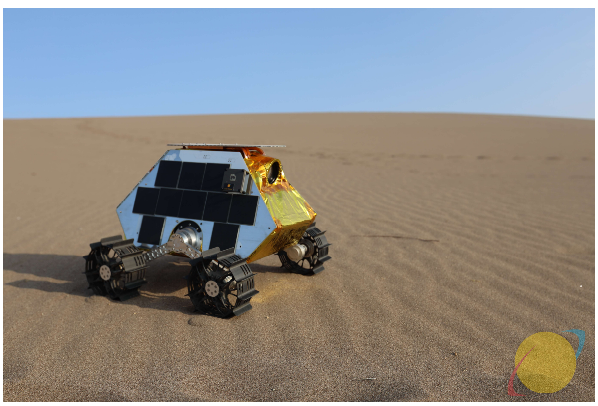

Figure 1: M1-MAPP / COLD-MAPP

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.

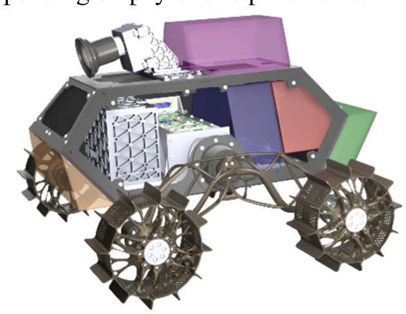

Figure 2: MAPP Payload Volumes

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).

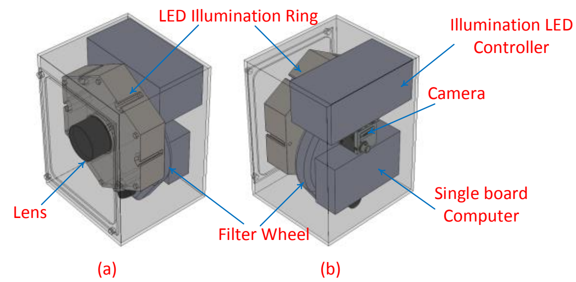

Fig. 1. Concept model of the AI-MSI instrument.

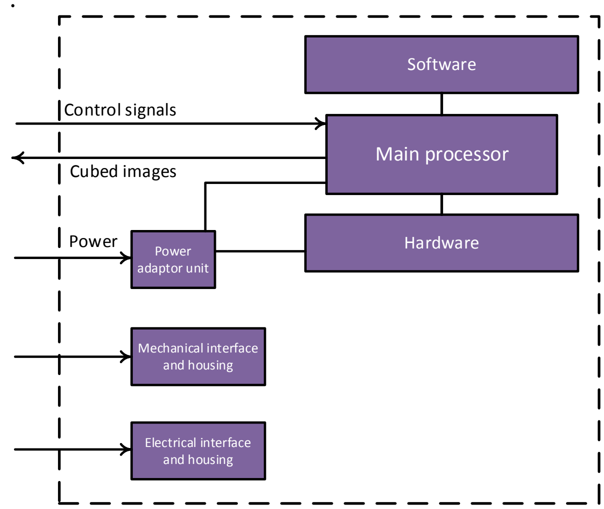

Fig. 2. A schematic of the AI-MSI subsystems.

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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.

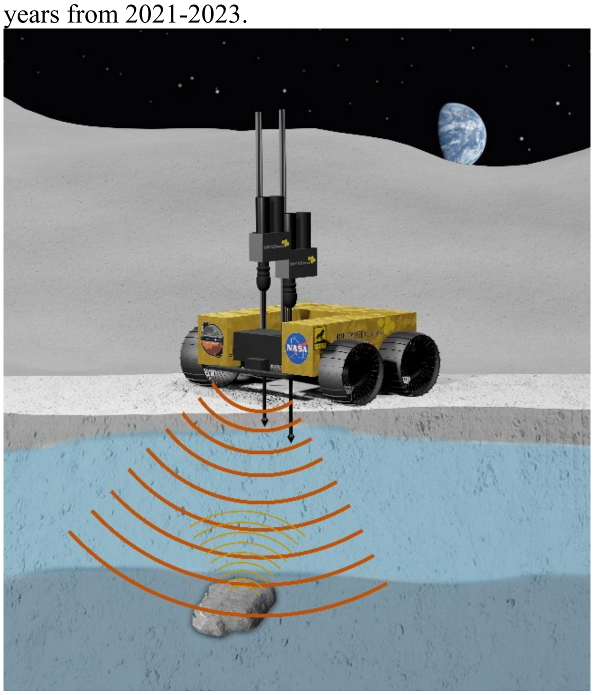

Figure 1: Rover Example showing PHCP using DSC and GPR

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

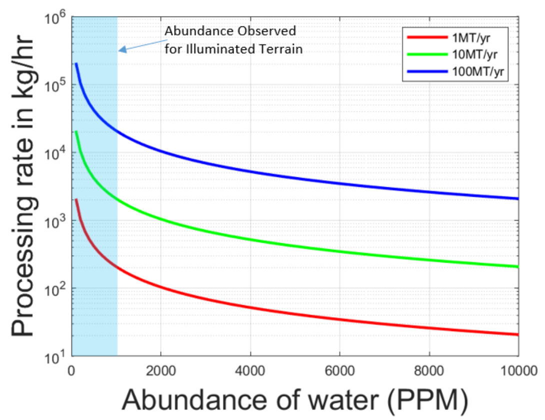

Figure 1. Approximate processing rates needed for water extraction from soil in illuminated terrain is at least 100s kg/hour and can exceed 1000s kg/hour of regolith assuming 200 days/year and 24 hours/day of processing time.

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.

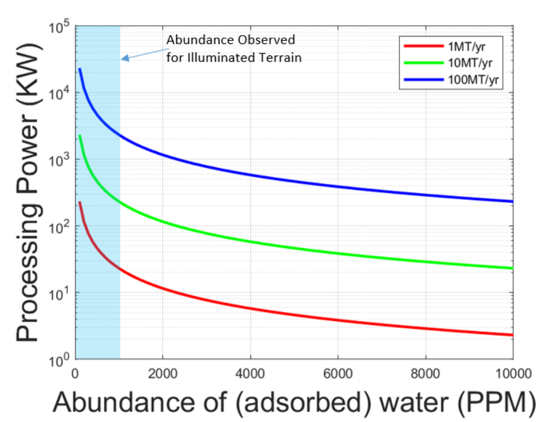

Figure 2. Even the most optimistic scenario of molecular water adsorbed onto grain surfaces requires copious amounts of energy for extraction. Assuming heating to 500K from a starting temperature of 300K and same rates as in Figure 1. If O_2 is desired, additional power would be needed for electrolysis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

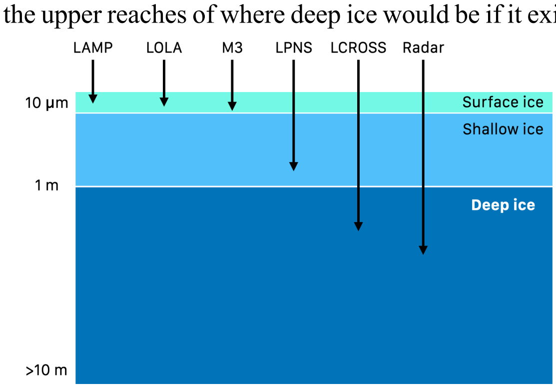

Fig. 1. Sensing depth of remote sensing techniques.

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.

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.

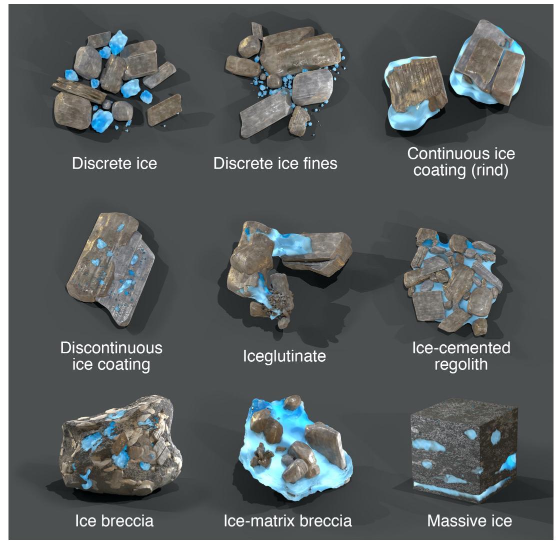

Fig. 2. Probable textures of water ice and regolith grains in lunar cold trap environments.

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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Refining the Concept of USGS Lunar Resource Assessments

L. Keszthelyi, T. S. J. Gabriel, L. R. Ostrach, and T. Crafford

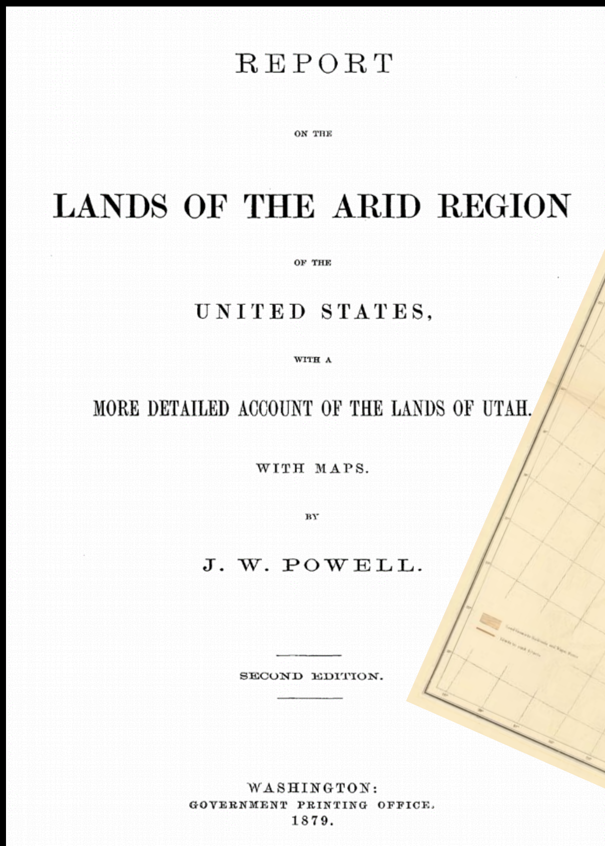
U.S. Department of the Interior
U.S. Geological Survey

Outline

- **Quick Recap**
  - USGS resource assessments
  - USGS extraterrestrial work
- **Lunar Resources**
  - Energy (solar and ^{3}He)
  - Minerals (regolith and ice)
- **Conclusions**
  - Landers should consider quality of existing topo maps
  - Useful regolith is essentially everywhere
  - We need *VIPER* to assess lunar ice

USGS

USGS: Doing resource assessments since 1879


REPORT

ON THE

LANDS OF THE ARID REGION

OF THE

UNITED STATES,

WITH A

MORE DETAILED ACCOUNT OF THE LANDS OF UTAH.

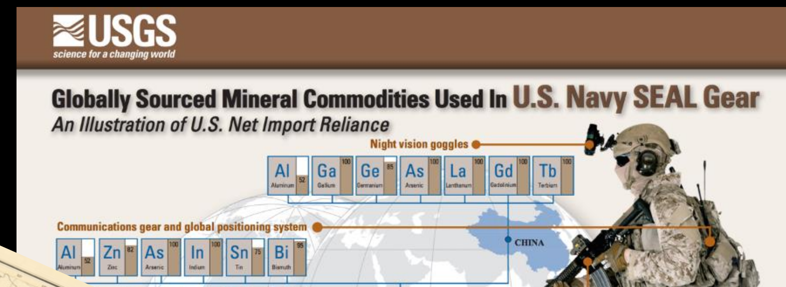
WITH MAPS.

BY

J. W. POWELL.

SECOND EDITION.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1879.

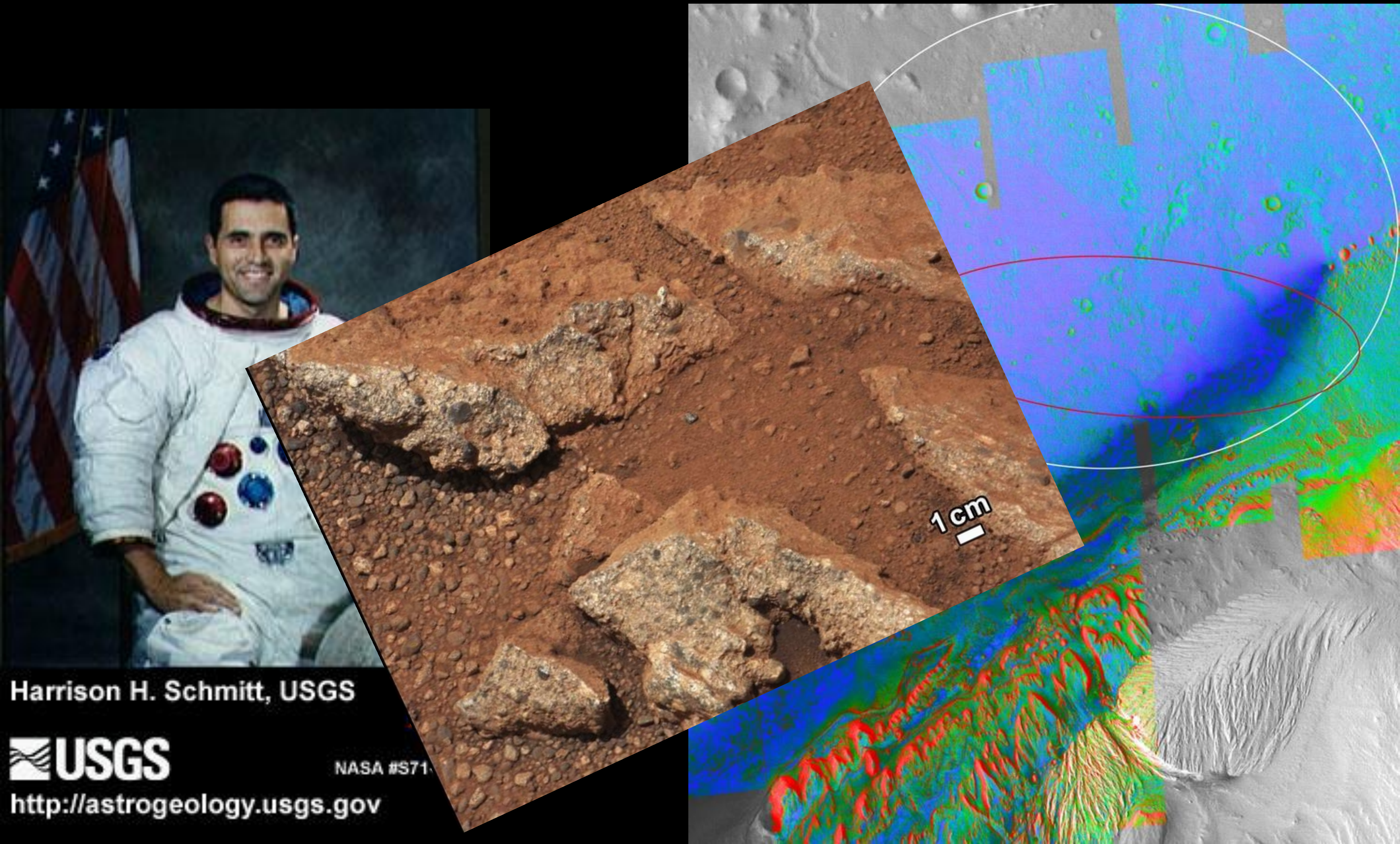


USGS

How does the USGS do quantitative resource assessments?

- **Key properties of USGS assessments:**
  - Openly available and unbiased
  - Quantitative but easy to understand
- **Composed of 5 parts (called 3-part)**
  - Descriptive Model of geologic processes
  - Spatial Model of areas to consider
  - Deposit-Density Model of deposits in study area
  - Grade-Tonnage Model of deposit population
  - Economic Model

USGS beyond the Earth



Energy

- **Solar**
  - Very low uncertainties except for topography on the scale of a lander.
    - *Positions of the Sun and Moon known, output of the Sun known, technology to collect solar energy known...*
    - *Peaks of (almost) Eternal Light near the poles!*
    - *Reliable topography at the scale of a lander (<1 m lateral and <0.5 m vertical) is lacking, especially near the poles.*
- **^{3}He**
  - Investigated by Jack Schmitt for fusion power
    - *Awaits industrial-scale fusion power plants*

Minerals (Regolith)

- **Useful!**
  - See many other talks and sessions!
    - *Construction (with and without additives)*
    - *Oxygen (the heavy part of rocket fuel)*
    - *"Metals" (waste from O_2 production)*
    - *Even some water! (Hibbits presentation this session)*

USGS

Minerals (Regolith)

- **We have a geologic model**

See, for example, Figure 4.22 from
Hörz et al (1991) Lunar Sourcebook

USGS

Minerals (Regolith)

- **We have (near) global data sets**

See, for example, the thermal inertia maps from *LRO* DIVINER
(Hayne et al. 2017, Fig 12)

Minerals (Regolith)

- **We have ground truth**

See, for example, figure 9.16 from Carrier et al. (1991**)**

Minerals (Regolith)

- **Extraction and processing technology is mid-TRL and maturing.**
  - See especially tomorrow’s “Extraction and Processing”and “Construction” sessions!
  - CLPS missions include demonstrations of regolith handling (e.g., SAMPLR)

USGS

Minerals (Regolith)

- **Is a formal quantiative assessment essential?**
  - Deposit density model is superfluous since there is a single global deposit (just avoid areas with ages less than 1 Ga)
  - Many processes use bulk regolith (i.e., 100 vol.%) so the concept of “grade” is largely superfluous
  - The regolith should be generally >5 m thick, which is deeper than one may want to dig so concept of “tonnage” is also pretty superfluous
- **Assessments most useful for**
  - processes that desire specific minerals (e.g., ilmenite)
  - local site studies to avoid steep slopes and small fresh craters

USGS

Minerals (Ice)

- **Not all water is in the form of ice!**
  - (e.g., Hibbitts talk this session)
- **Most like a mineral deposit on Earth**
  - Discrete deposits of variable size and quality
  - Formal assessment could be very useful
- **USGS methodology stuck at step 1**
  - We need a geologic model of how the ice got there!
    - *See Plate and Cannon presentations this session*
    - *VIPER is especially well-suited to solve this problem*
  - <u>There are other methods</u>, that do not rely on understanding the underlying geologic processes
    - *See Kleinhenz presentation this session*
    - *Still really want VIPER for ground truth*

USGS

Minerals (ice)

- **Spatial model (where ice is plausible) is OK**
  - Orbital thermal maps (LRO Diviner) give a sense of where ice is stable
  - Orbital epithermal neutron maps (LRO LEND) shows regions with near-surface hydrogen

Minerals (ice)

- **Deposit density and tonnage models missing**
  - The margins of a “statistically meaningful” number of ice deposits need to be mapped.
    - *Number depends on how variable they are and how many parameters influence the deposits.*
  - Plausible to make progress from orbit (e.g., Lawrence 2015) but ground truth is needed to determine the lower limit on deposit sizes
  - Also need depth to the bottom of the ice to get volume (tonnage)

Minerals (ice)

- **Grade model is missing**
  - Concentration of ice in the regolith is very poorly constrained by current data
    - LCROSS*: 5.6 wt.% H_2O ± 2.9 wt.% 1σ uncertainty means >100% uncertainty at 95% confidence level*
    - *Cannon talk this session will discuss more in detail*
  - Types and quantities of impurities are even less well constrained
    - *Many of the potential contaminants are toxic to humans and machines*

Minerals (ice)

- **Economic Model**
  - High uncertainty because technology is low TRL.
    - *To borrow language from the oil industry, need to define what constitutes a “technically recoverable” resource before we can talk about economic reserves*

Summary

- **Solar energy** does not need a USGS assessment but watch for limitations of high-resolution topography of the Moon
- **Regolith** is everywhere and useful but detailed local studies are important for specific ISRU technologies
- **Ice** assessments cannot be done reliably with the current data. The critical missing ingredient is statistically meaningful ground truth. ***VIPER*!**

USGS

WGM

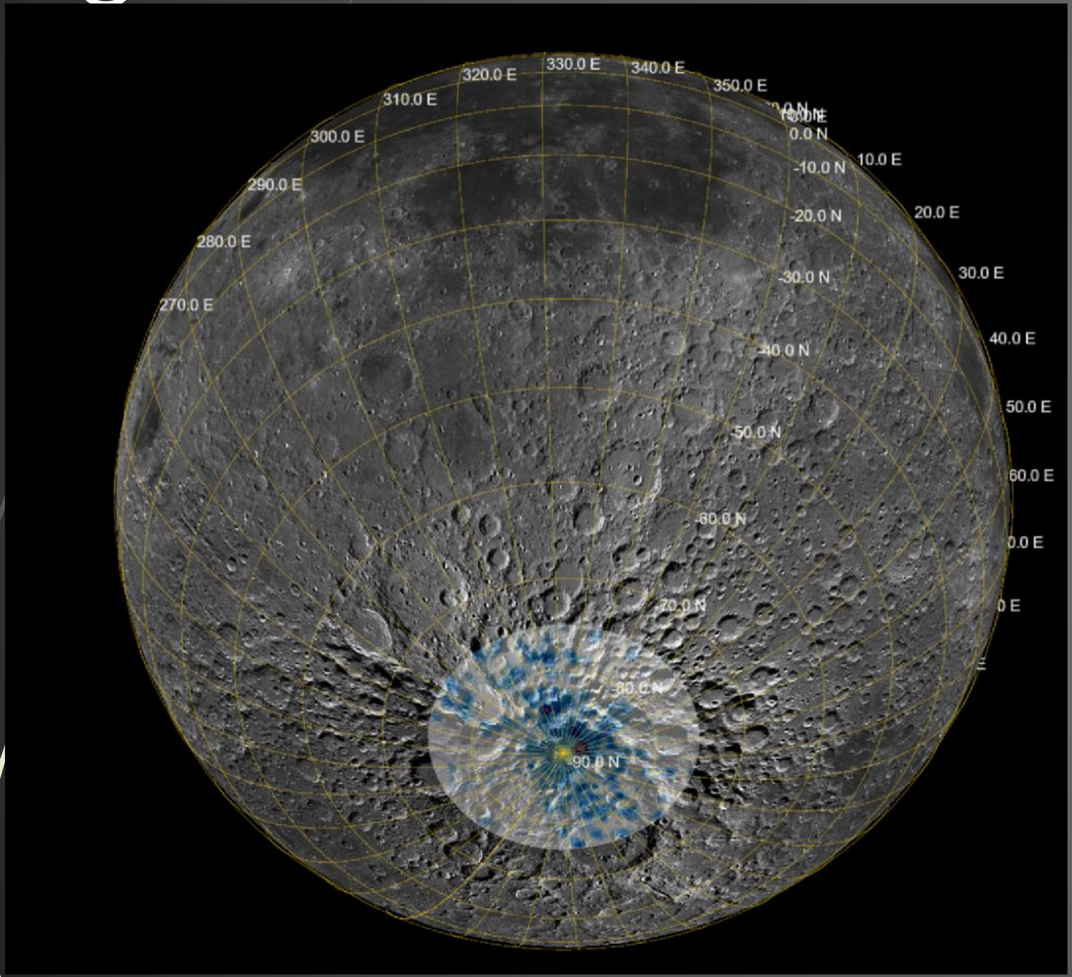
Water Works – Lunar Exploration Planning Group

Theoretical Lunar Water and Volatile Depositional Models

Water Works Members: G. Dave Keller, P.Geo, Jeff Plate, CFA, P.Geo, Nik Paskalev, M.Sc., Ricardo Franco, B.S.c, and Joe Hinzer, P.Geo

Special thanks to Emily Nield M.Sc. (Past Contributor)

Brief discussion of the origin of Lunar volatiles



Water Works Copyright@

Main sources:

- Carbonaceous chondrite asteroid and to lesser extent comet impacts forming transient volatile atmosphere.
- Volcanic activity venting volatiles as transient atmosphere.
- Solar/Earth wind implantation and micrometeorite impacts with lunar surface.

The importance of asteroid impacts forming transient volatile atmospheres (as summarized in Cannon and Brit, 2020) during a period intense meteorite impacts at orders of magnitude higher from current impacts, occurred from 4.5 to 3.5 Ga. Volcanic outgassing of volatiles has at levels of several magnitudes higher during approximately 3.8 and 3.5 Ga has been suggested by Needham and Kring 2017 and Needham et al, 2019.

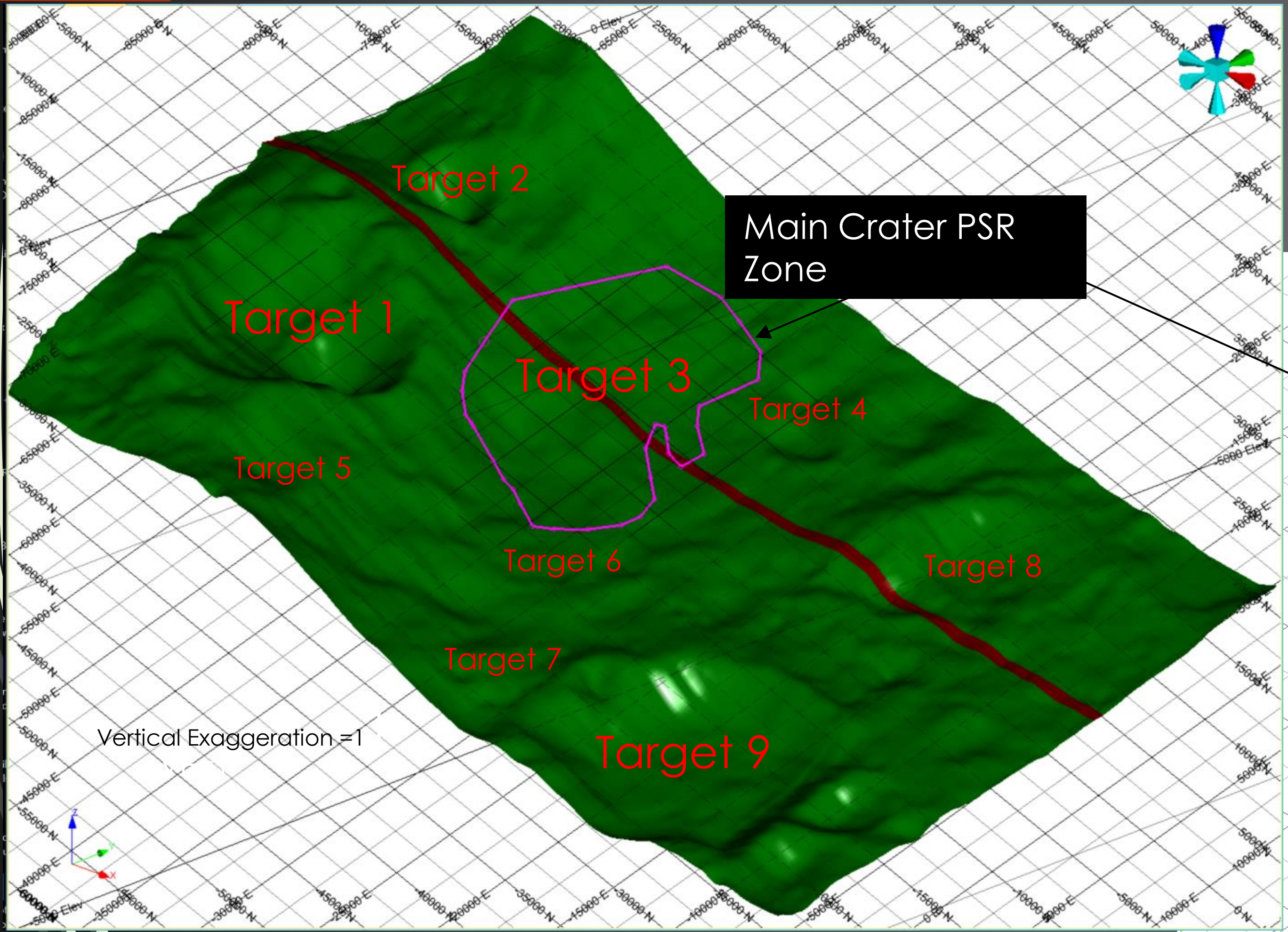
Either scenario is reported to account for theoretical quantities of lunar volatiles.

Solar wind implantation of H_2O and migration of H, OH and H_2O through ballistic hopping.

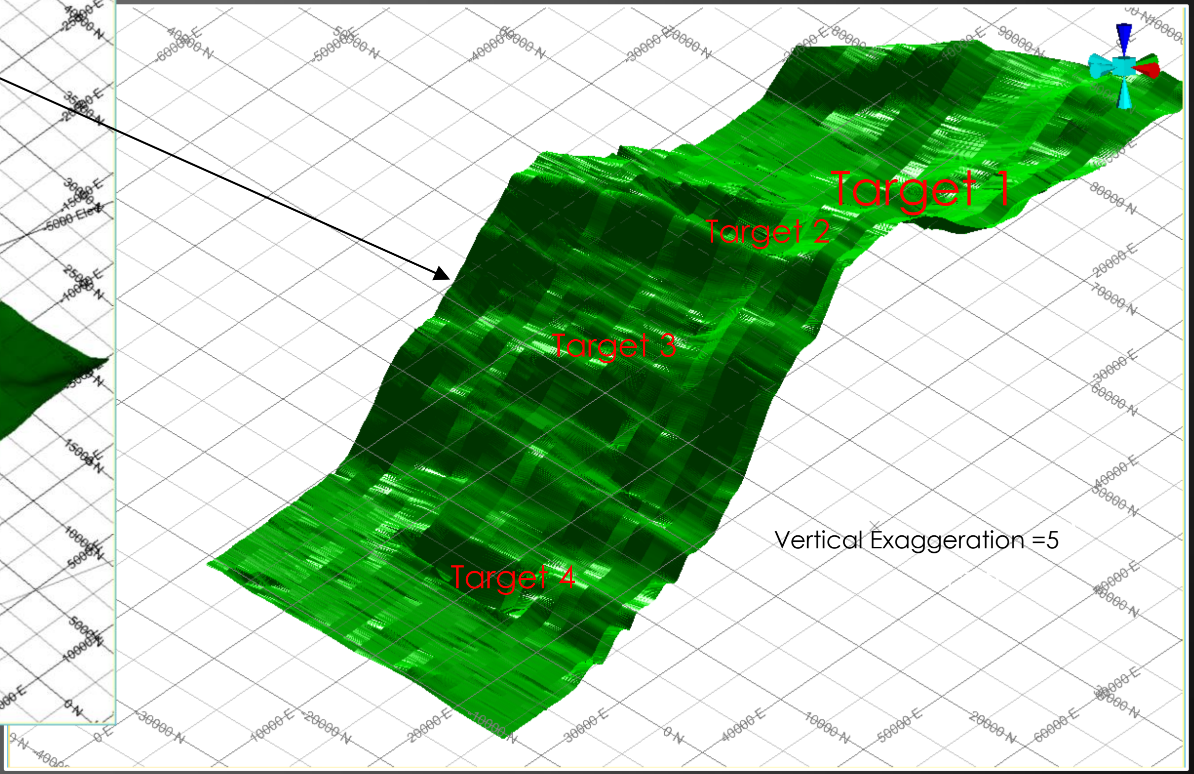
Exploration Targeting Domains

1. PSR zone type
   a. Crater PSR, encompasses much of crater
   b. Localized portions of crater PSR
      - Macro zone, nominally larger than 10^4 m^2
      - Micro zone, nominally less than 10^4 m^2
   c. SSR, seasonal shadowed region, may be adjacent to PSR
2. Geological
   a. Crater plain and walls
   b. Local gravity lows
   c. Geomorphological features
   d. Low slope angles, crater plain and local lows
   e. Relative geological age
   f. Super large scale geological features
   g. Crater sediment load estimation

PSR and Near PSR Target Identification



5x Vertical Exaggeration



Evaluation of Exploration Targets

1. Remote Sensing Data
   a) Chandryaan 1, Polar CPR
   b) Lunar Prospector, deconvoluted hydrogen
   c) LRO Diviner, polar temperature averages ~~an~~, minimums and maximums; paleo and current ice depth stability
   d) LRO LEND, polar water equivalent Hydrogen
   e) LRO Mini RF, Polar CPR
   f) LRO LOLA Slope
2. Other
   a) Crater sediment load estimate

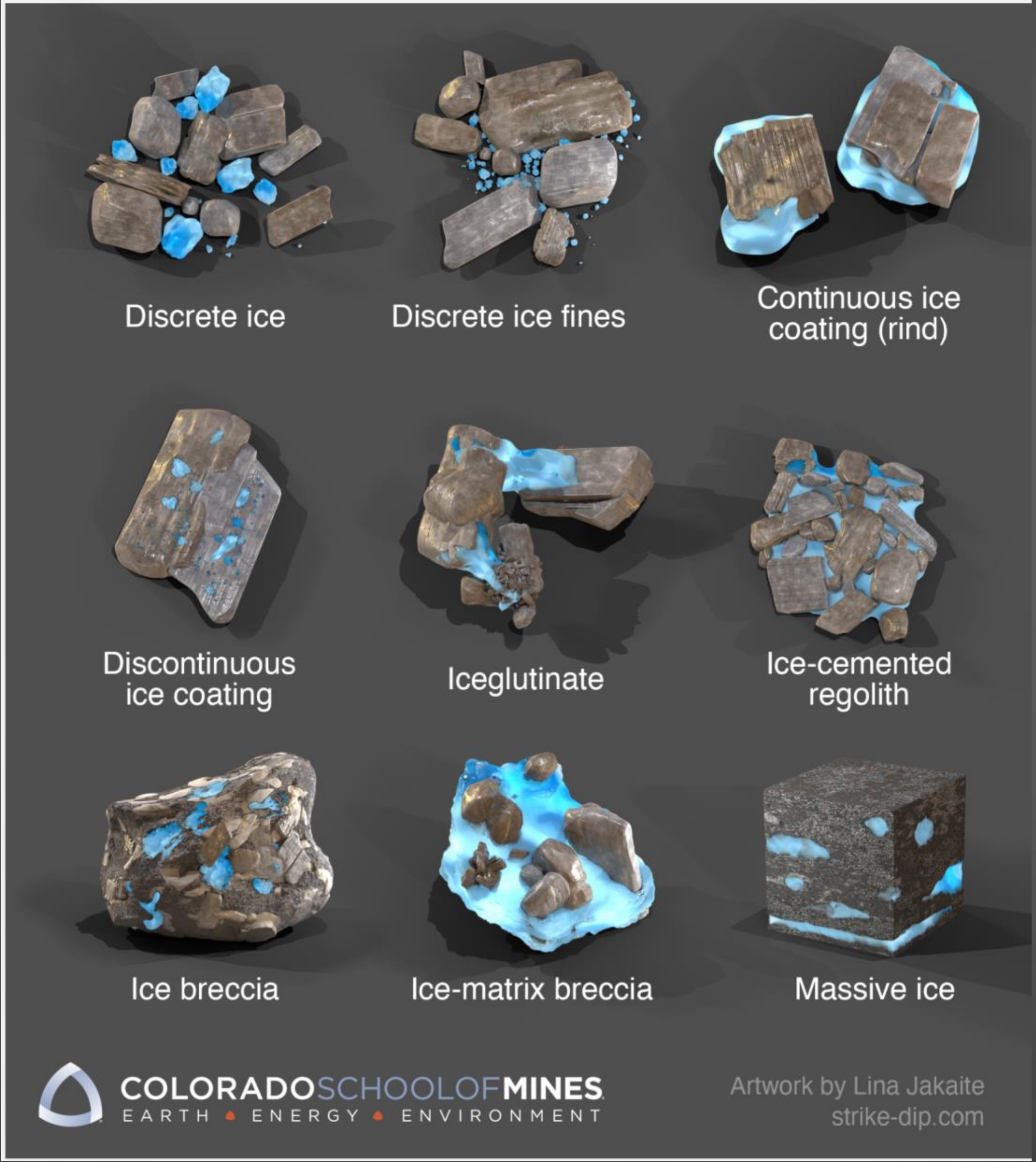
Target Ranking

1. Main craters
2. Inter crater areas
3. Regional

Lunar Deposits – Issues Unknown

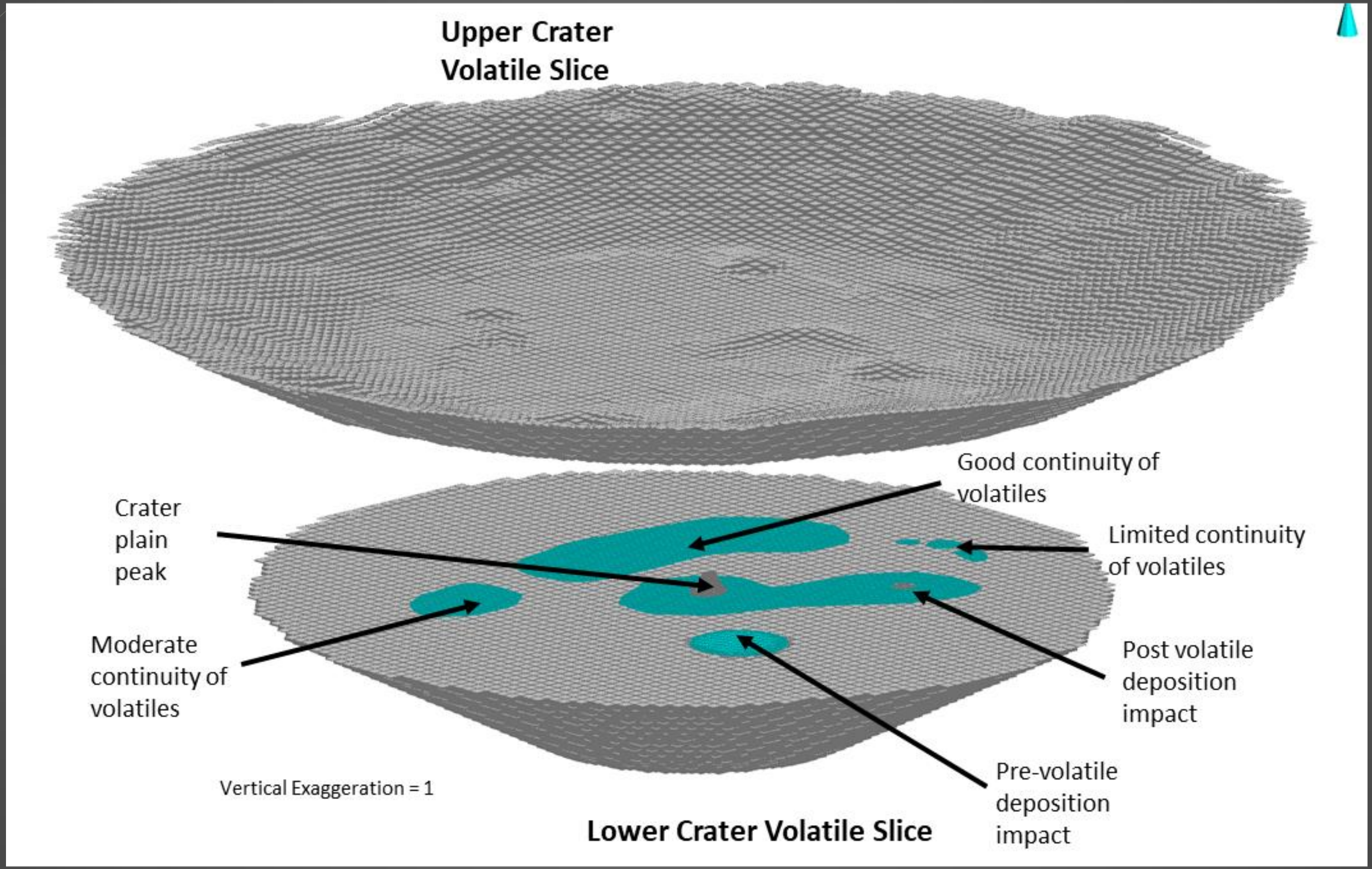
- Reworking and remobilization rates by meteorite gardening
- Geochemical interactions
- Effects of regolith blanket shielding
- Radioactive heating (cosmic rays or trace radioactive decay)
- Nature of the water and volatile deposits
- Continuity of volatile deposition and at micro and deposit scales

Potential Physical Textures of Ice and Regolith

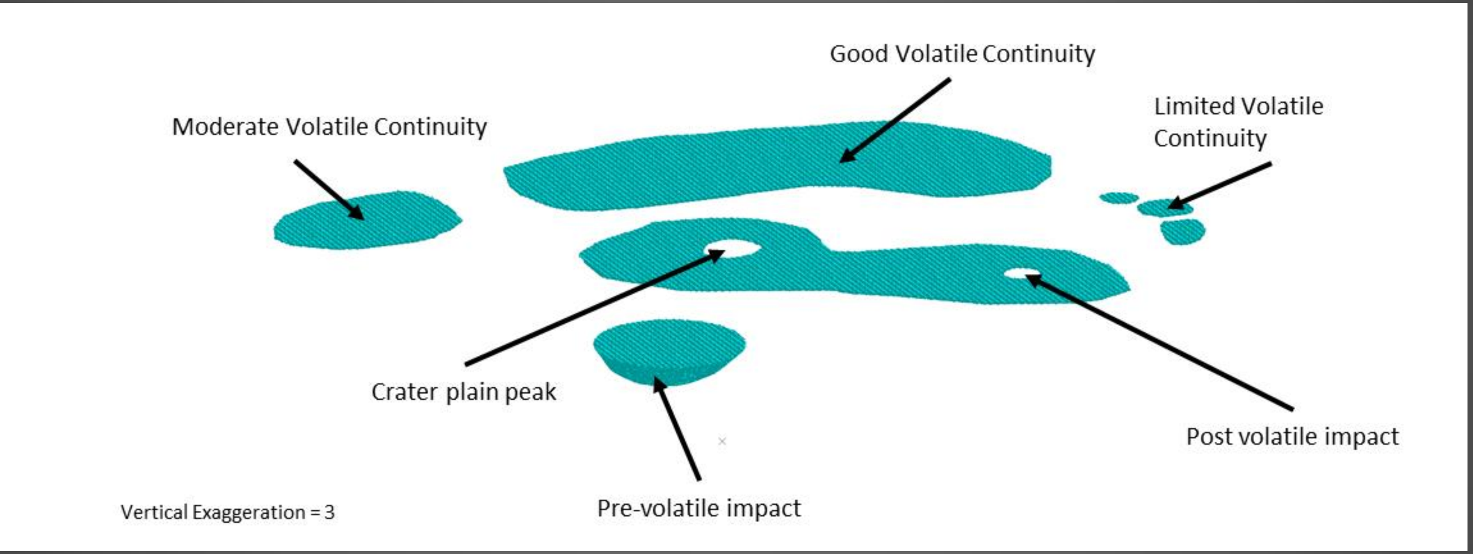


Lunar Mining & Landing Sites, Kevin M. Cannon, https://kevincannon.rocks/lunarmining

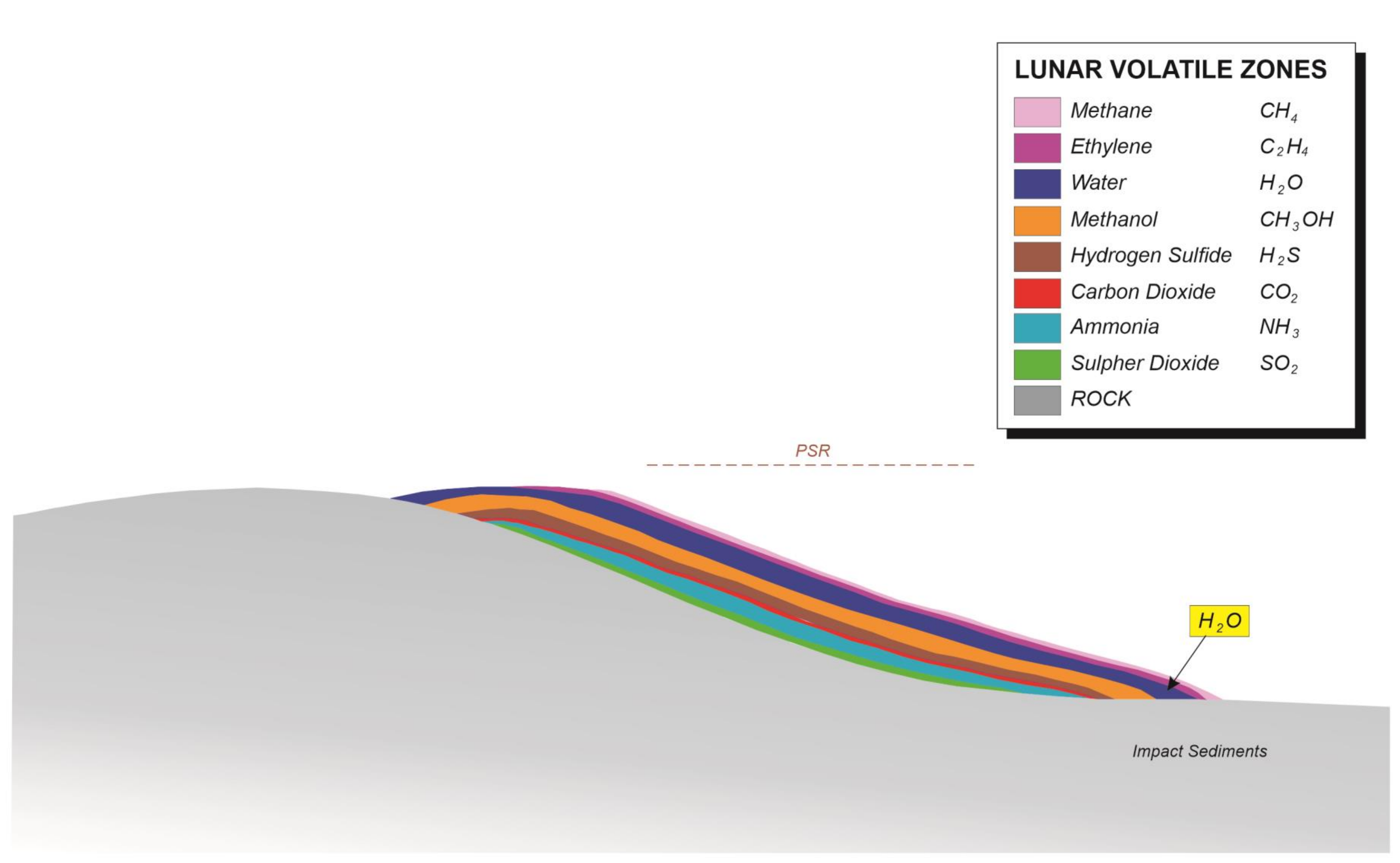
Possible Examples of Volatile Discontinuity Issues at Deposit Scale



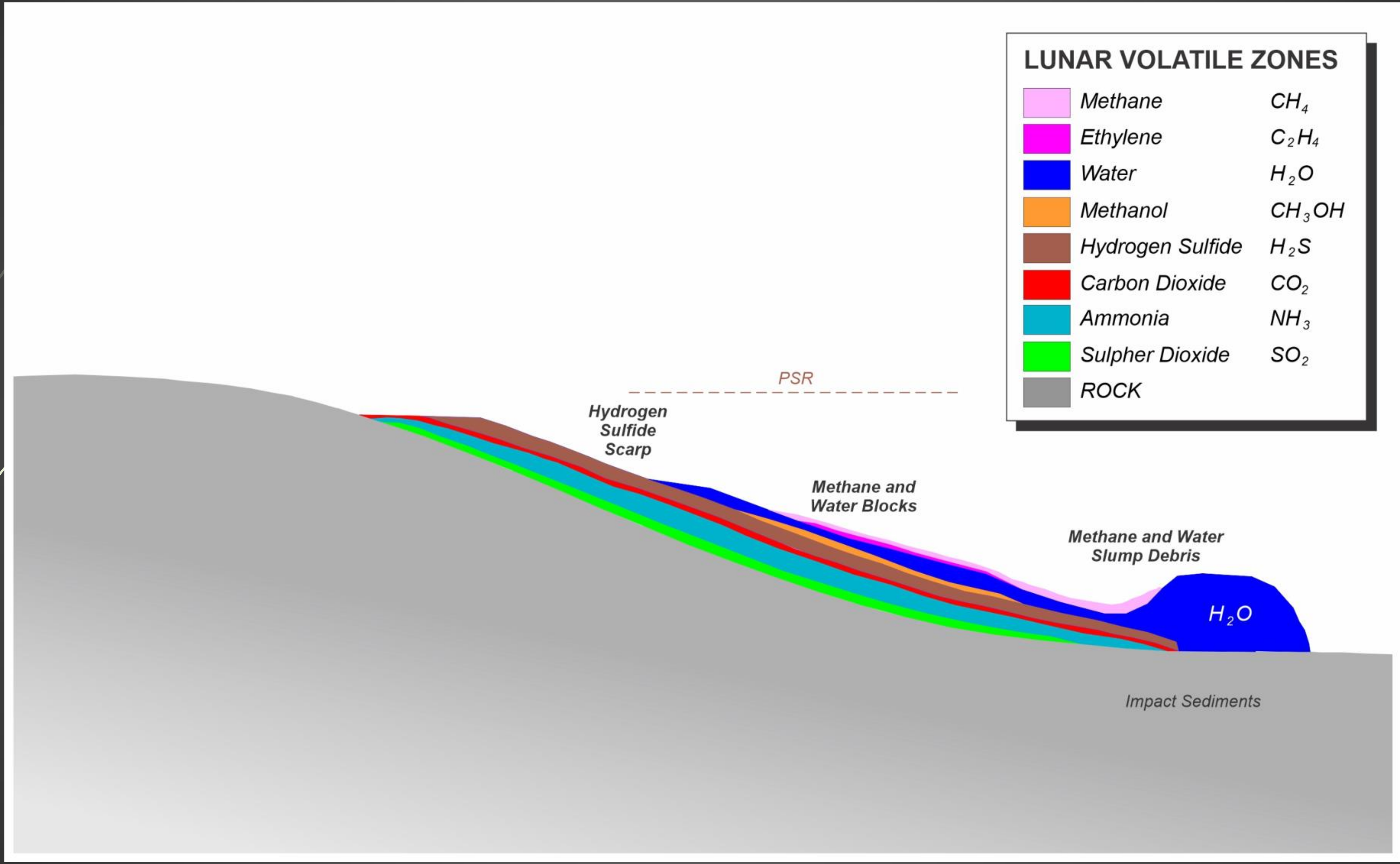
Large Scale Examples of Possible Volatile Discontinuity, Deposit Thickness Issues



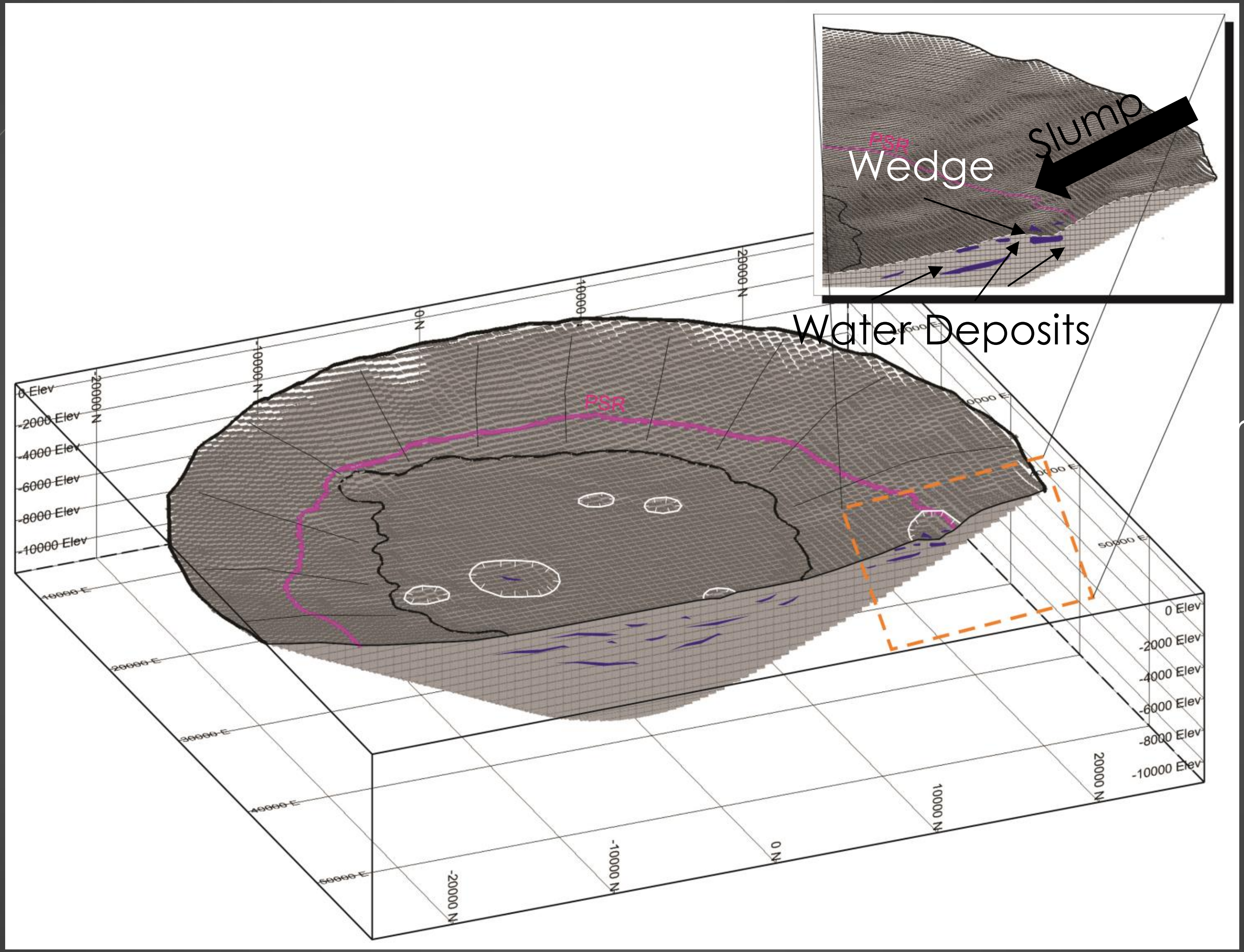
Zoning of Volatiles during Deposition



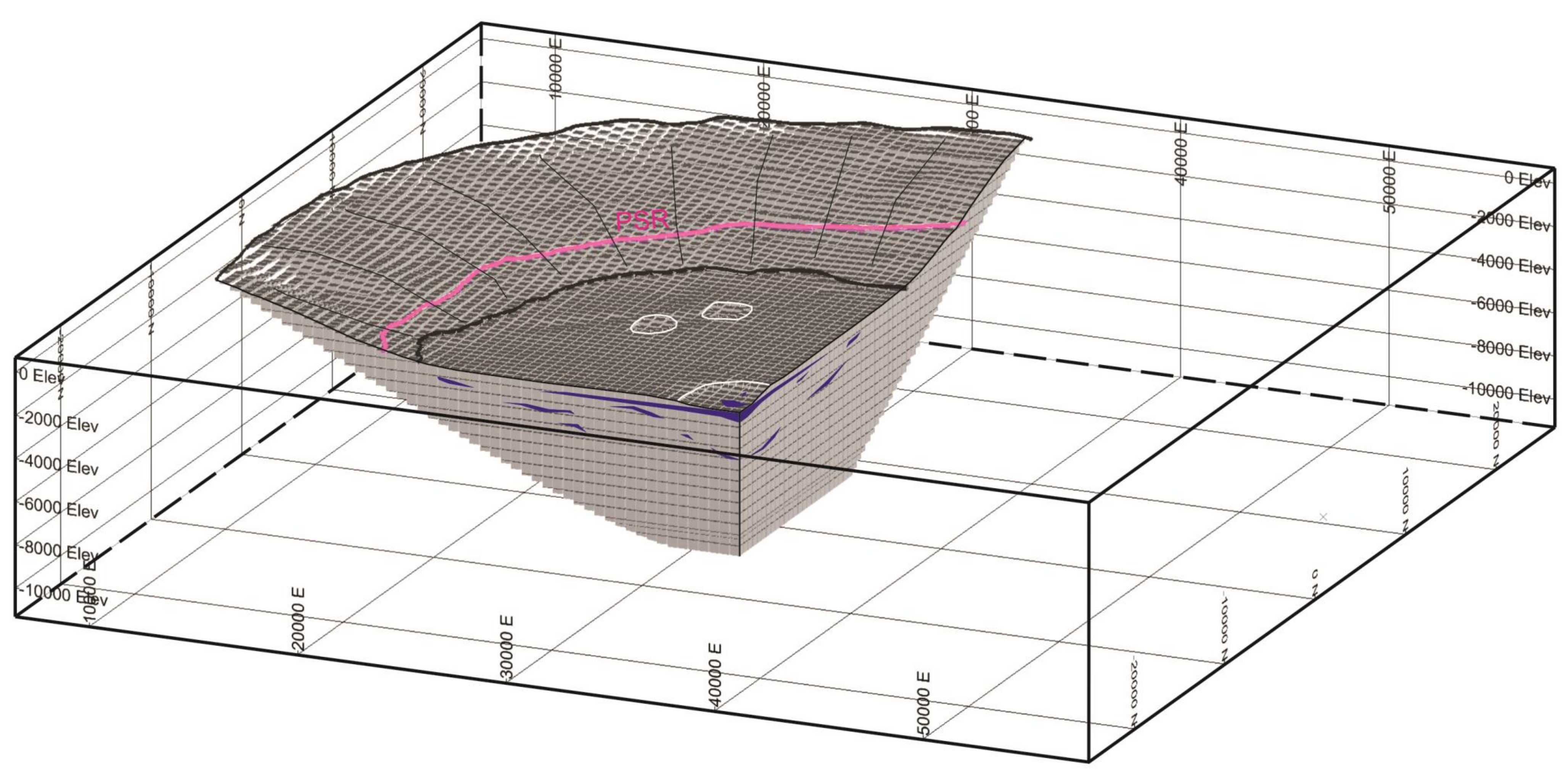
Slumping and competency of units



Wall Slump Volatile Deposit Type



Impact Excavated Volatile Deposit Type



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Cannon, Kevin M. and Daniel T Britt, 2020. A geologic model for lunar ice deposits at mining scales. Icarus no.347, 113773, p. 1-11.

Needham, D. H. and D. A. Kring, 2017. Lunar volcanism produced a transient atmosphere around the ancient Moon. Earth and Planetary Science Letters 478, 175-178.

Needham, D.H., Siegler, M., Li, S., Kring, D., 2019. Calculated thicknesses of volcanically derived water ice deposits at the lunar poles. In: 50th Lunar Planet. Sci. Conf., Abstract #1087

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

PTMSS/SRR

June 9, 2021

Julie Kleinhenz[1] and **Amy McAdam**[2]

Anthony Colaprete[3], **David Beaty**[4], **Barbara Cohen**[2], **Pamela Clark**[4], **John Gruener**[5], **Jason Schuler**[6], **Kelsey Young**[2]

[1]NASA Glenn Research Center, [2]NASA Goddard Space Flight Center, [3]NASA Ames Research Center, [4]NASA Jet Propulsion Laboratory / California Institute of Technology [5]NASA Johnson Space Center, [6]NASA Kennedy Space Center

Study Products

- This presentation is a subset of information from the full LWIMS and “LWIMS-B” Lunar Water Reference Case” studies

The full reports can be found:

- **LWIMS: https://ntrs.nasa.gov/search?q=20205008626**
  - Kleinhenz, J., A. McAdam, A. Colaprete, D. Beaty, B. Cohen, P. Clark, J. Gruener, J. Schuler, and K. Young, 2020, Lunar Water ISRU Measurement Study (LWIMS): Establishing a Measurement Plan for Identification and Characterization of a Water Reserve. NASA TM-2025008626

- **Lunar Water Reference Case Study**: **http://lsic.jhuapl.edu/Resources/files/Lunar%20Water%20Reference%20Cases%20Oct2020.pdf**
  - Kleinhenz, J., McAdam, A., Cannon, K., Colaprete, A., Siegler, M., Hurley, D., Gruener, J., Beaty, D., Metzger, P. Lunar Water Reference Case Study, 2020 http://lsic.jhuapl.edu/Resources/Community.php

Lunar Polar Water ISRU Measurement Study (LWIMS)

Background and Problem Statements

Background

Water identified in the permanently shadowed regions (PSRs) at the lunar poles can significantly enhance and enable lunar sustainability. But ISRU architectures (mining, conops, hardware design) requires knowledge of:

- Water content as a function of depth and area distribution (heterogeneity)
- Water form and energy to release from bound state
- The physical and mineral characteristics of the lunar regolith at mineable depths
- Topography and rock size distribution at potential mining infrastructure locations
- PSR environmental conditions

Problem Statements

1. Besides a single surface data point (LCROSS impact) there is significant uncertainty in the type, amount, physical parameters, and lateral/vertical distribution of water and volatiles in lunar PSRs
2. Before lunar ISRU water/volatile mining hardware and operations can even reach a preliminary design review, more ‘ground truth’ information on water/volatiles in PSRs is required.
3. While current and future lunar science instruments and missions can provide critical information, these science-focused efforts may not be sufficient for selecting mining locations, defining requirements for mining hardware designs, and planning mining operations

Water has been identified as a **RESOURCE**, but its potential for ISRU requires identifying and locating a water **RESERVE**.

Lunar Polar Water: Current knowledge state

Shallow bulk water is the target for ISRU.

- Potential lunar water sources include: surface frost, shallow bulk water, deep bulk water, and pyroclastic deposits
- There are 4 data sets for shallow bulk water (LCROSS, Chandrayaan-1, LRO, LP; see chart)
  - There are more data sets for surface frost detection (e.g., LAMP, LOLA and M3) than other data sets. While surface frost may be a geologic indicator of deeper water, there is currently no strong correlation between the two types of data sets (surface vs. buried reservoirs)

Water Equivalent Hydrogen (neutron spectroscopy) cannot give accurate concentration or depth distribution

- NS flux indicates there is hydrogen somewhere between the surface down to about 80 to 100 cm
- Conversion to WEH assumes uniform distribution laterally and with depth, and that all H is bound in water
- Is a function of assumptions regarding desiccated layer: concentration may be higher, but at depth

While regional distribution can be mapped from orbit significant local heterogeneity is expected

- Using Neutron Spectrometer: ~50 to 150 m (expected heterogeneity scale based on cratering statistics)

Radar data (CPR*) may suggest potential large volumes of water, but surface roughness can produce a similar signal.

Resolutions from current data sets are insufficient for Reserve definition.

- Reserve definition requires high resolution observation of a particular resource
- Current instruments and vantage points were designed with science objectives in mind.

Source	Sensing Depth	Resolution	Concentration	Extent	Comments
LCROSS	3 to 5 m	Single 50 m sample to 5 m deep	5.5 wt%, with other species	Single location	Consistent with the LP NS if distributed at 30% to 40% and/or buried under 10 to 30 cm desiccated layer
Chandrayaan -1 and LRO: RADAR CPR*	~1 to 2 m	150 m (baseline) up to 15 m (zoom- azimuth)	Wavelength scale ice blocks	Some PSRs	Source of high total volume estimates Could also be surface roughness
LP and LRO: Neutron count	0.8 to 1 m	LP: ~45 km at 30 km alt. LRO: ~75 km at 50 km alt. (STN) ~10 km at 50 km alt. (CSETN)-controversial	0.2 to several wt%	Poleward of 80°	Low resolution, deriving concentration depends on assumption of small scale and vertical distribution

*circular polarization ratio

ISRU and Science: Commonalities and Differences

EXPLORE MOONtoMARS

While Science and ISRU have common measurement needs that will support one another; distinct data sets are required for each.

ISRU Interest

Plan for interactions with engineered systems (physical properties)

Detect / locate water Reserves (mineable quantities)

Identify water, location, attributes and distribution

Predict potential Reserve locations

- Science objectives are broad, with a wide variety of data required to build knowledge about natural processes.

Identify water, location, attributes and distribution

Understand history and origin of water

Understand Natural processes

Compare to other celestial objects

- ISRU objectives are targeted; focused on applied outcomes. There is an essential relationship to engineering.

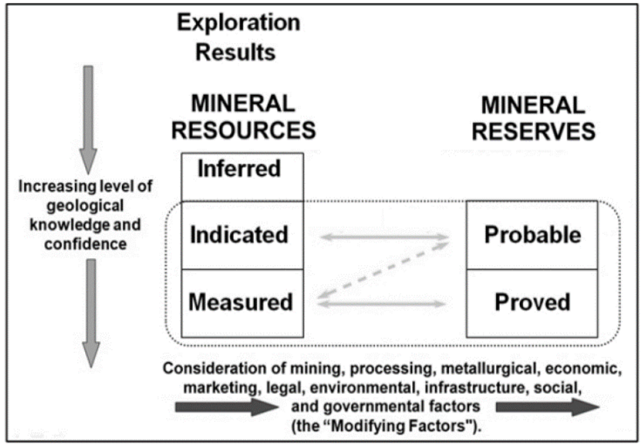
Critical Commonalities

Science Interest

Reserve Definition

Terrestrial Reserves

- Driven by **Economic** factors
  - Confidence in reserve is a cost trade:
    - Will a mine at the reserve site turn a profit?
    - Will a bank front the loan to start the mine?
- Exploration is known:
    - Geologic context is established
      - Models exist to map/define reserve
      - Measurements (model inputs) are defined
    - Measurement techniques (instruments, methods) are established and available
    - Exploration sites are (largely) accessible
- Exploration is an initial investment; consider cost benefit: confidence in profitability vs. up front cost
  - "Proven" Reserves vs. "Probable" reserves



Extraterrestrial reference Reserves

- Driven by **Mission Success** factors
  - Confidence in reserve impacts potential for mission success
    - Is engineering feasible and can the mission productivity goals be met?
    - Is production in critical path? (survival/productivity of crew, mission success)
    - Criteria for ISRU Reserve is listed on Slide 39
- Exploration is not established
  - Geologic context is not well understood
    - Models to predict or map/define reserve are in development
  - Measurement techniques are more restricted, potentially distinct from terrestrial options
  - Exploration sites are extremely difficult to access
- Exploration cost and timelines are much greater than terrestrial case.
  - Required confidence in reserve is therefore program dependent
  - Long term activity at extraterrestrial location will cause the terrestrial and extraterrestrial definitions to converge

Threshold Criteria for a Reserve

EXPLORE MOON to MARS

ISRU System	
ISRU Requirement	**Criteria**
Water Concentration	≥2 wt% to a 1 wt% detection limit
Water Depth distribution	5 to 100 cm, ≤10 cm increments
Overburden depth	5 to 50 cm ≤10 cm increments
Lateral distribution	500 m radius
Target yield	15 tons water per lander

- Criteria according to current ISRU system models which use current technologies and architecture concepts (Kleinhenz and Paz, AIAA ASCEND 2020)
- Criteria are highly dependent on:
  - Amount of consumables needed
  - Timeline allotted for ISRU production
  - Architecture interface to HLS (location of produced consumables, power)
  - Assumptions about mobility options and capabilities including autonomy and operational life
- Consideration to Oxygen from Regolith (O2R) as the alternative to water from ice
  - When possible, identify breakpoints where O2R is clearly advantageous over water from ice
- Additional knowledge to design ISRU systems and architectures (next page)

Human Landing Systems		
Lander Requirement	**Initial**	**Sustained**
Daylight Operations	continuous light	50 hours darkness (threshold) 191 hours (goal)
Surface Access	84° S to 90° S	global
Habitation Capability	two crew for 8 earth days	four crew lunar sortie with pre-emplaced surface infrastructure
EVA Excursion Duration	lasting a minimum of 4 hours	lasting a minimum of 8 hours
Landing Site Vertical Orientation	vertical orientation of 0 to 8° (threshold) and 0 to 5° (goal) from local vertical for surface operations.	
Landing Accuracy	landing within 100 m (3-sigma) of target landing site	
Surface Operations	operating on the lunar surface for a minimum of 6.5 Earth days	
EVA Excursions per Sortie	at least two (threshold) and five (goal) surface EVA excursions per sortie.	
Scientific Payload Return to Lunar Orbit	returning scientific payload of at least 35 kg and 0.07 m^3 volume (threshold) and 100 kg and 0.16 m^3 volume (goal)	

- For infusion of ISRU into Human campaign, the HLS site requirement must be considered
- ISRU reserves must have adequate proximity to HLS sites
- Information per HLS BAA Appendix H requirements

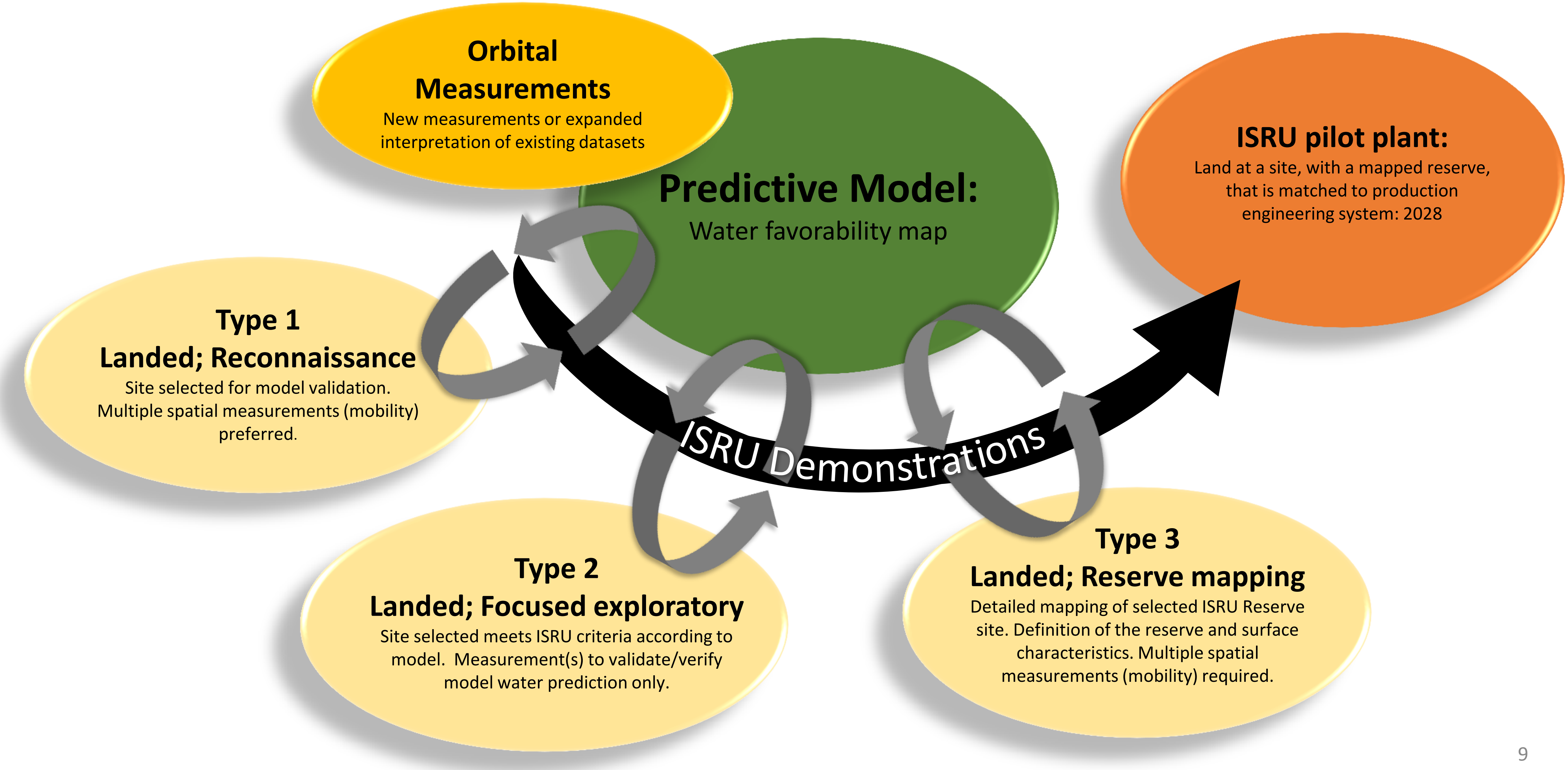
ISRU knowledge gaps

- The following information is required to design ISRU systems and architectures
- These parameters would not eliminate a site from consideration, but are key design parameters

Regolith reactivity	
Required Input	**Required Range (if applicable)**
Water Release Temperature profile (Release Energy and Quantity)	≤~200°C
Volatiles released at temperature H_2S, SO_2, NH_3, Hg, HFl; CO_2, CO	≤~200°C

Geotechnical properties	
Required Input	**Required Range (if applicable)**
Cohesive Strength (c)	0 to 100 kPa
Internal Friction Angle (Ø)	10° to 50°
Particle size distribution	1 to 1000 µm
Soil bulk density	0.5 to 2.5 g/cm^3
Compressive Strength	1 to 100 MPa
Terrain features including rock abundance	

Measurement Plan Structure



Proposed Polar Resource Measurement Plan

EXPLORE MOON to MARS

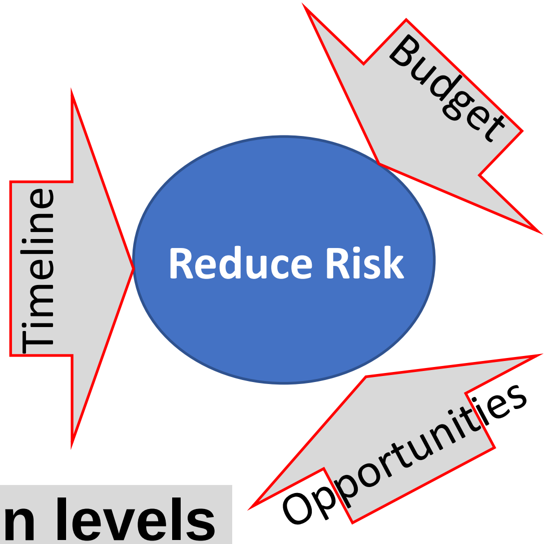
The **GOAL** of a measurement plan is to **REDUCE RISK** for an ISRU pilot plant
Increase confidence in water reserve; reduce uncertainties
Decrease hardware operational risks: designed for conditions

Polar Resource Measurement Plan includes a framework with the following:

- A detailed list of measurements with target detection ranges and accuracies
- A list of potential instruments that could achieve measurements goals, depending on mission constraints
- An iterative approach to obtain and evaluate measurement data to achieve target goals, based on risk postures

Definition of a Measurement Plan requires the following Constraints

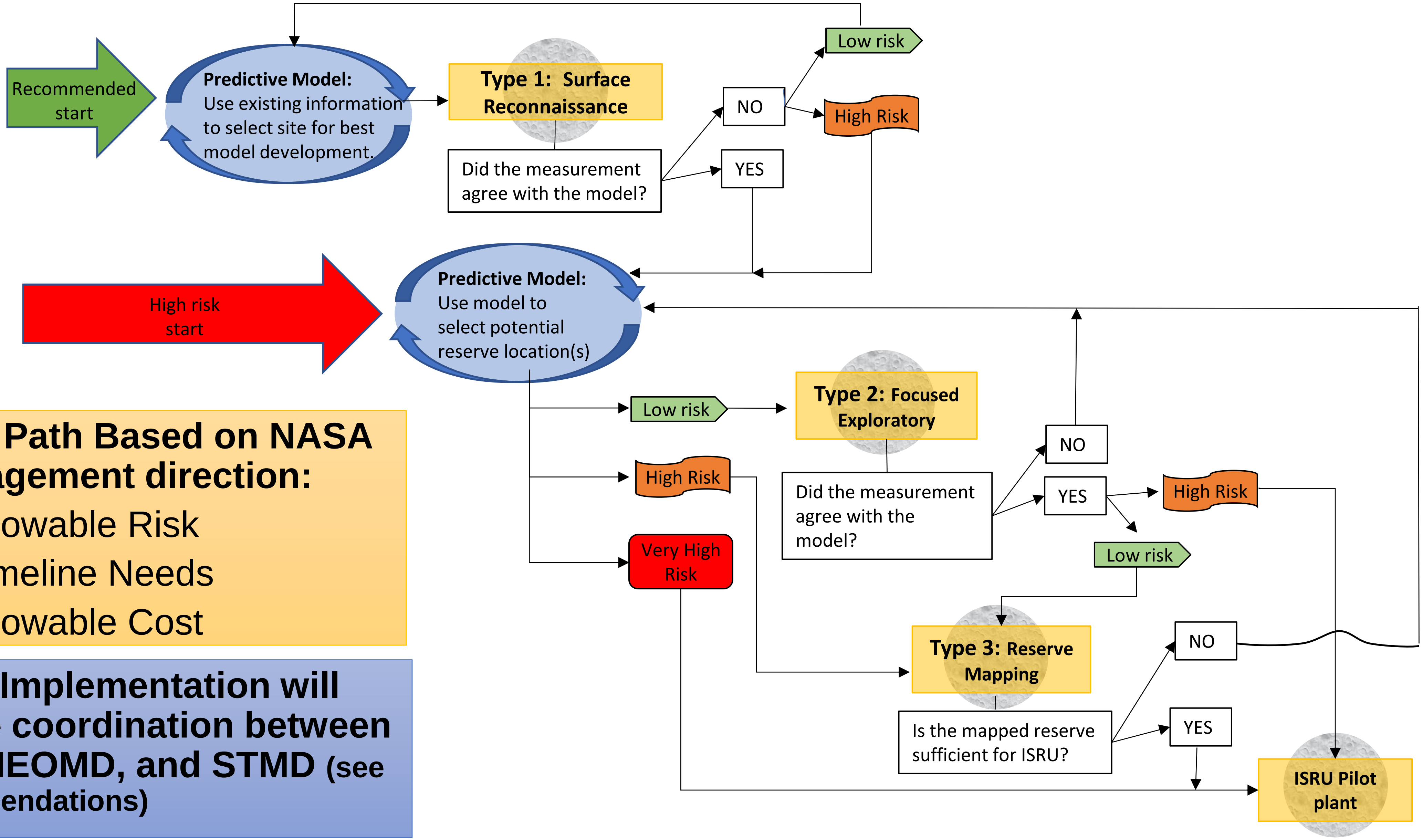
- **Timeline**
  - Need date for ISRU hardware (ISRU Pilot plant by 2028)
  - Instrument availability/development cycles
- **Mission opportunities**
  - CLPS payload selection and cadence of opportunities
- **Cost**
  - Instrument development and delivery (type/scale of missions)



Strategic and Tactical planning required at programmatic and mission levels

- Coordinated selection of instruments, sites, operational concepts, etc.
- Consideration on impact to plan due to mission failure or null results

Decisional Flow diagram



- **Flow Path Based on NASA Management direction:**
  - Allowable Risk
  - Timeline Needs
  - Allowable Cost

Actual Implementation will require coordination between SMD, HEOMD, and STMD (see Recommendations)

Type 1: Surface Reconnaissance

Measurement Definition

EXPLORE MOON *to* MARS

Measurement *(Relative priority from top to bottom)*	**Benefit**	**Potential approach(es) /platform(s)**	**Target measurement parameters**	***Example* method(s)/ instrument(s)**
Shallow (1 m) water horizontal and vertical distribution, abundance	Critical ISRU input. Even if not potential reserve site, data gained can be matched to orbital measurements for better interpretation and support of predictive modeling.	Active subsurface sampling from stationary or mobile platforms, with complementary sample analysis instruments.	Water abundance with vertical resolution <20 cm depth intervals to 1 m, 1% detection limit	Drill, scoop, or volatile drive off mechanism with attached analysis capability via Mass Spectrometer, Tunable Laser Spectrometer (TLS)
		In situ survey from network of small platforms equipped with cubesat-scale payloads, small mobile platforms, network of impactors, hoppers	Water abundance with vertical resolution <20 cm depth intervals to 1 m, horizontal resolution 50 m, to 1% detection limit	Miniaturized payloads (<10 kg) neutron spectrometer, ground penetrating radar, IR imager on mini-rovers
Potential ISRU contaminants (e.g., S compounds, HF, NH_3, Hg, organic compounds) in situ or in regolith	Neutrals and charged particles (generated from external or internal processes) could impact ISRU processing as an additional resource or a contaminant	Same as shallow water, active subsurface sampling with complementary payload or in situ survey	Element/compound identification (>1 to 100 Da or 150 Da baseline) and abundances (best effort)	mass spec, APXS/XRF (elements), LIBS (elements) for in situ analysis; mass spec with pyrolysis front end for analysis of sample; energetic neutral or charged particle analyzer

Findings

- **Current data sets are insufficient to define a reserve**
  - Identifying shallow bulk water can only be accomplished (currently) with NS (LRO,LP) and Radar (Chandrayaan-1 and LRO), but interpretation of data, particularly regarding distribution is inadequate
  - Coverage of this data at the Lunar poles and in PSRs is limited
  - LCROSS, while extremely valuable, was only a one point measurement

- **Schedule is a driver** (target: 2028 ISRU pilot plant), **which limits options** for instruments and implementation options.
  - May prefer reuse/re-flight of instruments hardware to reduce operational risk and improve data interpretation
  - Measurement plan (type and cadence) of missions must be reflective of Risk posture and results returned
  - Development of ISRU production systems have to occur in parallel with reserve identification to meet schedule; delaying measurements will result in less input to system design and result in higher hardware risk

- **Existing measurement techniques can achieve data needed, but must be adapted for lunar application**
  - Hardware (mobility, sampling, some instruments) must be adapted for operation in PSRs
  - Water quantification using heated sampling techniques, will likely provide highest accuracy, but are least developed for these applications

Recommendations

- **To meet aggressive schedule, a coordinated, focused effort must be implemented**
  - This impacts all Mission Directorate interests (STMD: ISRU hardware development, HEO: implementation of ISRU, SMD: volatiles measurements and overlap of science objectives)
- **Additional regional data sets (orbital)** including high spatial res Hydrogen maps, thermal, surface water detection **would be of high value to help reduce overall risk/uncertainty**
  - Missions (LunaH-map, Lunar Flashlight and the Lunar Trailblazer concept) should all go forward
- **Support ISRU relevant instruments in PRISM and LuSTR programs** (or similar) for advancement of ISRU technologies.
- **Recommend 'Best' Path based on Low to Moderate Risk is:**
  - Proceed with currently planned cubesat and smallsat missions to advance orbital/regional data sets
  - Support development of predicative model capability asap
  - Perform VIPER as planned for first Type 1 mission
  - Perform a minimum of 3 landed exploration missions: a Type 1, Type 2, and Type 3
- **Future Work Recommendations**
  - Establish a multi-discipline standing group and follow-on activity(s) to support coordinated measurement strategy
    - Coordinate activities across NASA mission directorates with clear handoffs
    - Consensus on extraterrestrial "reserve' definition, evolving evaluation
    - Focused effort to develop and update predictive model capability

Study Products

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Western
Institute for Earth
& Space Exploration

Multispectral Imager With Active Illumination For Resource Prospecting With A Lunar Micro-Rover

Jayshri Sabarinathan[1,2], Aref Bakhtazad[1,2], Gordon Osinski[1,3], Eric Pilles[1,3], Livio Tornabene[1,3]

Contact: jsabarin@uwo.ca

[1]Institute for Earth and Space Exploration
[2]Department of Electrical and Computer Engineering
[3]Department of Earth Sciences
The University of Western Ontario,
London, Ontario, Canada

Planetary and Terrestrial Mining Sciences Symposium, June 9, 2021

Outline

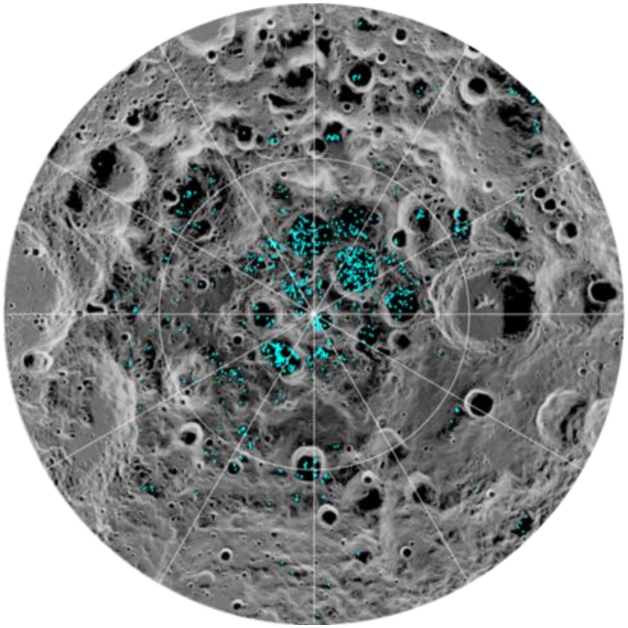
- Overview
- Scientific goal and objectives
- Current MSI instrument development
- AI-MSI Operational concept
- AI-MSI base specifications
- Conclusion

Overview

- A compact multispectral imager with active illumination source (AI-MSI) which can be interfaced with a lunar micro-rover for detection and characterization of:
  - Water ice,
  - Olivine,
  - Pyroxene,
  - Plagioclase,
  - Spinels, and
  - Lunar glasses

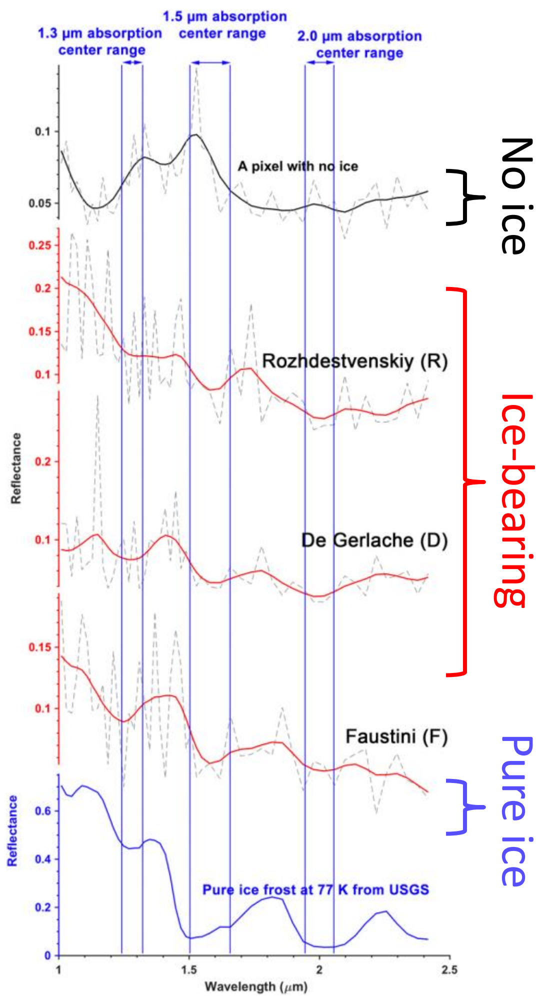
The significance of Permanently Shadowed Regions (PSRs)

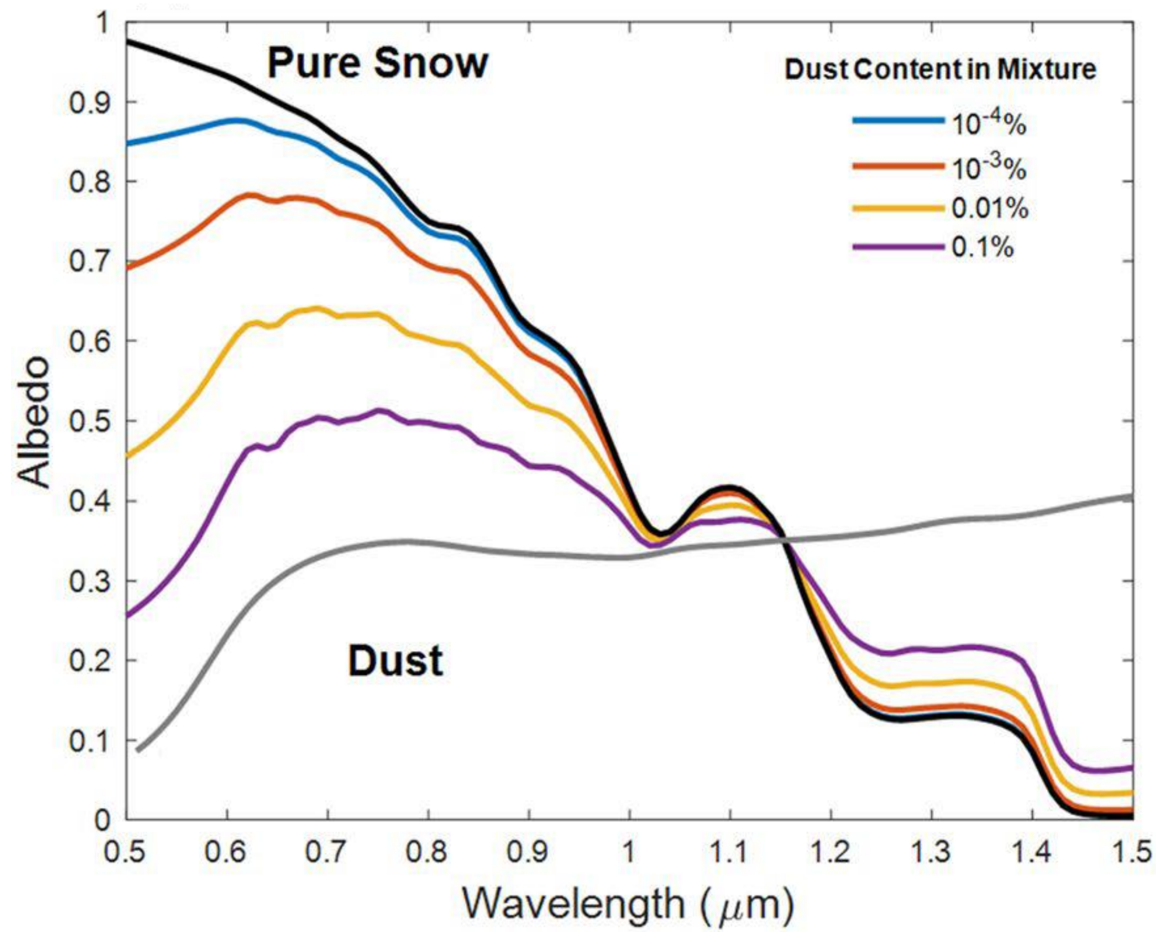
- Potential water ice and other volatile components have been identified from orbit in PSRs on the Moon
- Many fundamental aspects of lunar PSR water are not well understood, including: its existence, distribution, and characteristics
- Surface studies may be necessary to place constraints on the nature of the water ice



Distribution of lunar surface ice at the Moon's poles detected by NASA's Moon Mineralogy Mapper Instrument
Image credits: NASA

Detection of ices with M3 orbital data (left)
The non-linear impact on spectra of ices due to mixing (right)

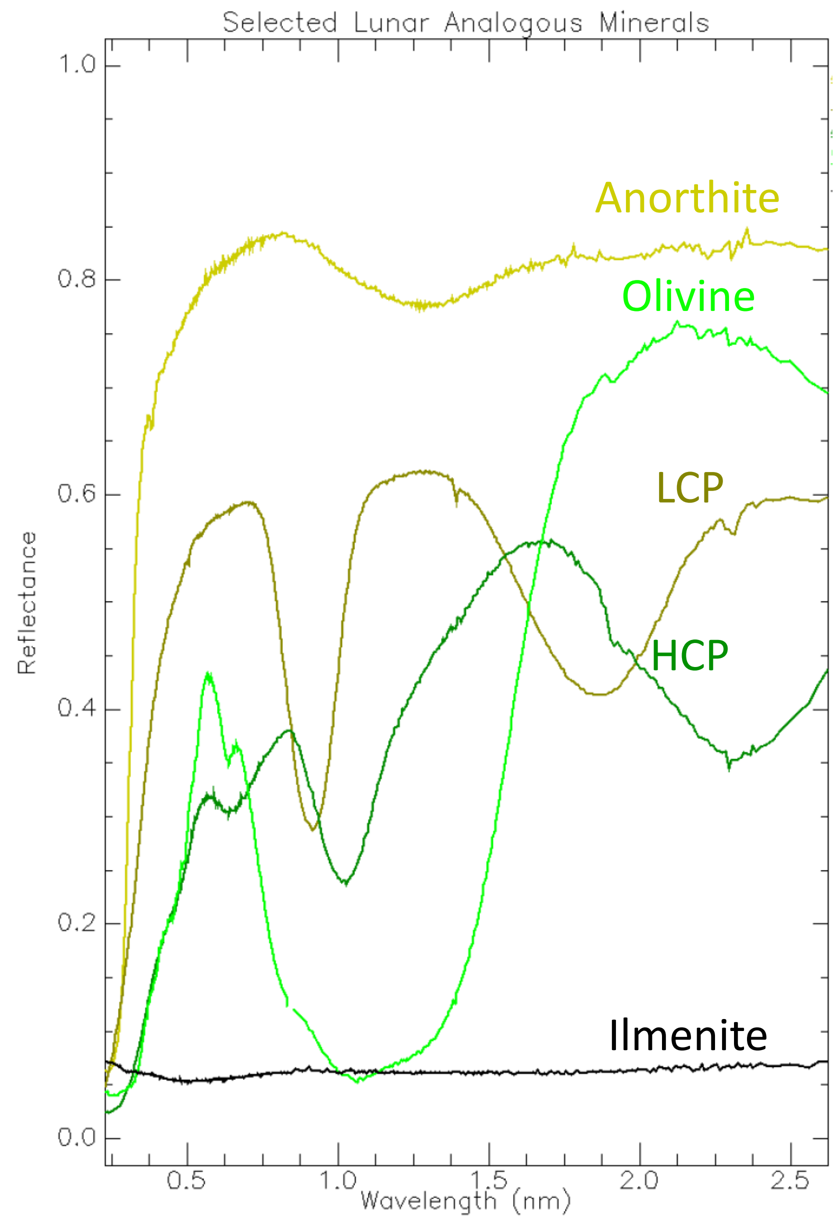




Right: Rai Khuller, et.al, 2021. Journal of Geophysical Research: Planets, 126(2), p.e2020JE006539
Left: Li, S et.al, 2018, Proceedings of the National Academy of Sciences, 115(36), pp.8907-8912

Characterizing lunar rocks

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

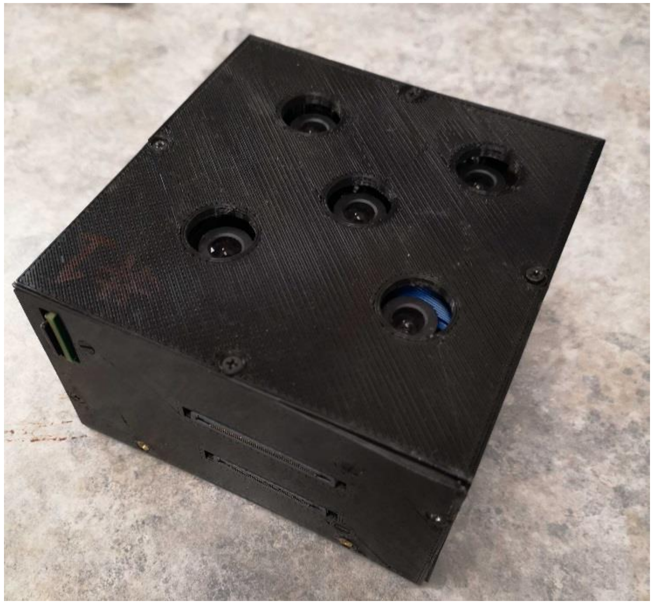


AI-MSI Goal: Evaluate the ISRU potential of permanently shadowed regions of the lunar poles

1. Characterize the composition of rocks and regolith within PSRs
    - Filter selection based on common lunar minerals (anorthite, olivine, LCP, HCP)
2. Characterize the texture and grain size of regolith/rocks within PSRs
3. Identify ice within PSRs
    - Potential spectral features observable in VIS-NIR range (<1000 nm)

Western-A&L current VIS/NIR multispectral Camera

- This camera's features
  - is 10cm x 10cm x 6cm in size,
  - Mass of 300g
  - Power consumption of only 4W.
  - Uses five 1/3" silicon sensors (four mono, and one color).
  - It uses a patented mipi switching scheme.
  - It incorporates QUALCOMM Snapdragon 410 processor.
  - **In pre-production stage**



- *The module has been calibrated and field tested successfully on various conditions, and*
- *The spectral response was superior to leading commercial one.*

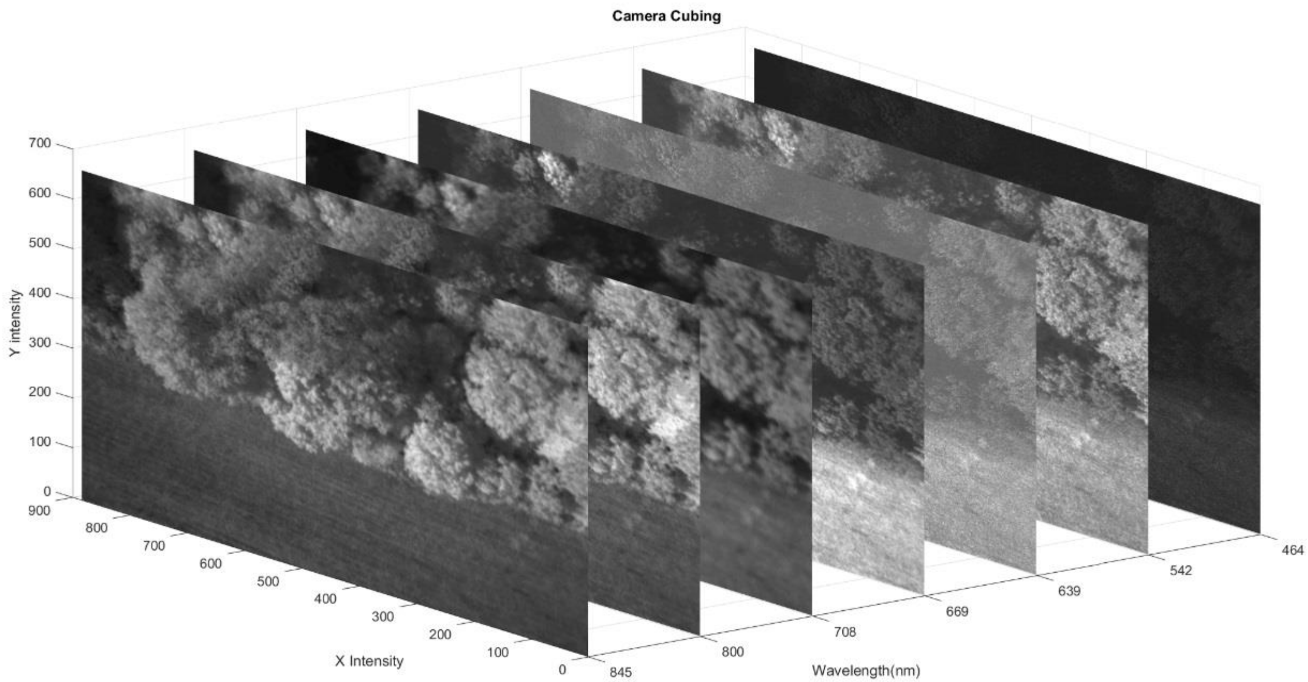
LightSail Next Generation VIS-NIR Multispectral Camera

- This camera's features
  - is 8cm x 8.2cm x 6.1cm in size, has 300g of mass and power consumption of only 5W.
  - Uses five 1/1.8" silicon sensors (four mono, and one color).
  - It uses a patented mipi switching scheme.
  - **In prototype stage**

- *The new module will increase the camera FOV by about 30 degrees, maintain the same resolution as the current module.*
- *The unit volume will decrease by about 30% too.*

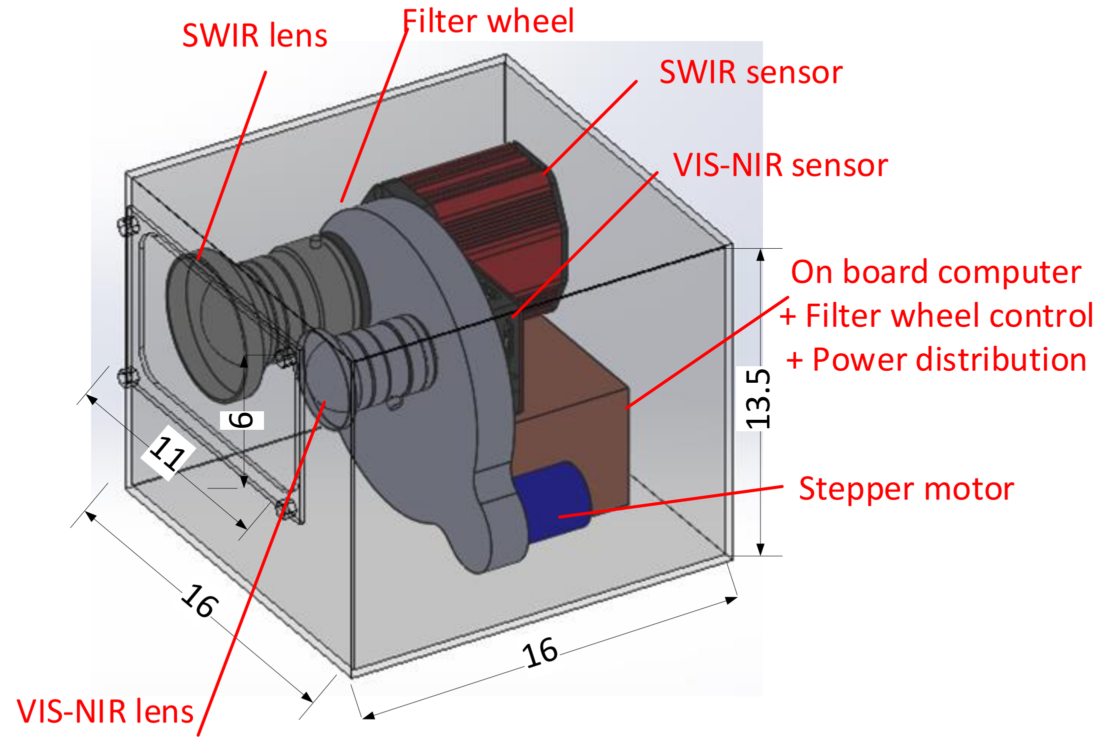
Image Cubing Data Product

- Images from multiple sensors have been registered by post processing (we have a good experience of registering images in our current multispectral camera).



Integrated Vision System (IVS)

- IVS is a stand-off instrument that would be mounted on a rover mast for exploration of the lunar surface.
- The instrument integrates:
- A multispectral imager (MSI) and
- A multispectral LiDAR
- CSA funded contract to Western University and with partner MDA



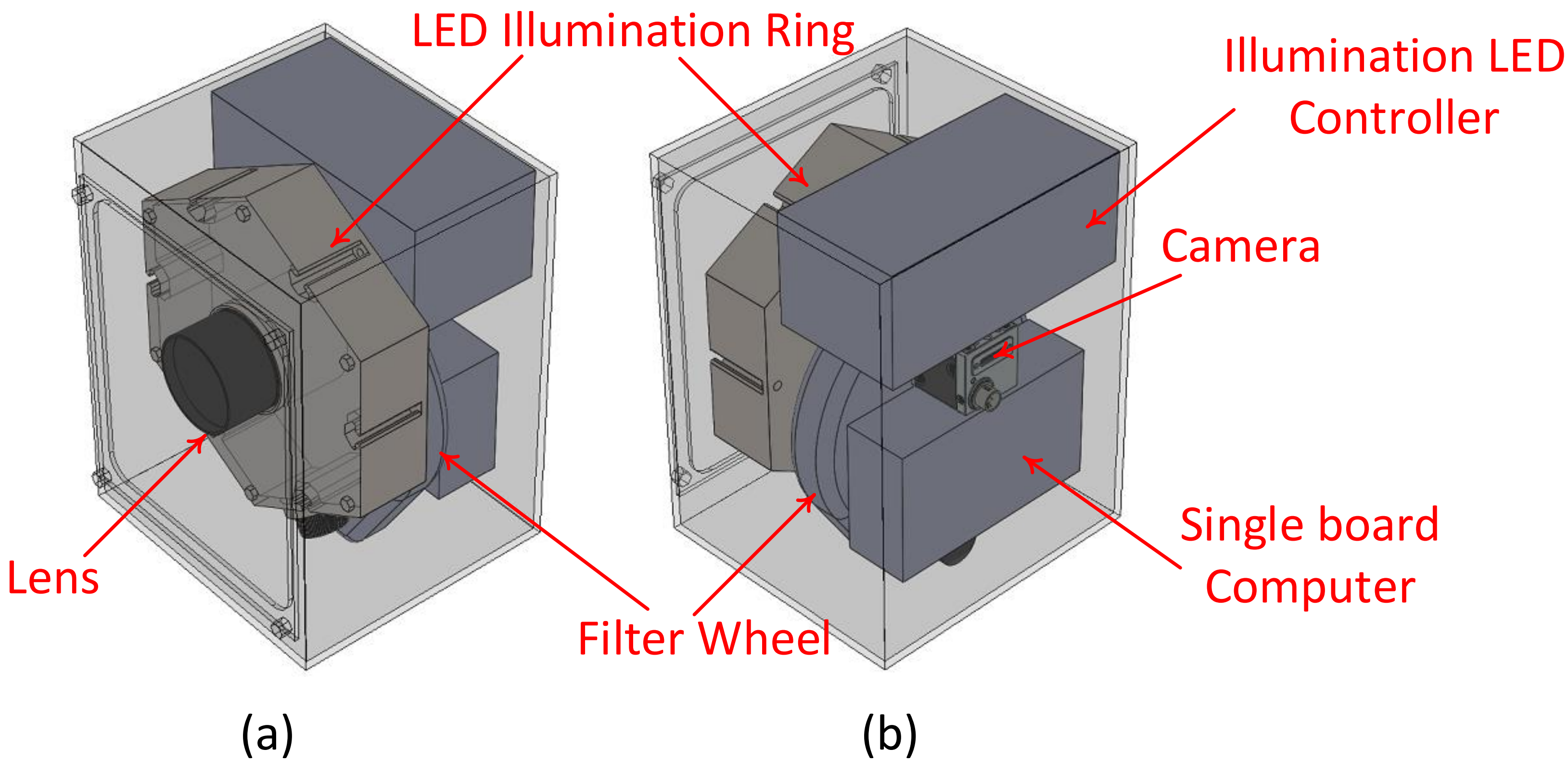
- The MSI unit includes:
- A Silicon image sensor and an InGaAs image sensor,
- A filter wheel, and an on-board computer

Western Institute for Earth & Space Exploration
MDA

Operational Concept of AI-MSI

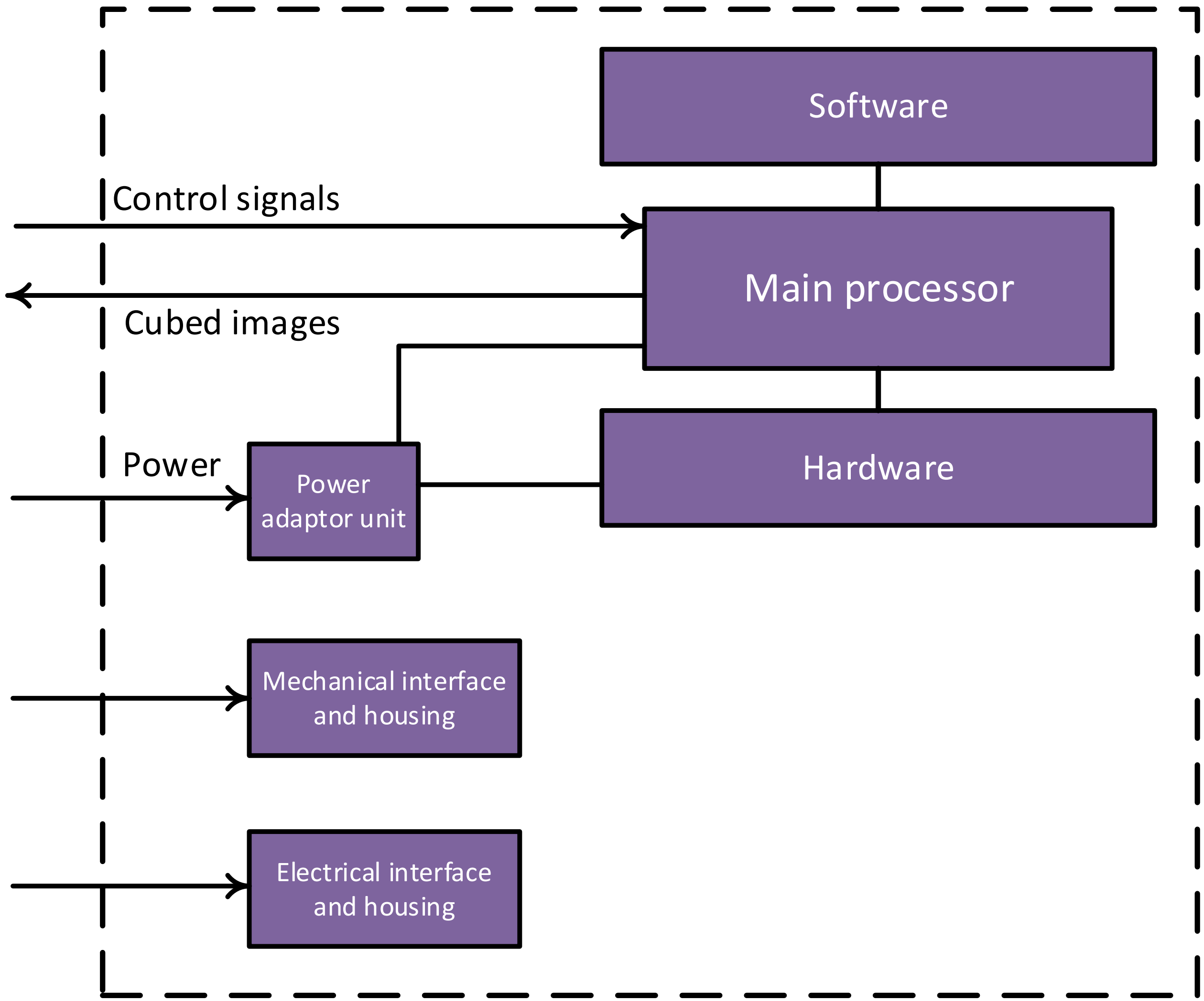
- The AI-MSI is designed for micro-rover class of vehicles (mass less than 3kg) for lunar exploration.
- It integrates:
  - A multi-spectral imager (MSI),
  - An LED light source module in flash mode, and
  - On board processor
- The imager is uncooled silicon sensor with spectrum coverage from 350nm to 1100nm.

Concept Model



- The AI-MSI instrument will be mounted on the mast of a micro-rover at a specific height and tilted downward.

AI-MSI subsystems



Mission Requirements

- The instrument can be used for scientific 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).
- 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 processing and communication system.

AI-MSI main specifications

Parameters	Values
Resolution at 2m	~2mm
Mast height	1.5m
Camera-mast angle	55.6^o
Imaging range	0.75m – 2.1m
Imaging span	81cm-99cm
Spectral range	350nm to 1100nm
Imaging time for each waveband	~1 second
Power consumption	~20-30W (depends on flash mode operation)
Operating temperature	0 to 45^{o}C
Non-operating temperature	–40^o to 60^{o}C
Weight	<3kg

- Thermal management power budget is not included.

Summary

- 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.
  - Additionally, it can provide multispectral images when 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.

Acknowledgements

Western Institute for Earth & Space Exploration

CSA ASC

MDA

NSERC CRSNG

OCE Where Next Happens

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

Ontario Research Fund

CMC MICROSYSTEMS

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Lunar Surface Innovation
CONSORTIUM

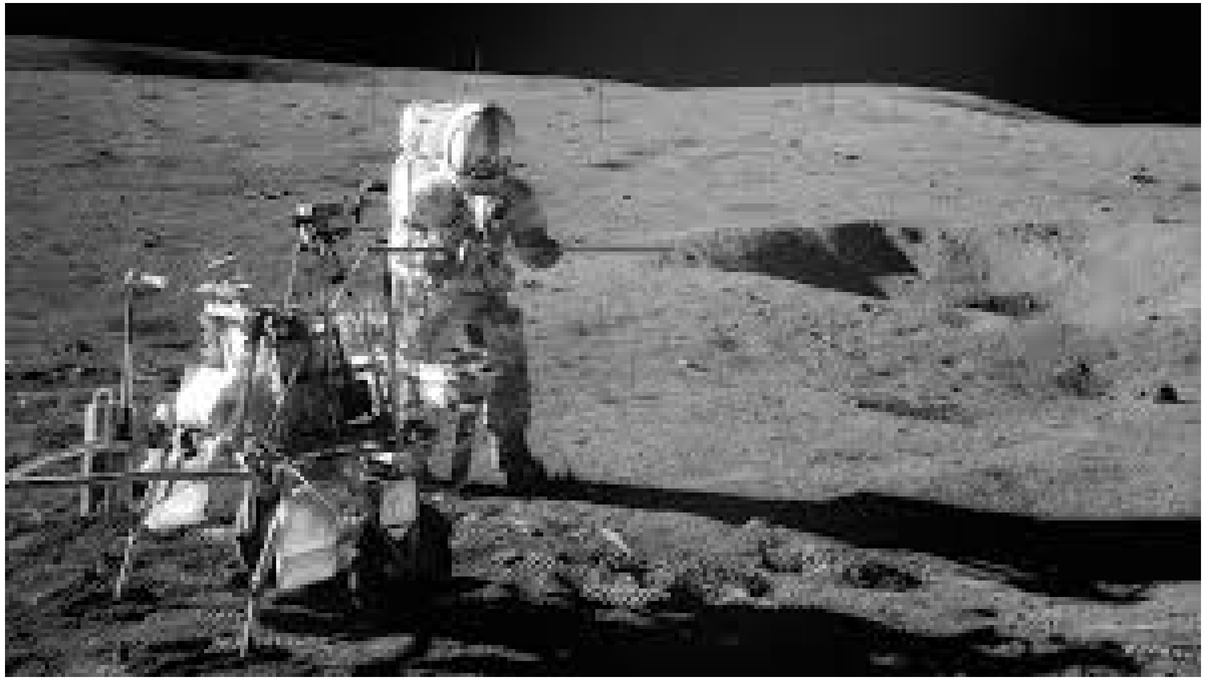
An Evaluation of the Water on the Illuminated Moon as an In-Situ Resource

C. A. Hibbitts, K. Runyon, M. Nord
JHU-APL

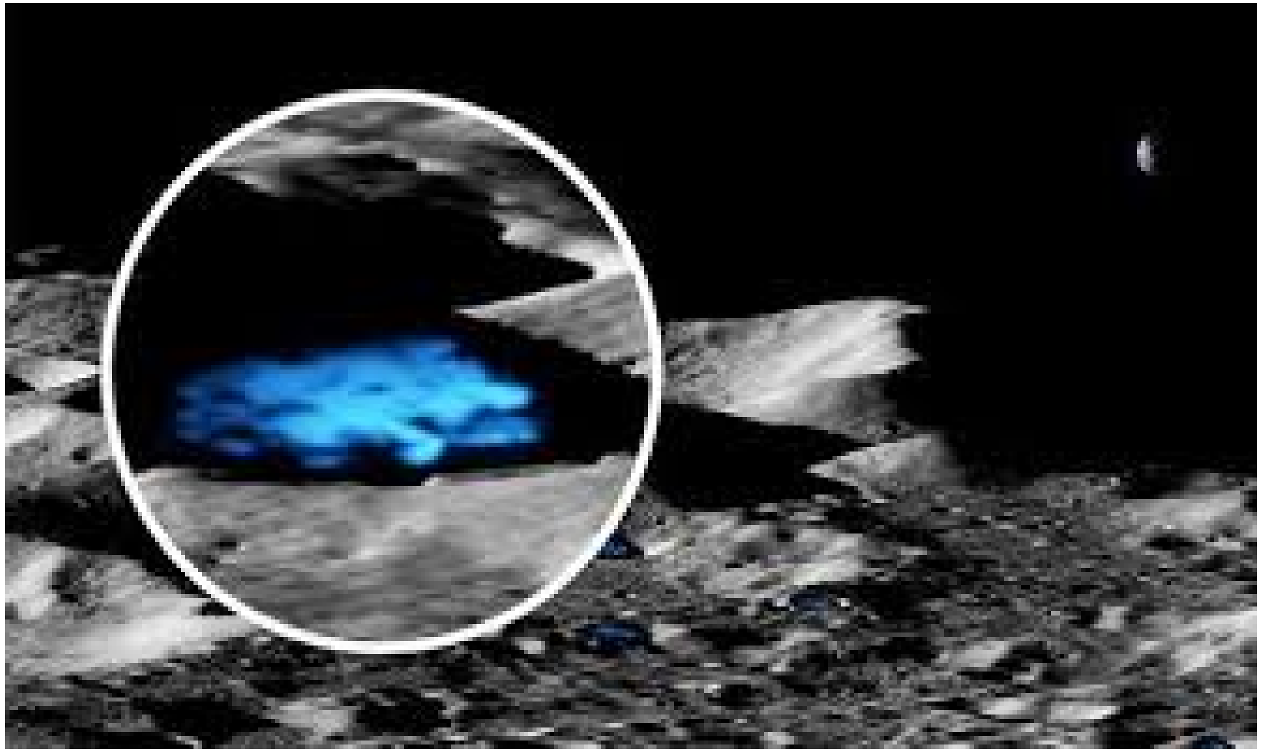
PTMSS Meeting
June 9, 2021

Obtaining Water from the Moon

Potential availability of water here….



…..as an alternative to here



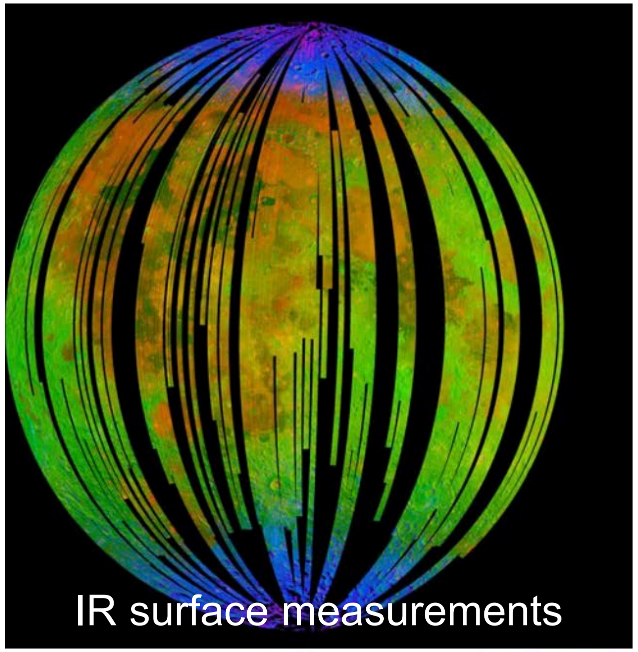
There are signs for water everywhere, but it's different on the illuminated Moon vs in PSRs

Sunlit Moon

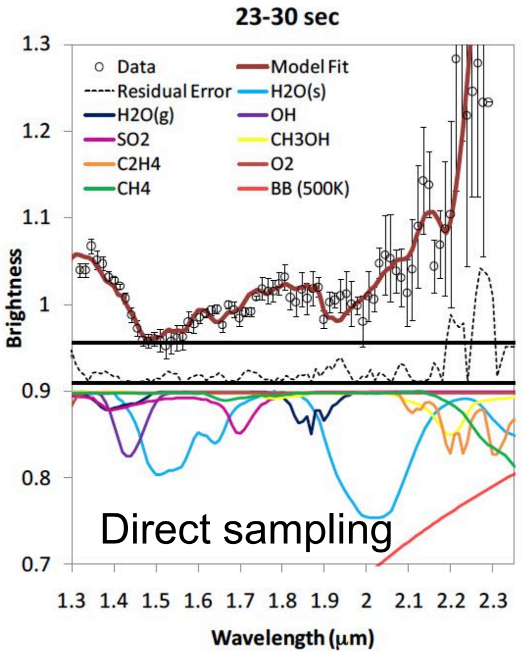
Poles

<0.1%

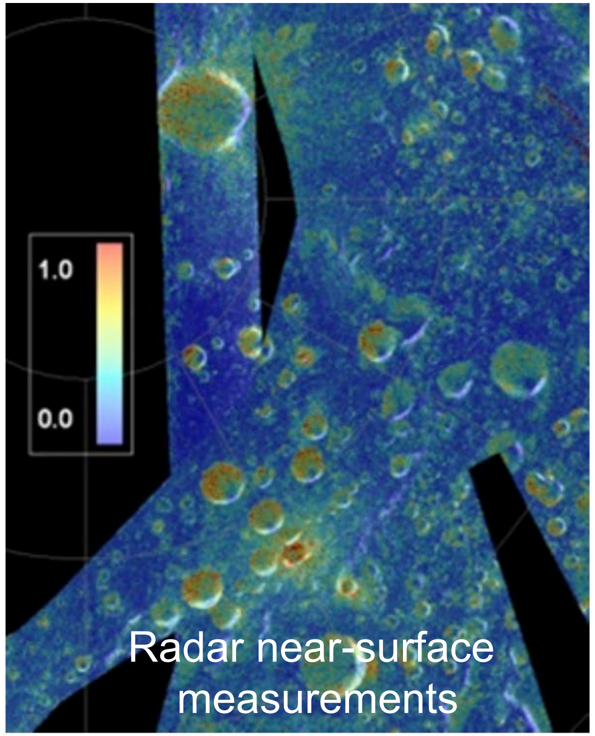
a few % to many %



Pieters et al., 2003



Colaprete et al., 2010



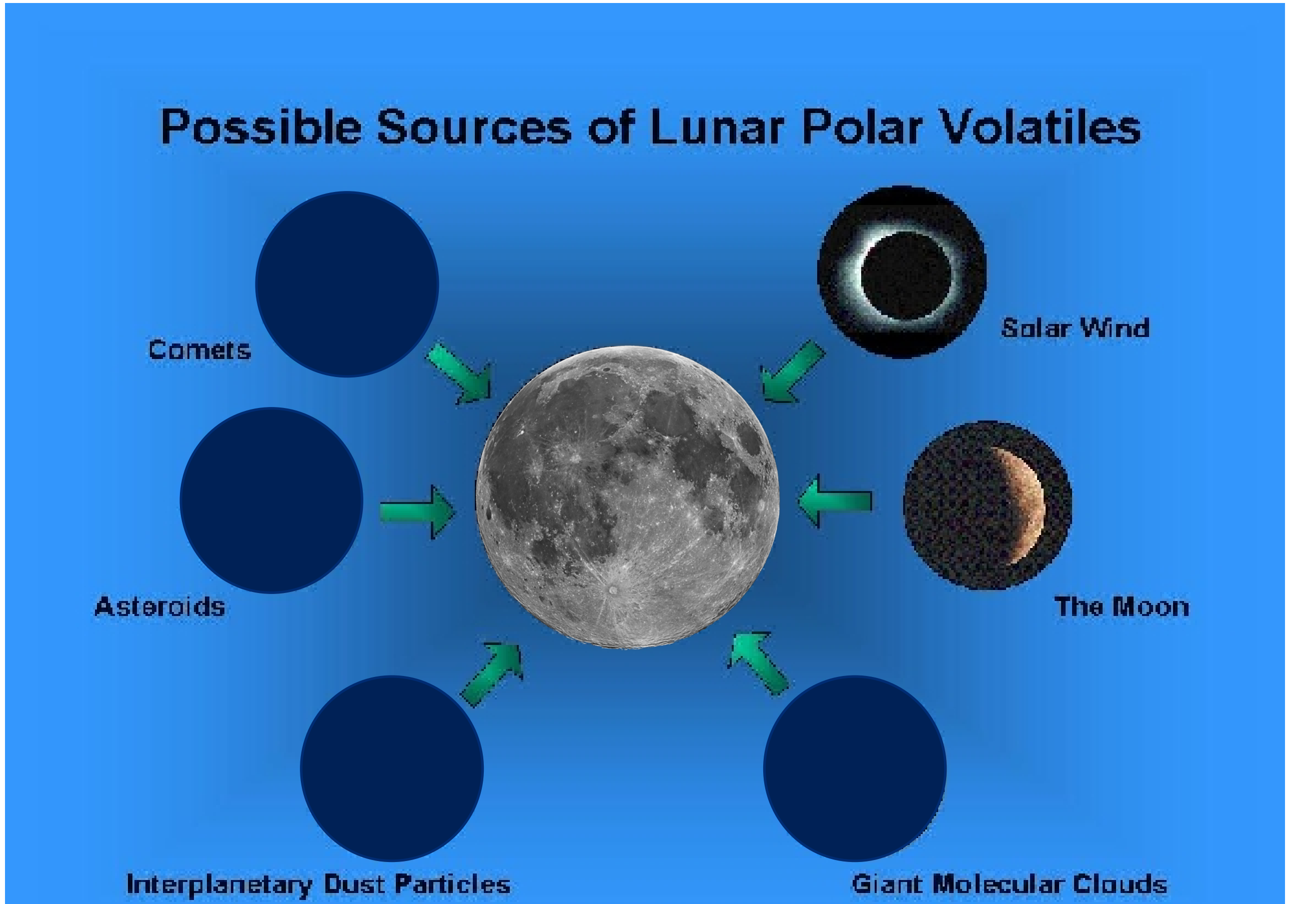
Spudis et al., 2010

Origin and State of Water on the Moon

Understanding the origin and state of the lunar water is essential to understanding its potential value as ISRU

There are many sources for the water found on the Moon

But only a couple of them can be responsible

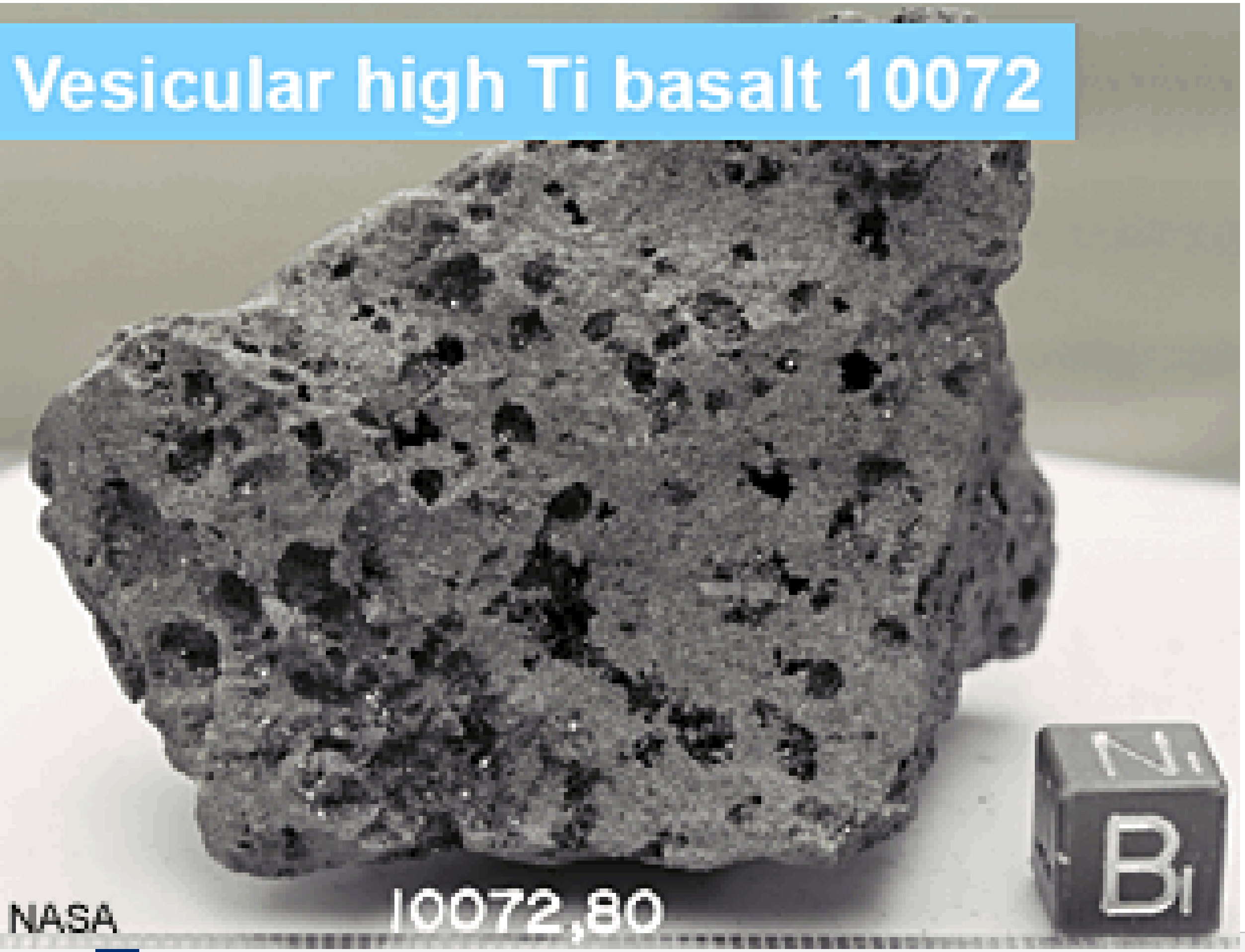


Modified from Lucey et al.

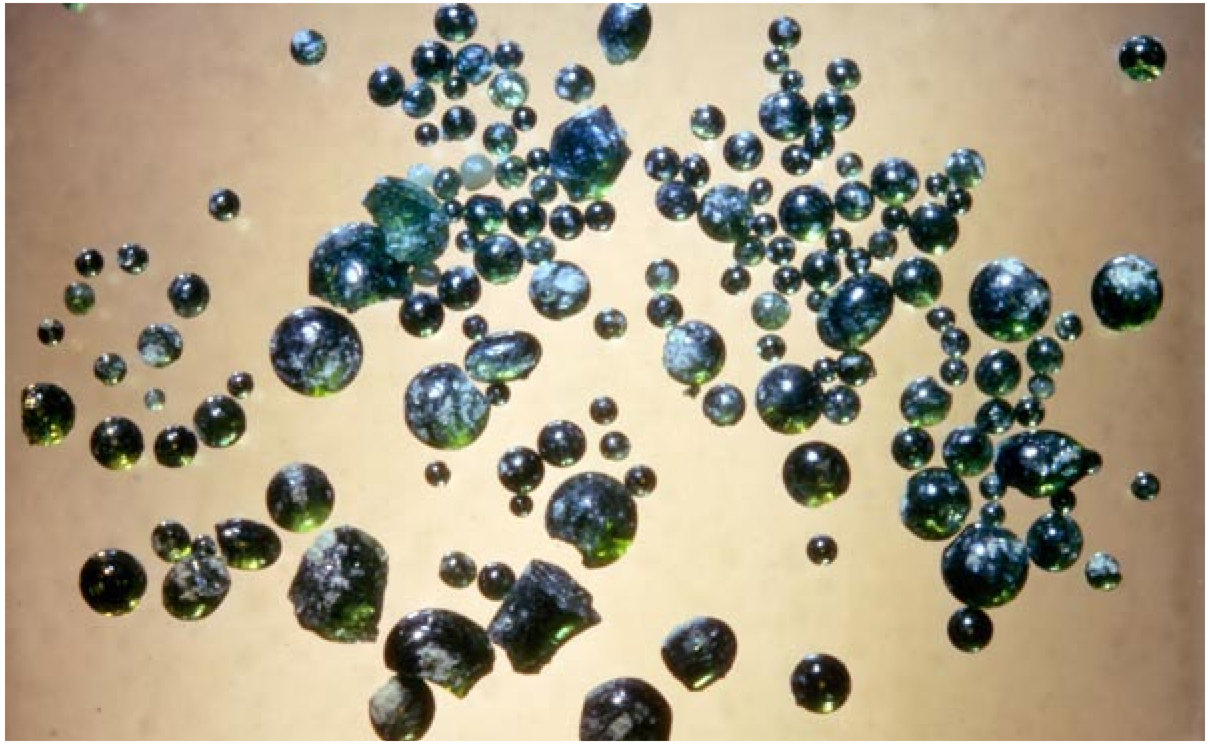
- *Primordial Water*
- *Hydroxyl formed from the implantation of solar wind protons*
  - *With possible evolution to H_2O*

Primordial Interior Water

10s to 100s ppm



Fire fountain glasses and vesicular basalt

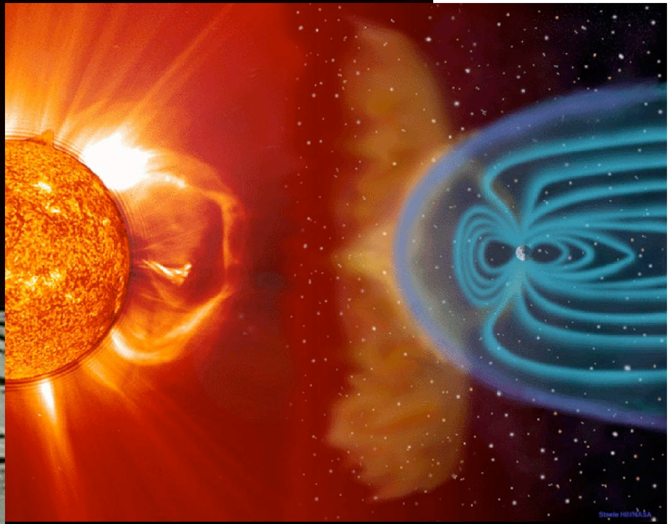


Water in the Parent Magma: few 100 ppm

Hauri et al., (2011, Science 333, 213-215); Elkins-Tanton & Grove (2011, *EPSL* **307**, 173-179); Hui et al. (2013, *Nat. Geosci*. **6**, 177-180)

Water from chemistry between Solar Wind and surface

Solar wind: provides protons that may become hydrogen to form OH after implantation by reacting with the O in the silicate and oxide surface materials.



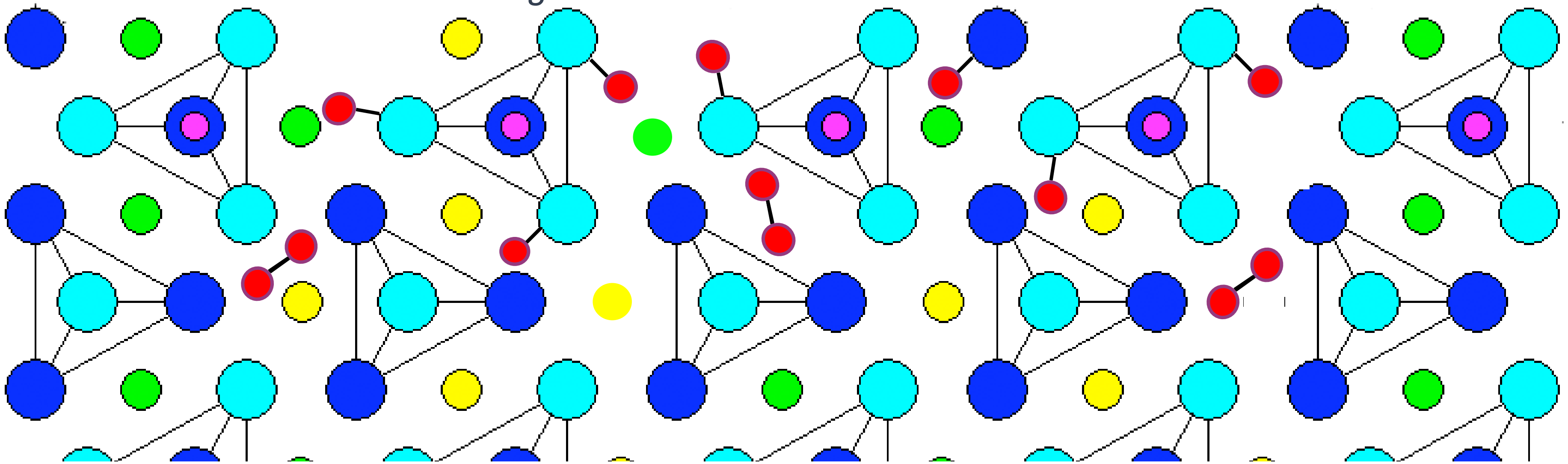
Earth's magnetic field, or magnetosphere, protects us from most effects of solar storms and the solar wind.
Credit: SOHO image composite by Steele Hill (NASA)

But the Moon spends most of it's time outside the Earth's magnetopause and thus is exposed to the energetic protons that dominate solar wind.

Solar Wind formed OH is part of the mineralogy

OH is ‘ephemeral’ in that exists only as part of the nominally anhydrous silicate or oxide mineralogy.
H_2 likely evolves through thermal processes
Any H_2O formation would require an additional step

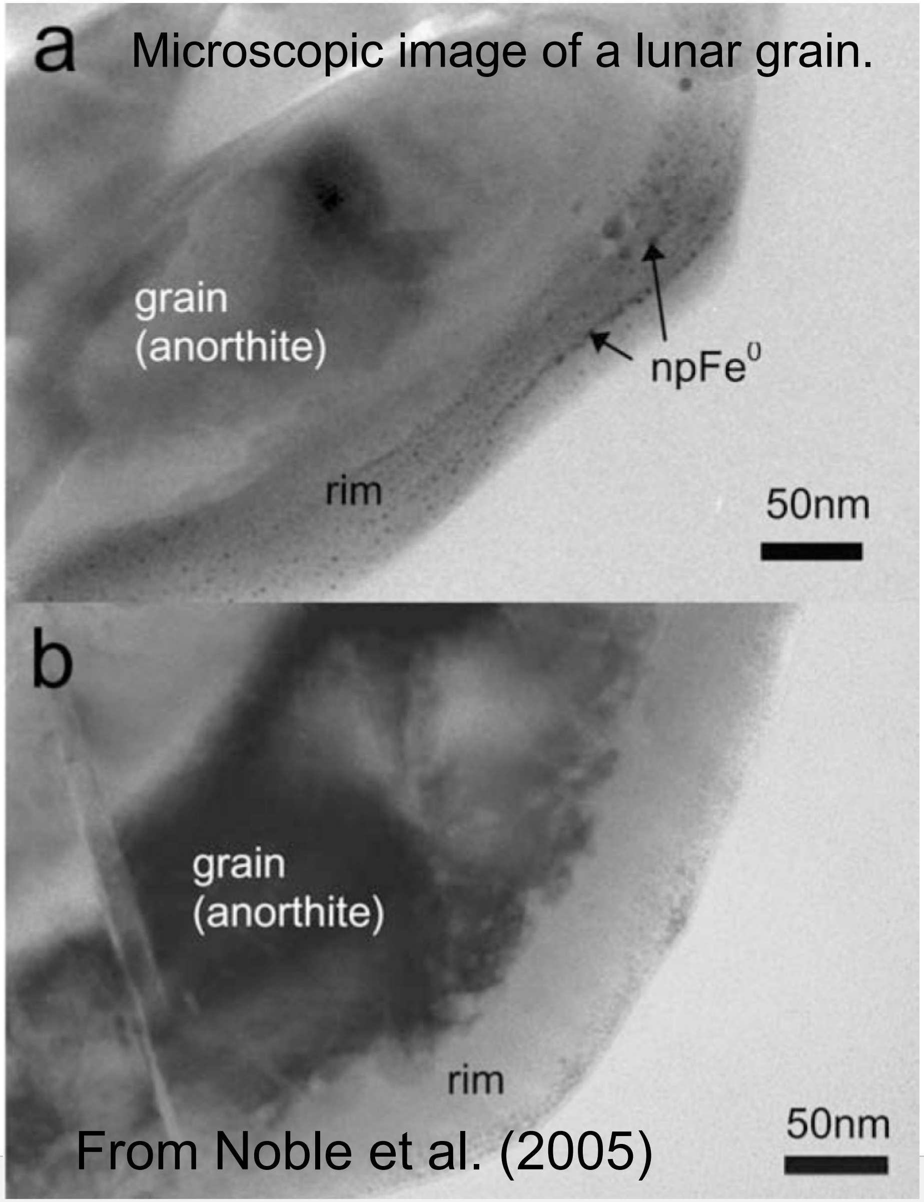
Diagram of a lunar silicate mineral



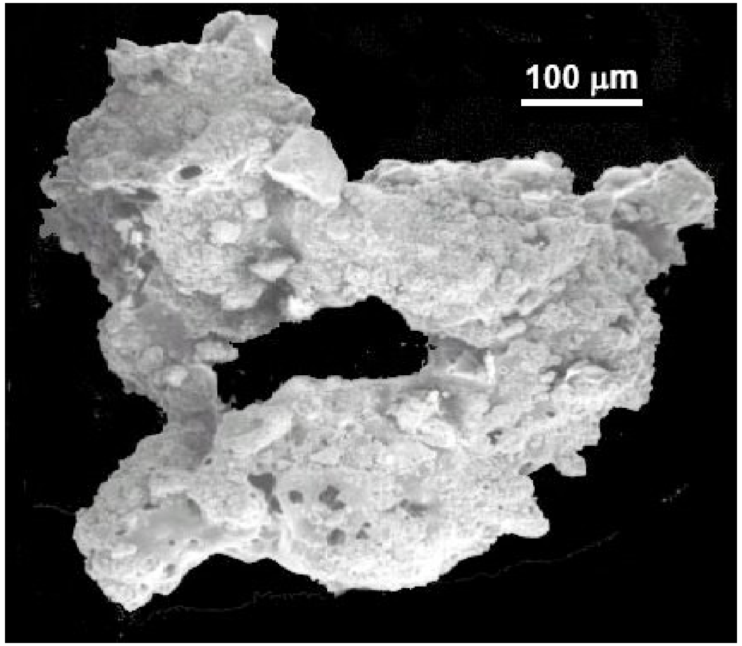
1. Solar wind particle implants
2. Mineral lattice disrupted and some atoms sputtered
3. Some solar wind bonds to O to form OH, others form H_2
4. Hydrogen accumulates as OH and H_2

Solar wind OH in surfaces of grains

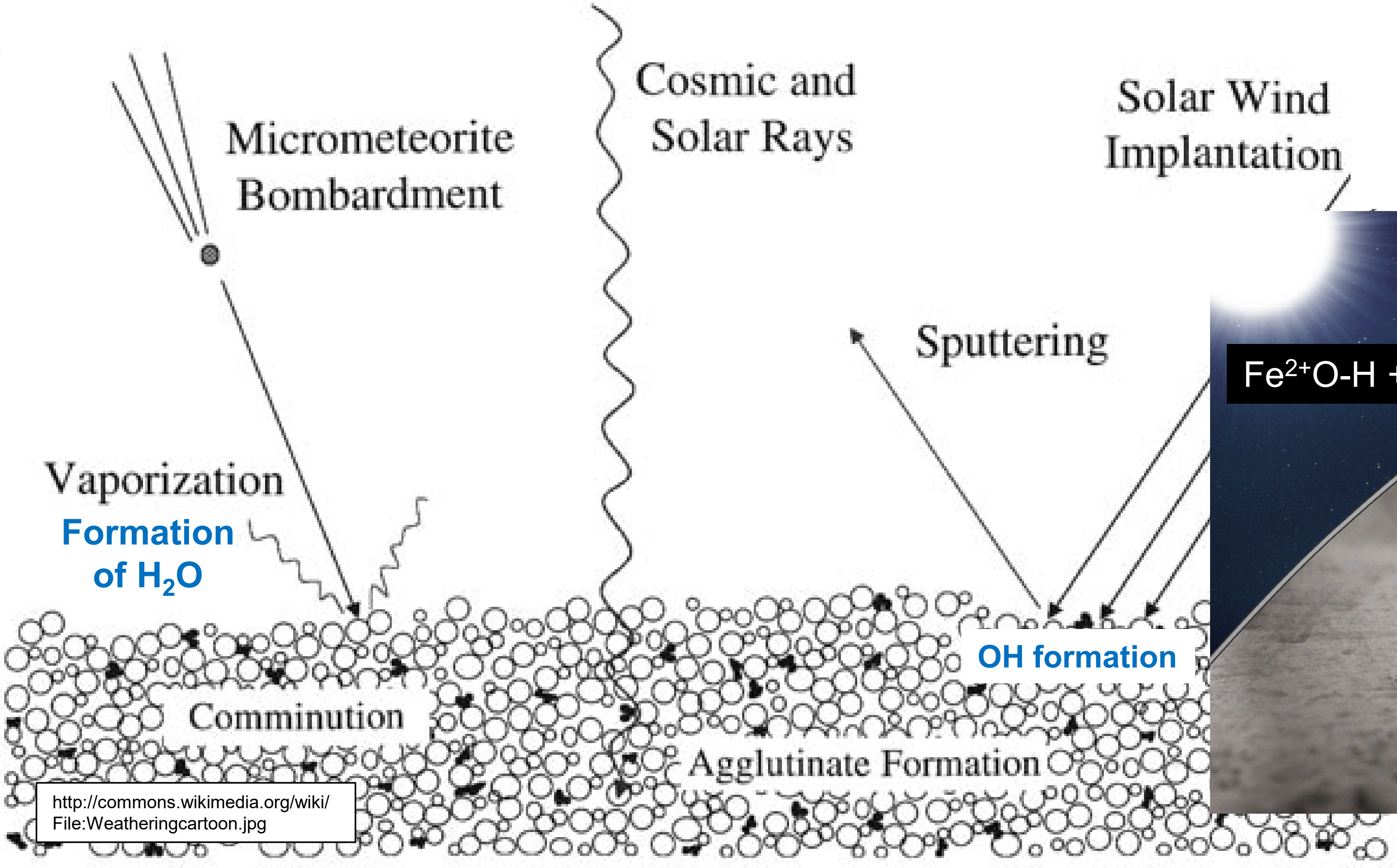
- Solar wind implantation to no more than ~ 100nm
- Solar wind flux of ~3e8 #/cm^2/sec
- Rind saturation: ~ 1e17 cm^3
- Time to saturation 10s to 100s yrs
- Equivalent bulk abundances of 10s to 100s ppm



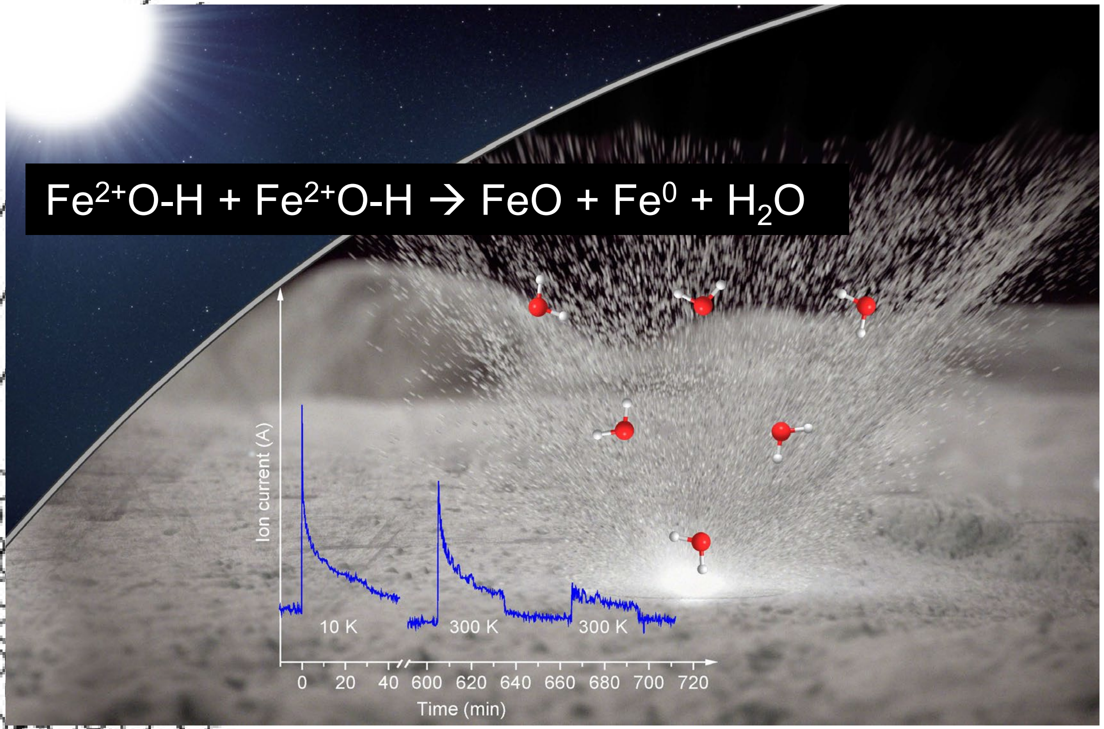
From Noble et al. (2005)



“Space weathering” evolving the OH and H_2O

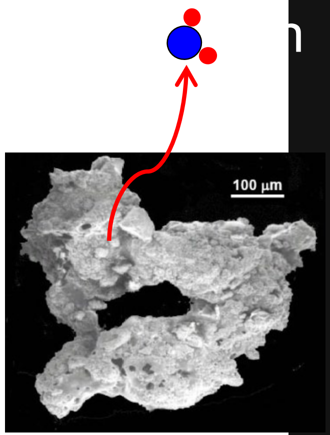


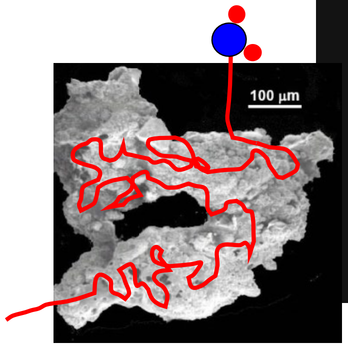
Forming H_2O in the reducing environment of micrometeroid plumes

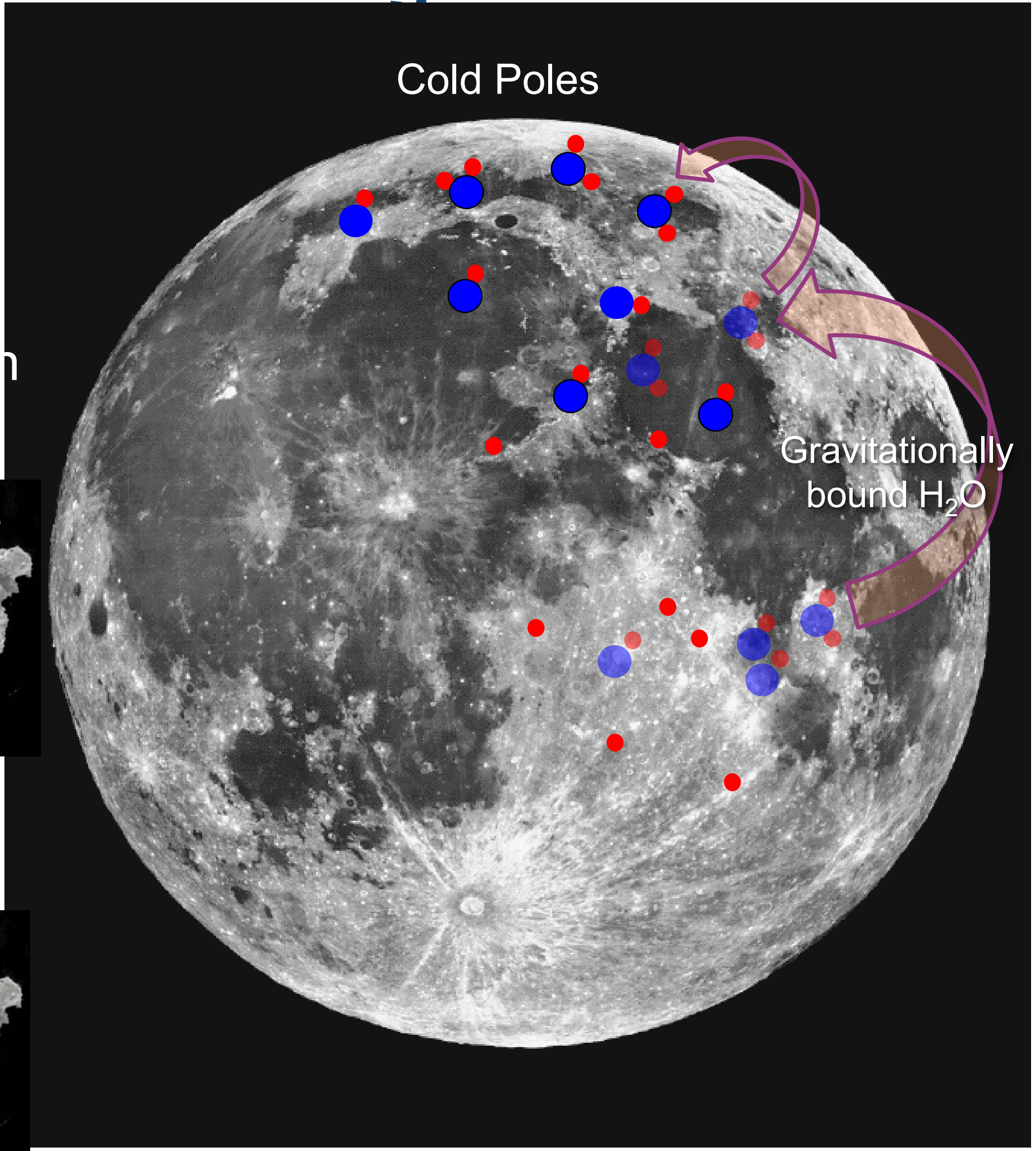


Gillis-Davis et al., 2018

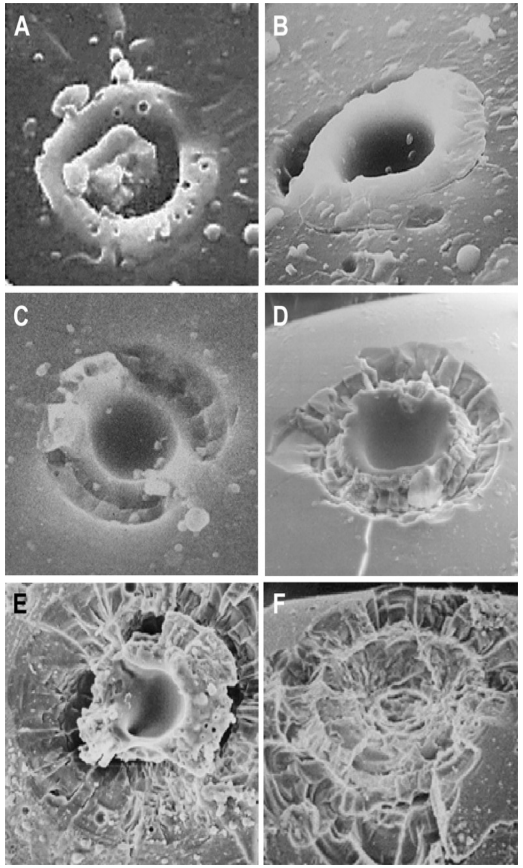
Possible sequestering of H_2O in colder regions on the Moon

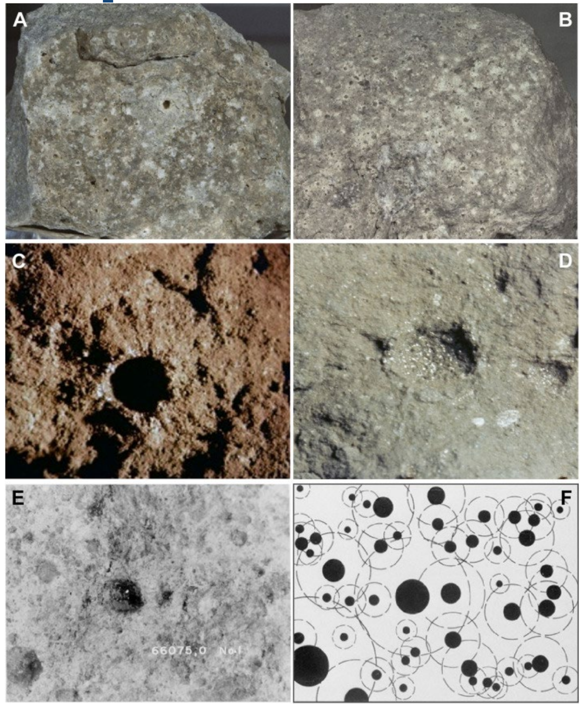






Possible trapping of H_2O in 'melt spashes'





From Horz et al. (2020)

Explanation also used by Honniball et al., 2020 to explain the presence of 100's ppm of H_2O on the illuminated Moon, that would otherwise not be thermally stable

Thermal Release of Water from Lunar soils

Estimated Processing Temperatures

Surface adsorbed H_2O – 350K

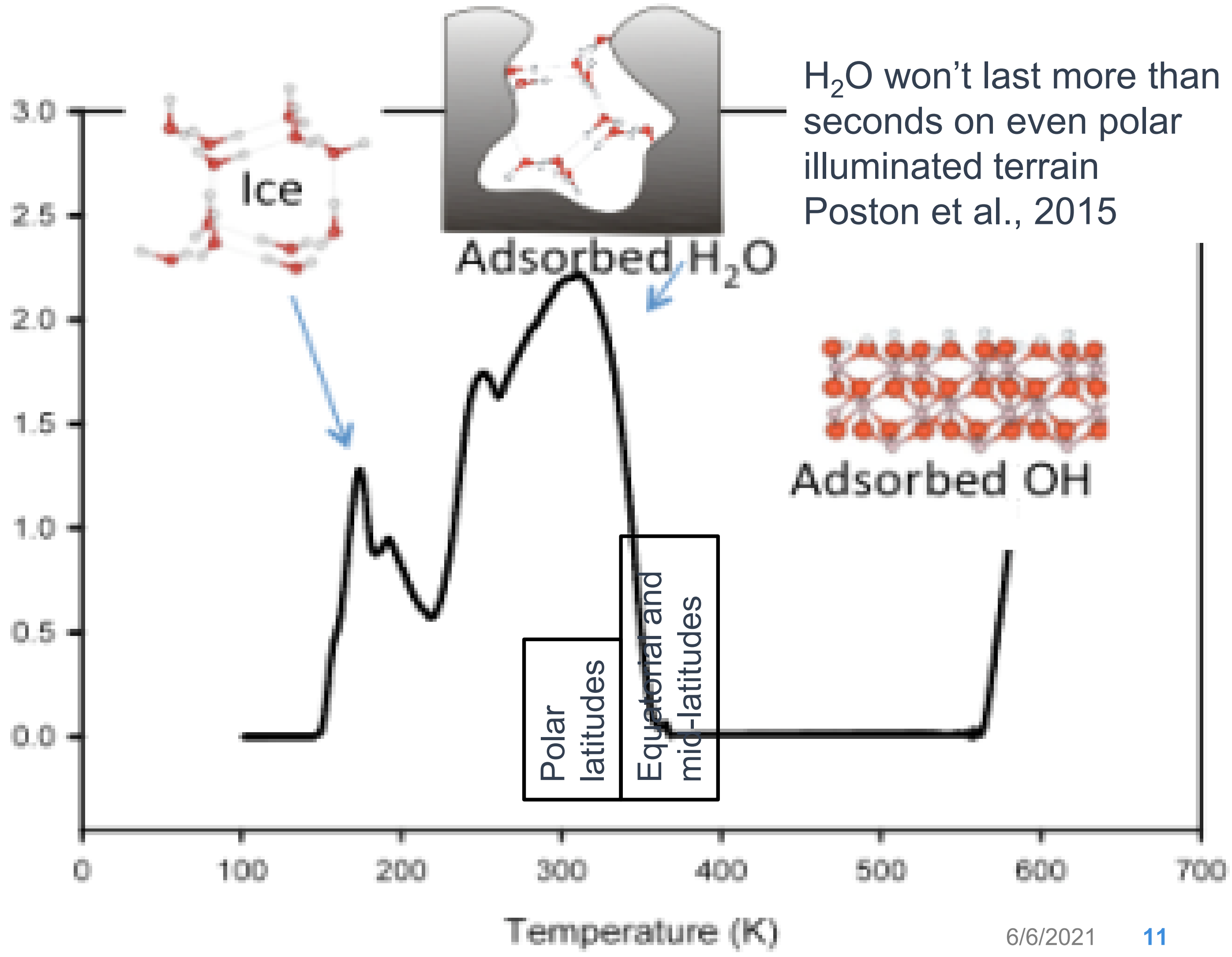
Surface chemisorbed OH – 600K

Internal OH – 1600K (melting) -
not clear what percentage of internal OH that would evolve out as H_2O or H_2.

Internal H_2O - 1600K (melting)

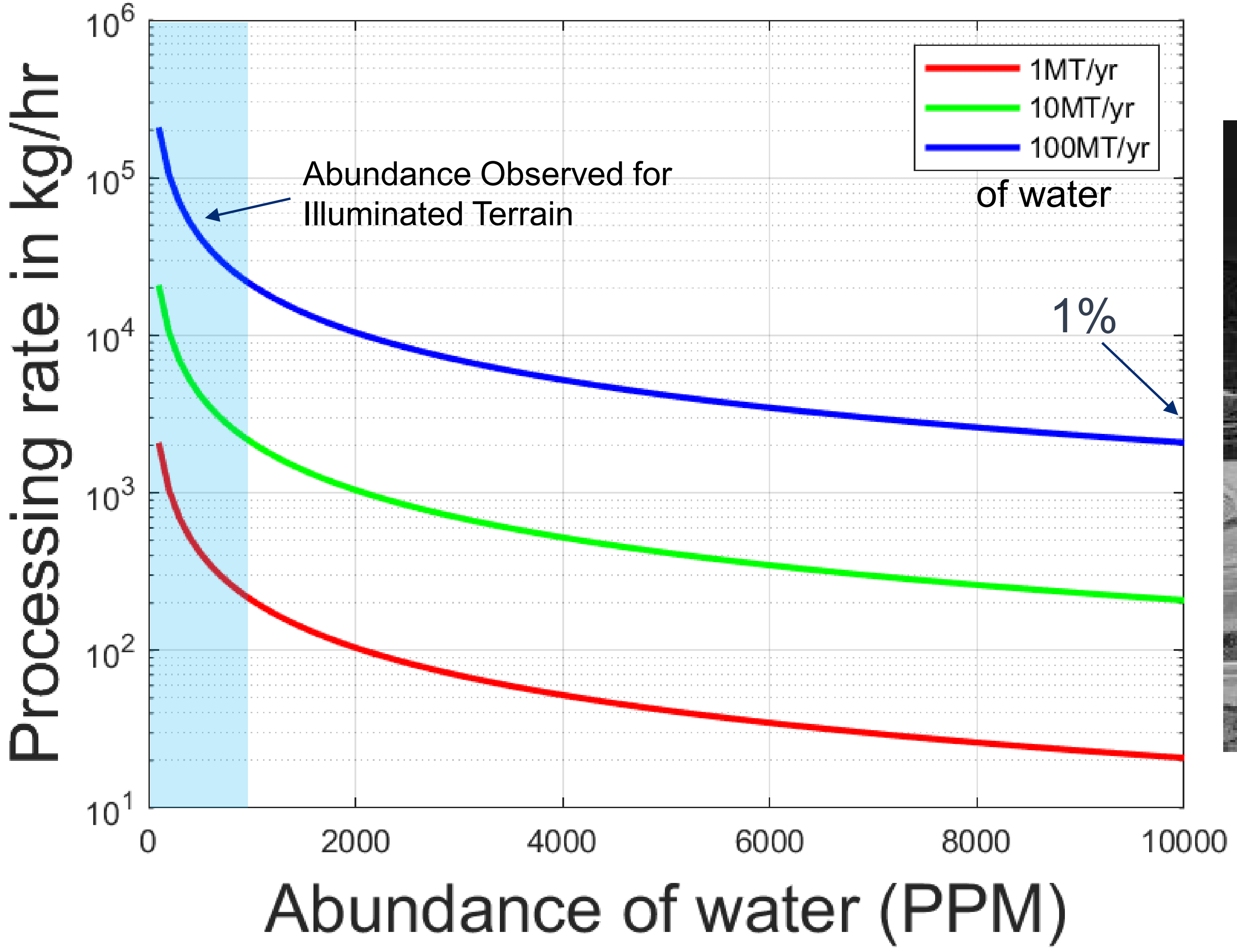
Must also consider the evolution of the desorbed waters through any bulk regolith. Diffusion will take time and energy

Instantaneous Desorption temperatures



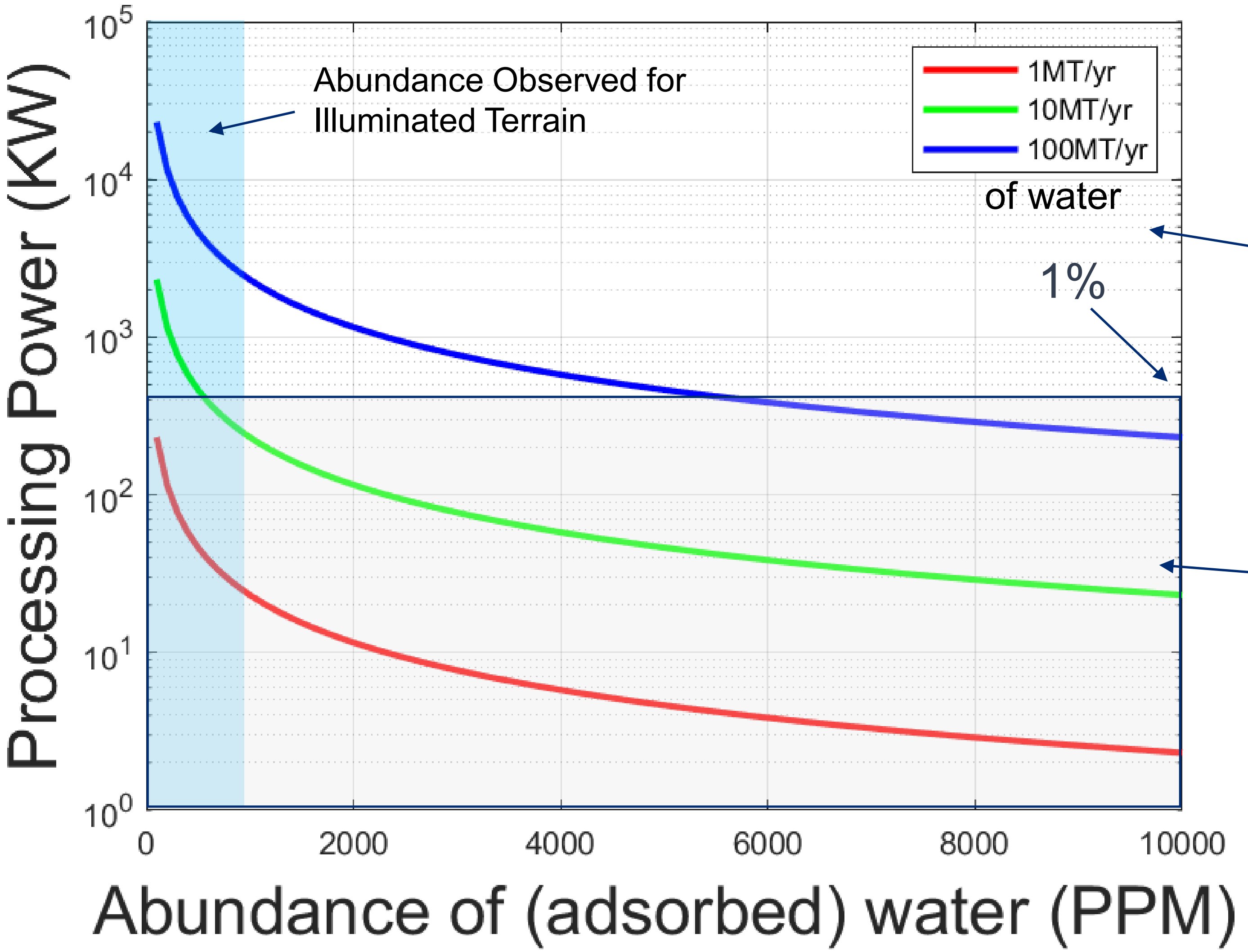
H_2O won't last more than seconds on even polar illuminated terrain
Poston et al., 2015

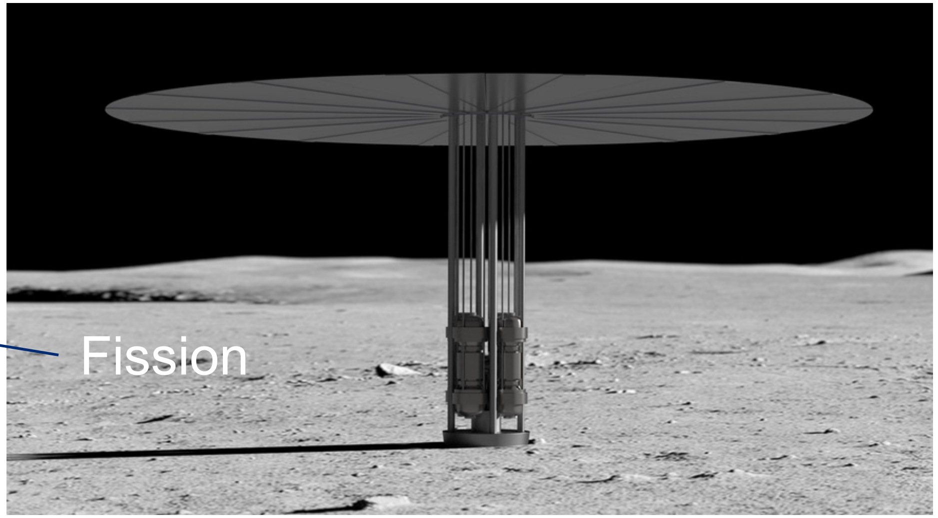
Implications for Regolith Processing Rates

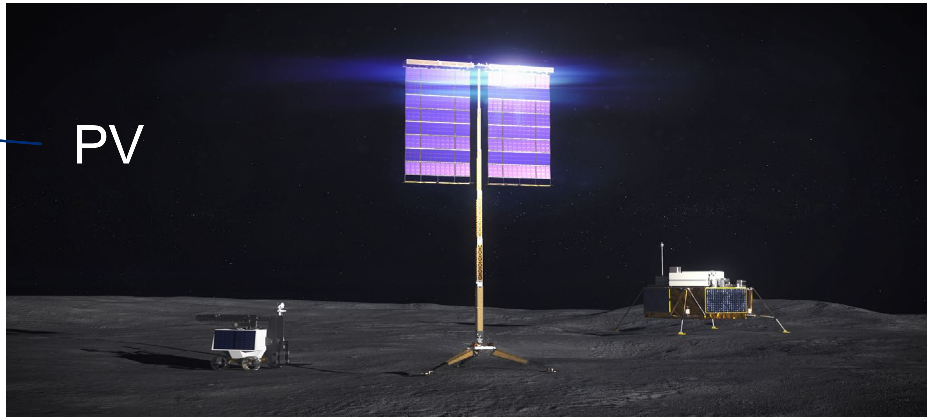


Processing Power (yearly)

(assuming surface adsorbed H_2O)







Summary: Water on the illuminated lunar surface for ISRU

It's a complex combination of primordial and exogenous origins.

OH and H_2O have important differences.

Trace amounts

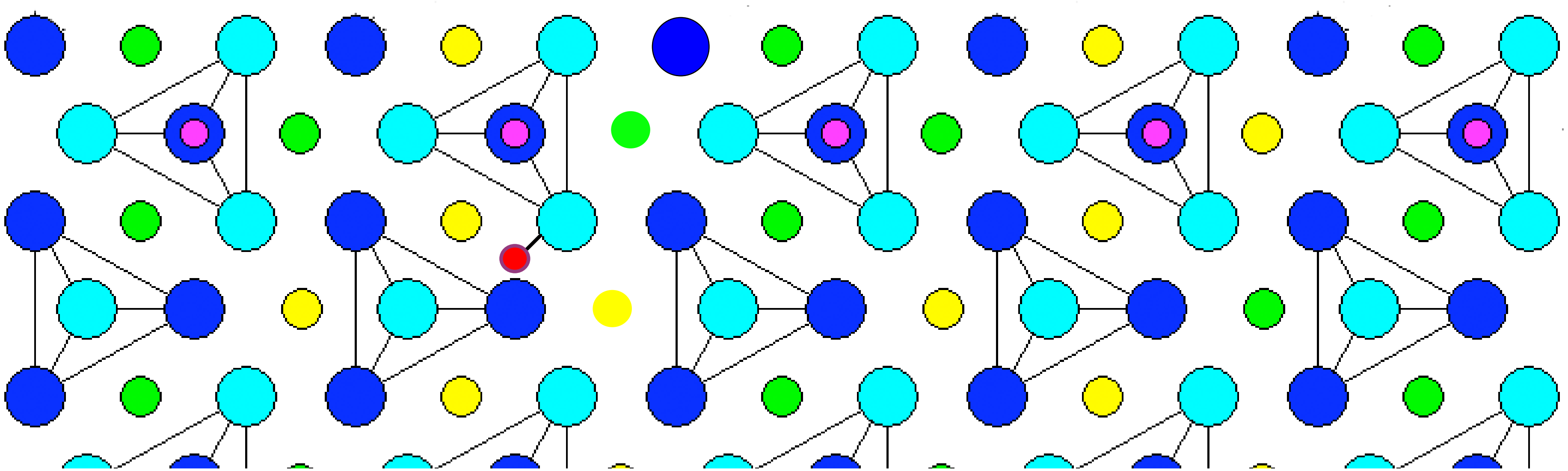
- There is hydroxyl and molecular water.
- Both are at 10s to several/many hundreds of ppm
- On the warmer parts of the Moon, OH or H_2O, is only in the grains, and the grains would have to be melted to extract the water. (Might as well extract O_2 from the minerals?)
- Could surface adsorbed H_2O on grains buried in cooler illuminated polar terrains? (less heating needed to extract).
- Surface and temporal variations not yet understood – see upcoming SIMPLEX and CLPS missions.
- Vertical distribution uncertain – landed CLPS missions may shed more light on this.

For more information and discussion, join the Lunar Surface Innovation Consortium ISRU focus group.

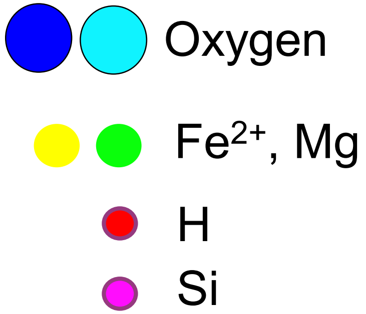
Contact Karl.Hibbitts@jhuapl.edu; Michael.Nord@jhuapl.edu; Kirby.Runyon@jhuapl.edu

Solar Wind forms OH

(H_2O and/or H_2 would need to evolve through thermal processes)



1. Solar wind particle implants
2. Mineral lattice disrupted and some atoms sputtered



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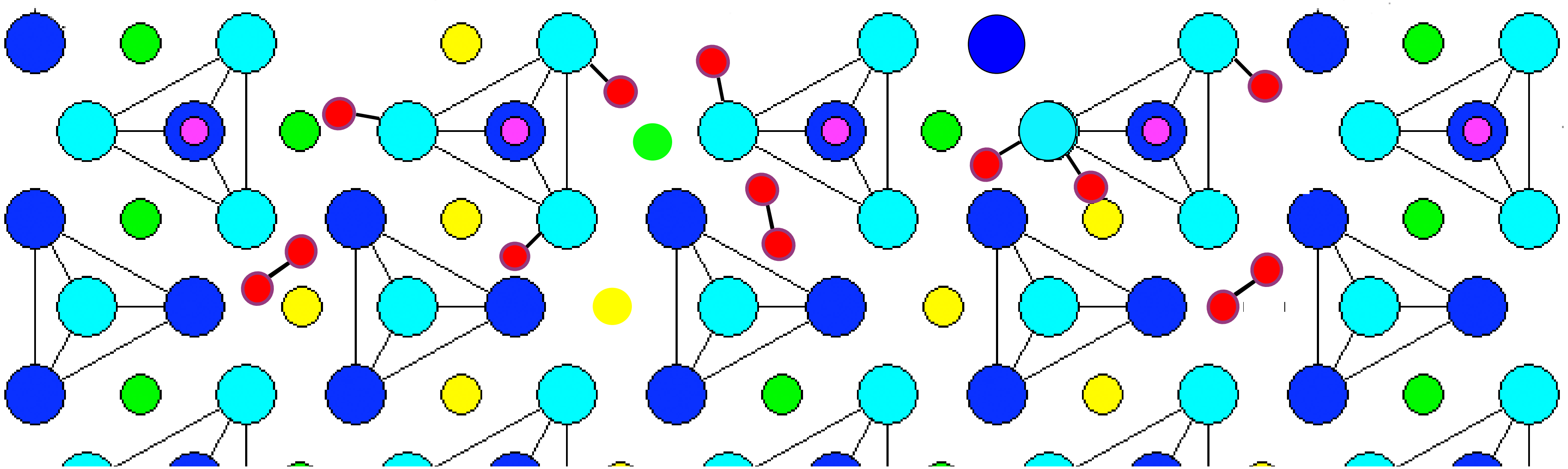

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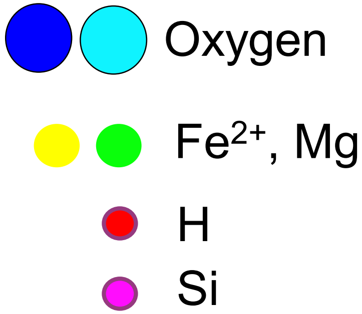
4. Hydrogen accumulates as OH and H_2
5. If there is sufficient thermal energy, OH can mobilize, combine and desorb as H_2O or as H_2



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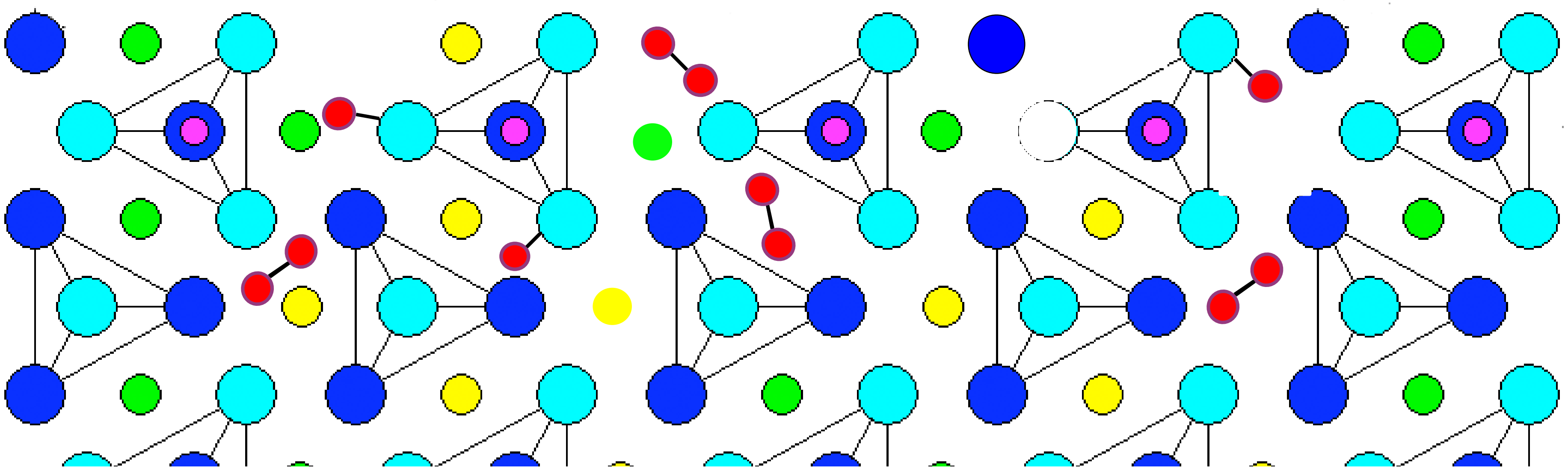

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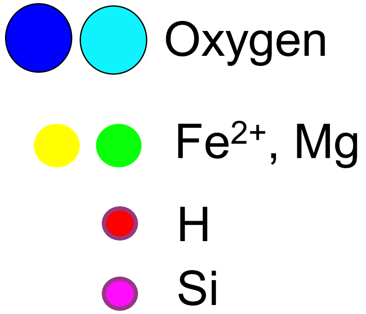


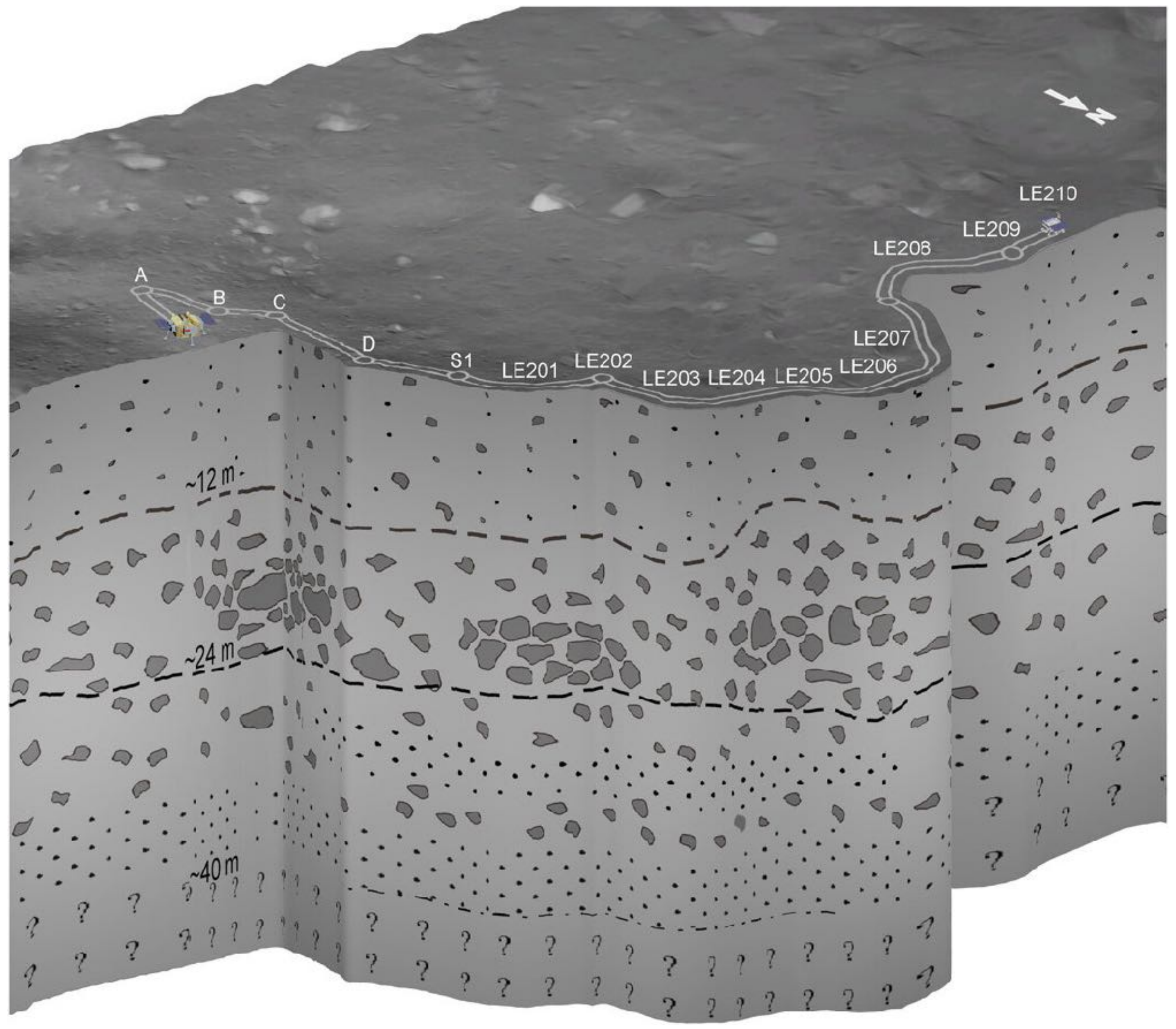
WATER ICE ON THE MOON: AN OASIS OR MIRAGE?

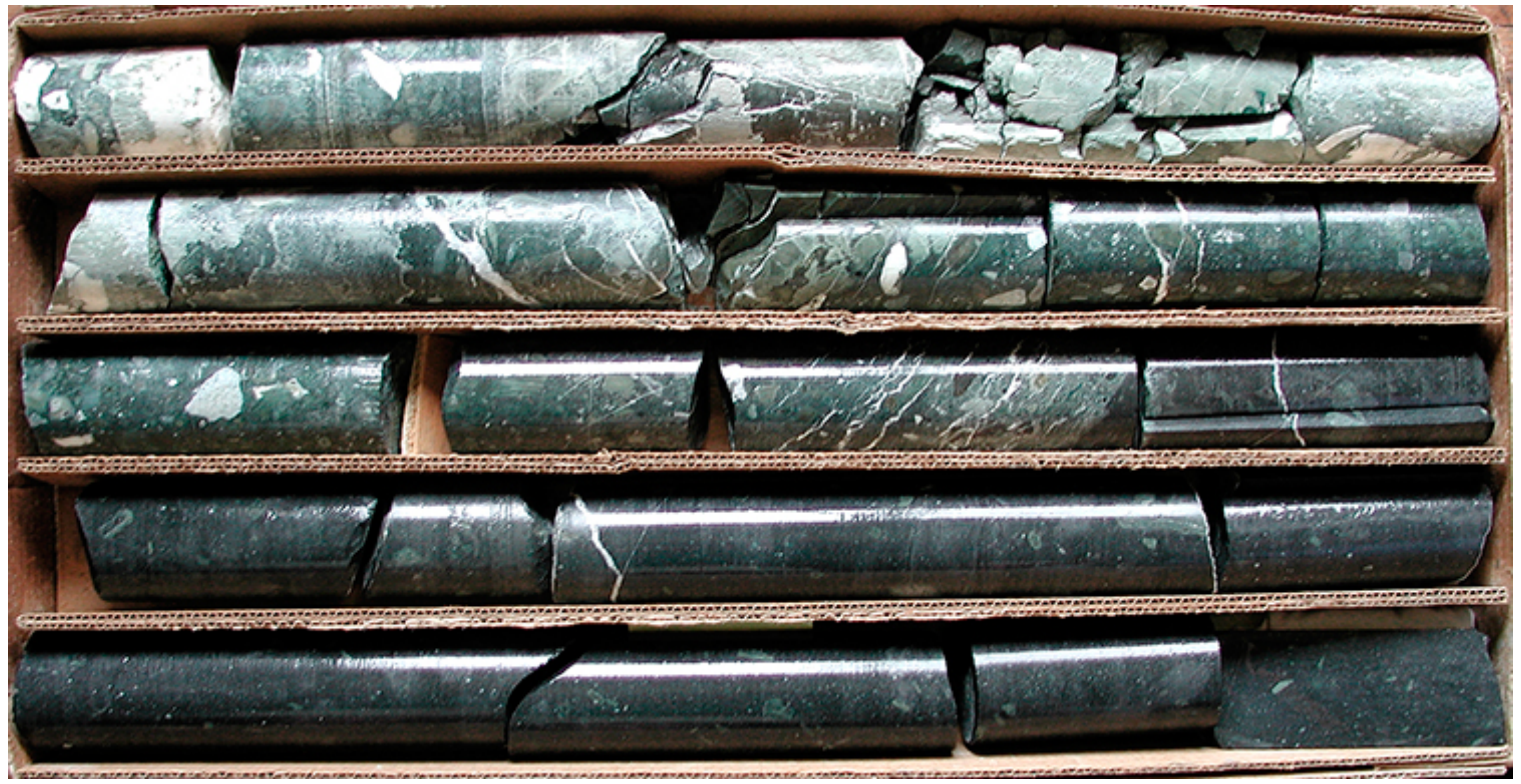
Kevin M. Cannon

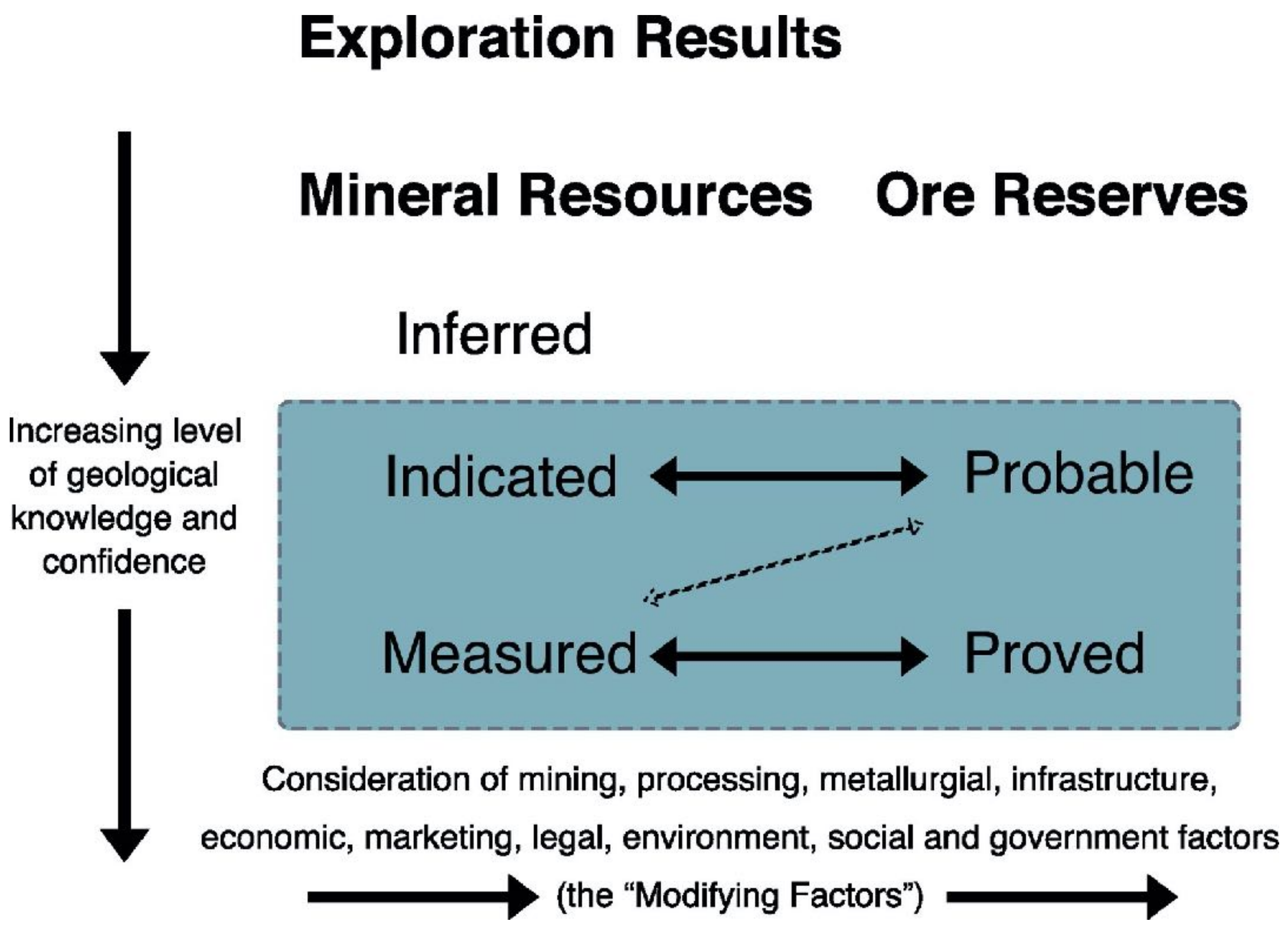
cannon@mines.edu

@kmcannon

What we don't have: ground truth, detailed prospecting, ground-based geophysical techniques, sample analysis







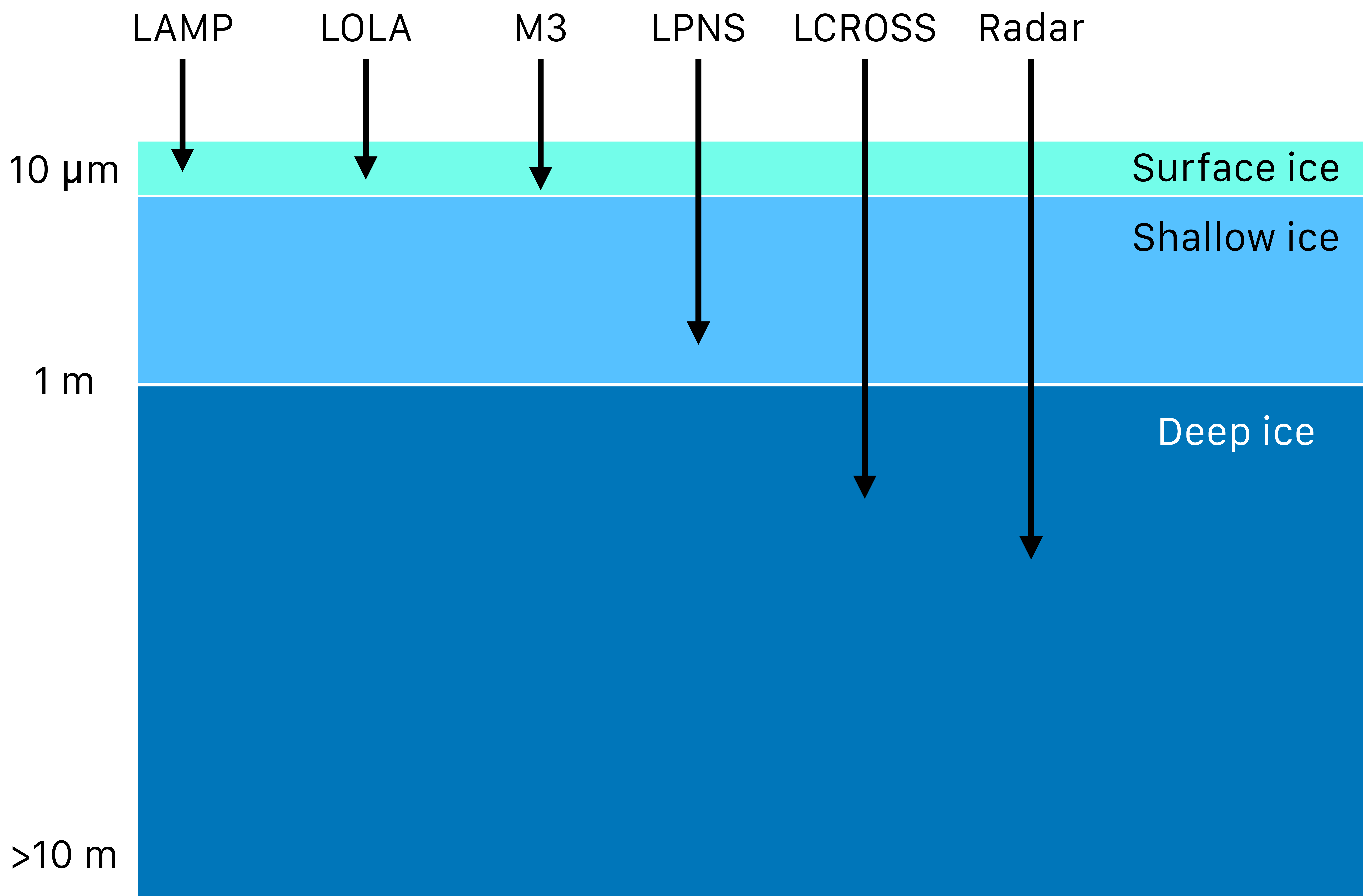
What we do have:

Decades of orbital remote sensing data

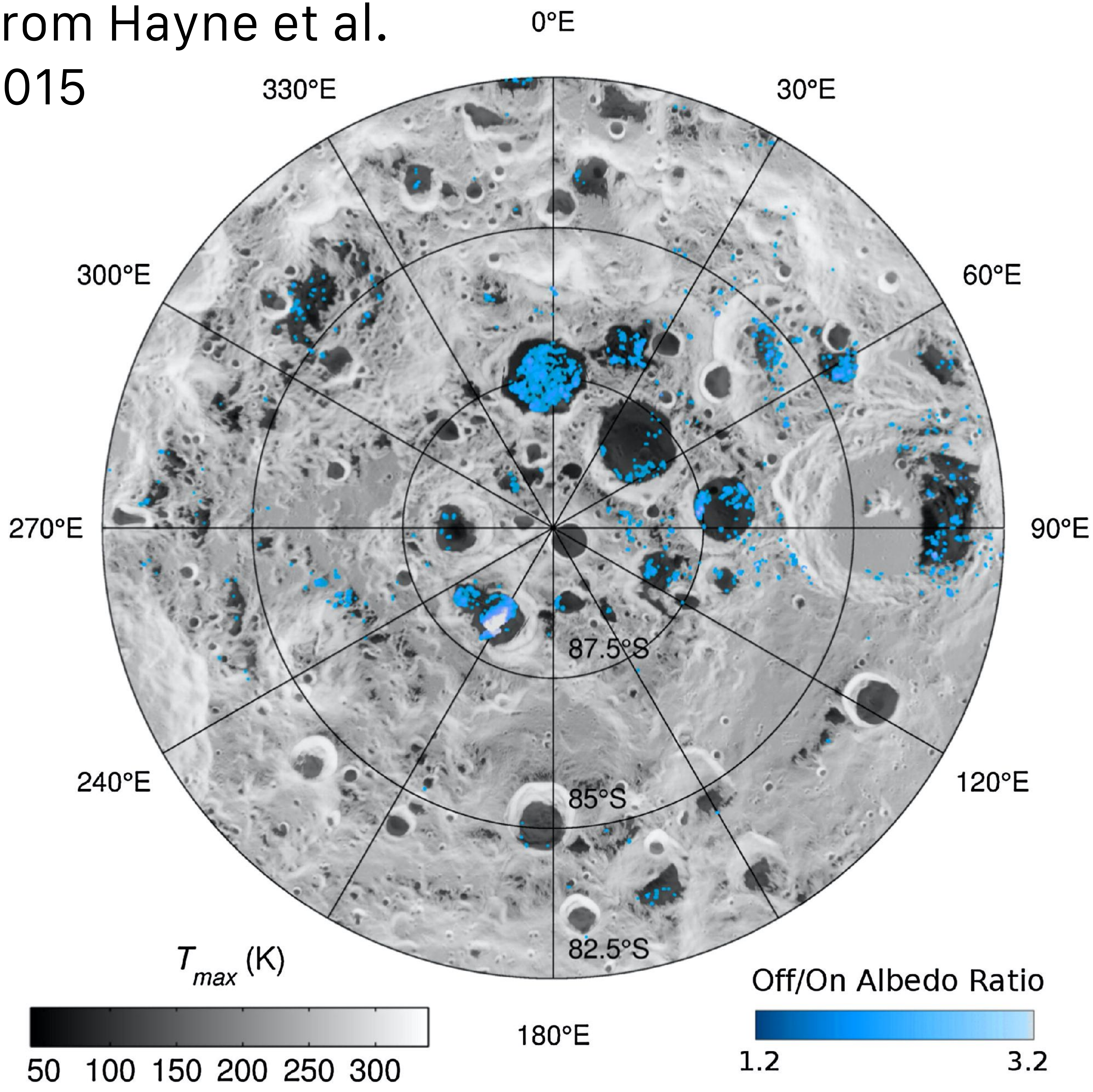
A dedicated impact experiment (LCROSS)

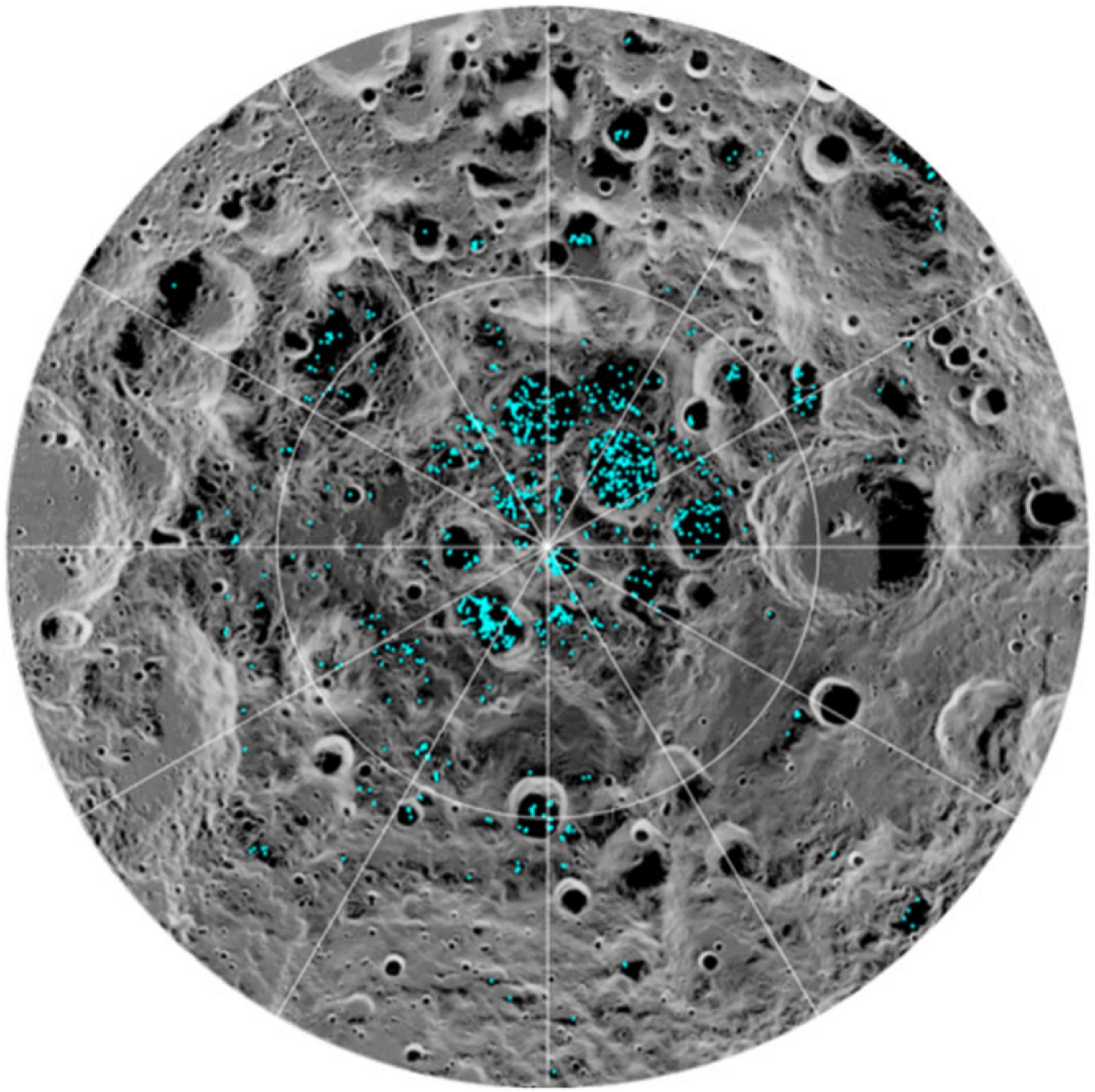
Thorough understanding of the geologic processes occurring on the Moon (including at the poles)

These are sufficient to make **informed predictions**


LAMP
LOLA
M3
LPNS
LCROSS
Radar
10 µm
Surface ice
Shallow ice
1 m
Deep ice
>10 m

From Hayne et al. 2015

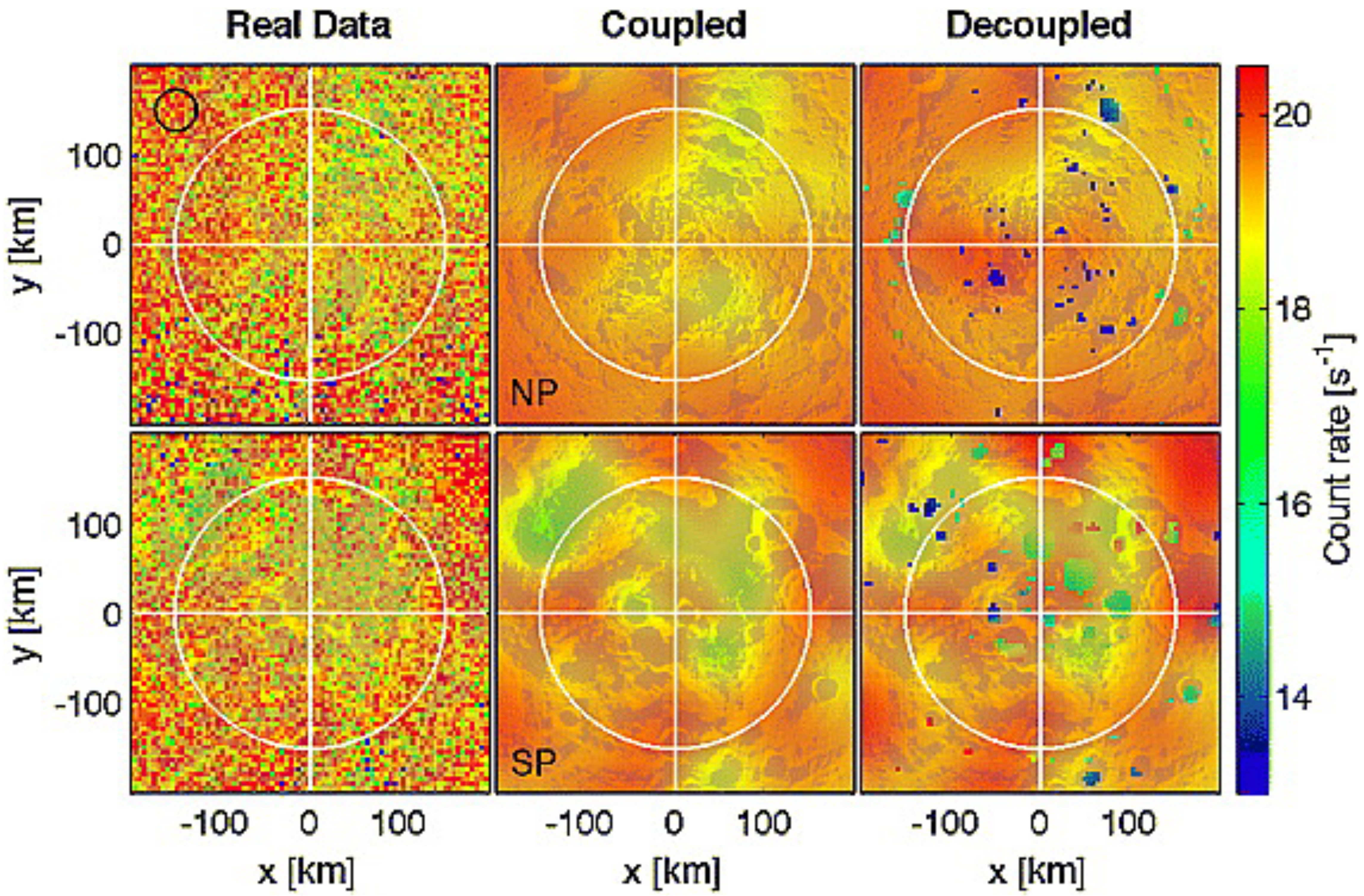




From Li et al. 2018

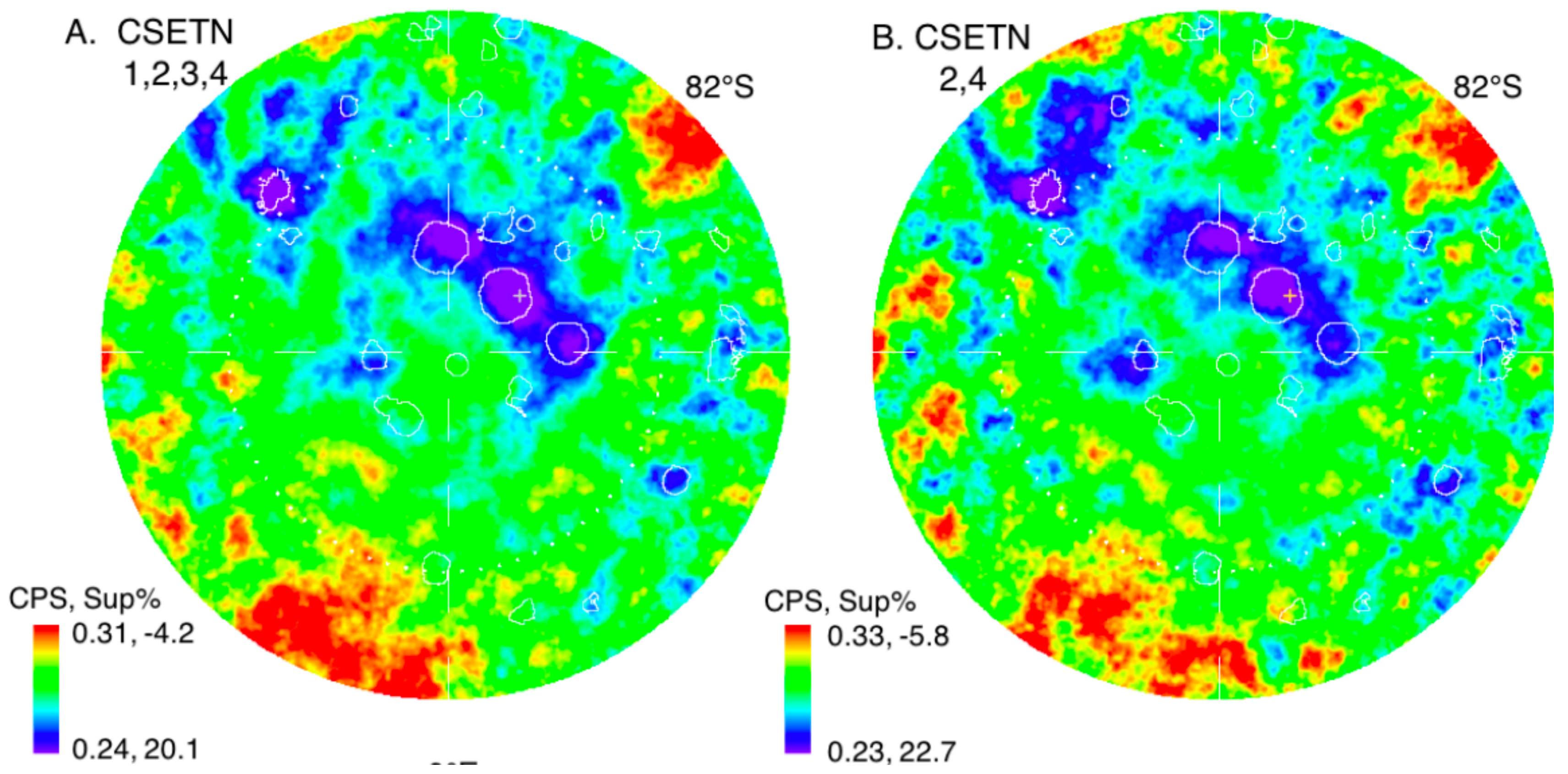
"We conclude that the LAMP-observed icy regolith sensed in the top 500 nm on the floors of PSRs has to be relatively young (<2 kyrs old) and dynamic given the surface erosion by the space environment."

Farrell et al. 2019



From Teodoro et al. 2010

Crater	WEH ± Error (wt%)
Hermite	$3.7_{-0.8}^{+2.3}$
Nansen F	$0.3_{-0.1}^{+0.2}$
Peary B	$3.2_{-1.1}^{+1.9}$
Unamed	$3.1_{-0.8}^{+1.2}$
Unamed	$1.0_{-0.4}^{+0.5}$
Unamed	$1.9_{-0.5}^{+0.6}$
Cabeus	$1.0_{-0.3}^{+0.3}$
Cabeus A	$1.6_{-0.3}^{+0.5}$
Faustini	$0.3_{-0.1}^{+0.1}$
Haworth	$0.2_{-0.1}^{+0.1}$
Shackleton	$0.6_{-0.1}^{+0.2}$
Shoemaker	$0.2_{-0.1}^{+0.1}$

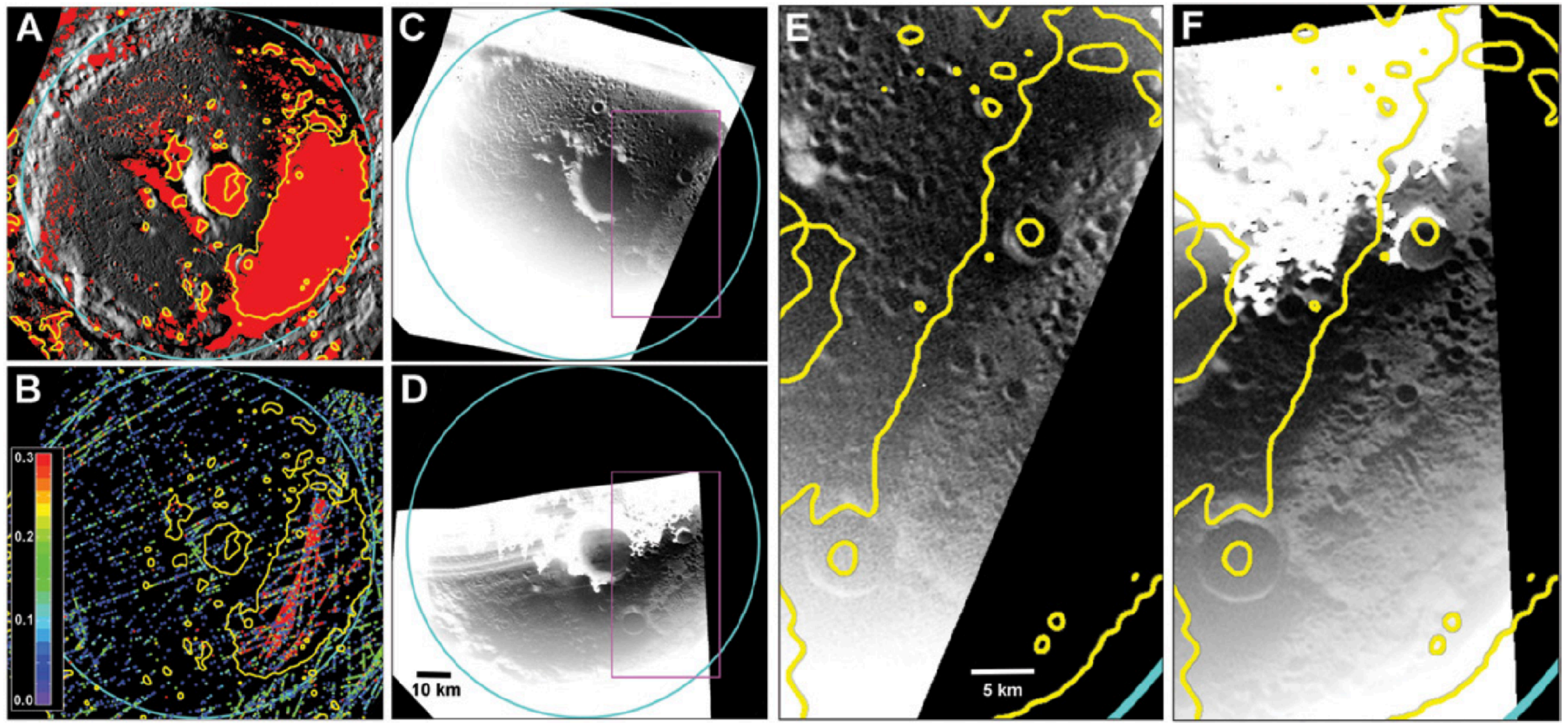


"…the maximum neutron suppression…occurs in the Shoemaker PSR, thus indicating the location at which the greatest concentration of hydrogen-bearing volatiles is thought to occur in the Moon's southern hemisphere.

That location is consistent with 1% WEH based on the regolith composition model of Lawrence et al. (2006)"

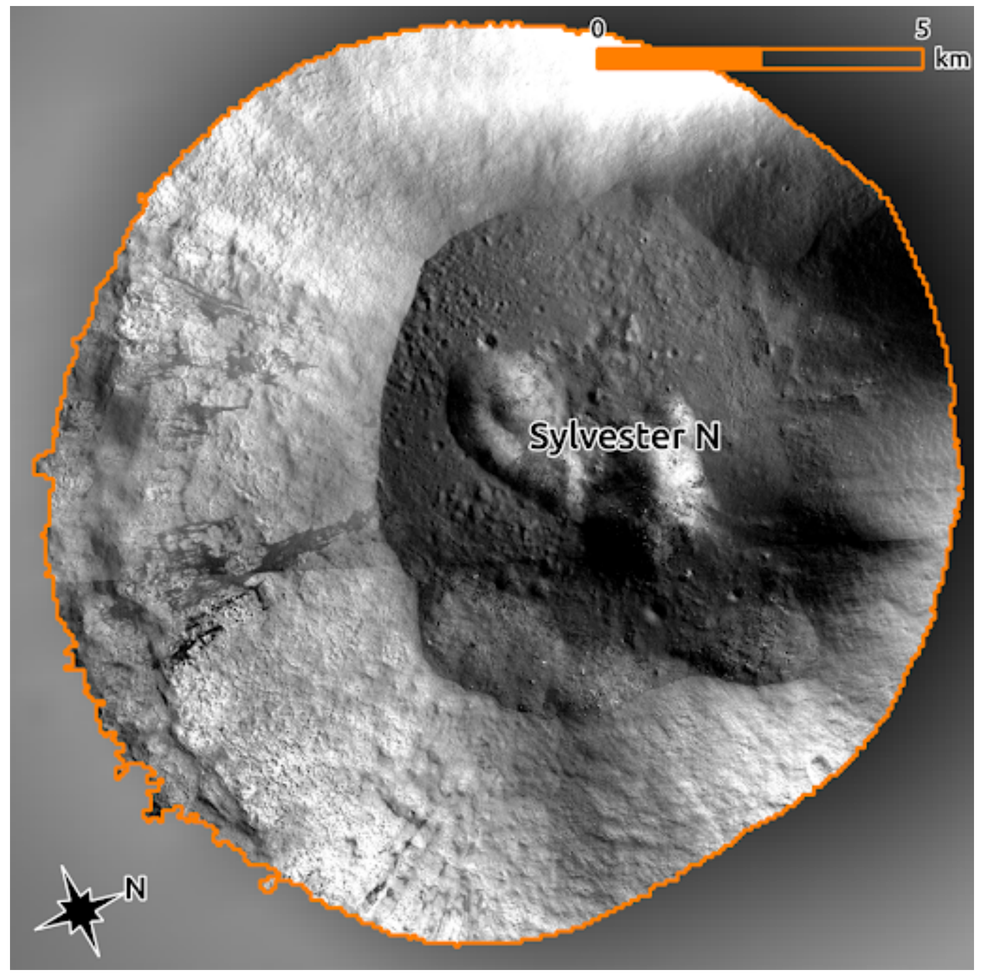
Su et al. 2021

On Mercury you can literally see the polar ice deposits in visible imagery:



From Chabot et al. 2014

What about on the Moon?

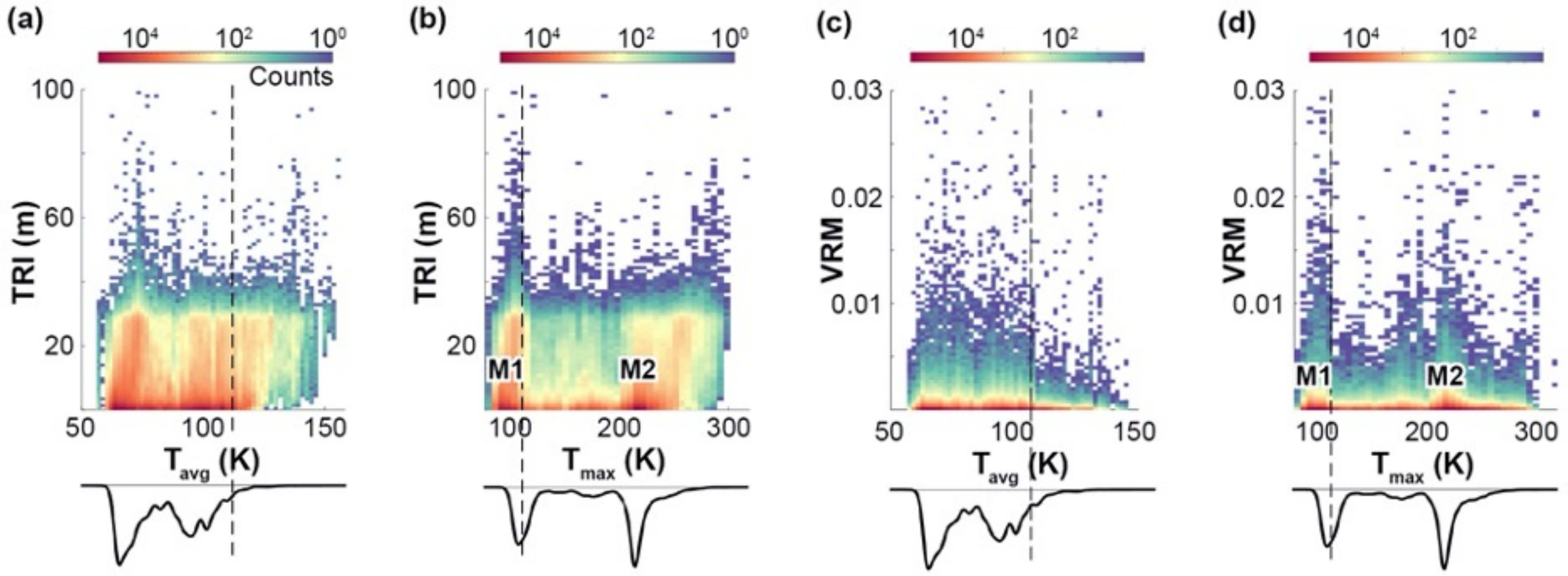


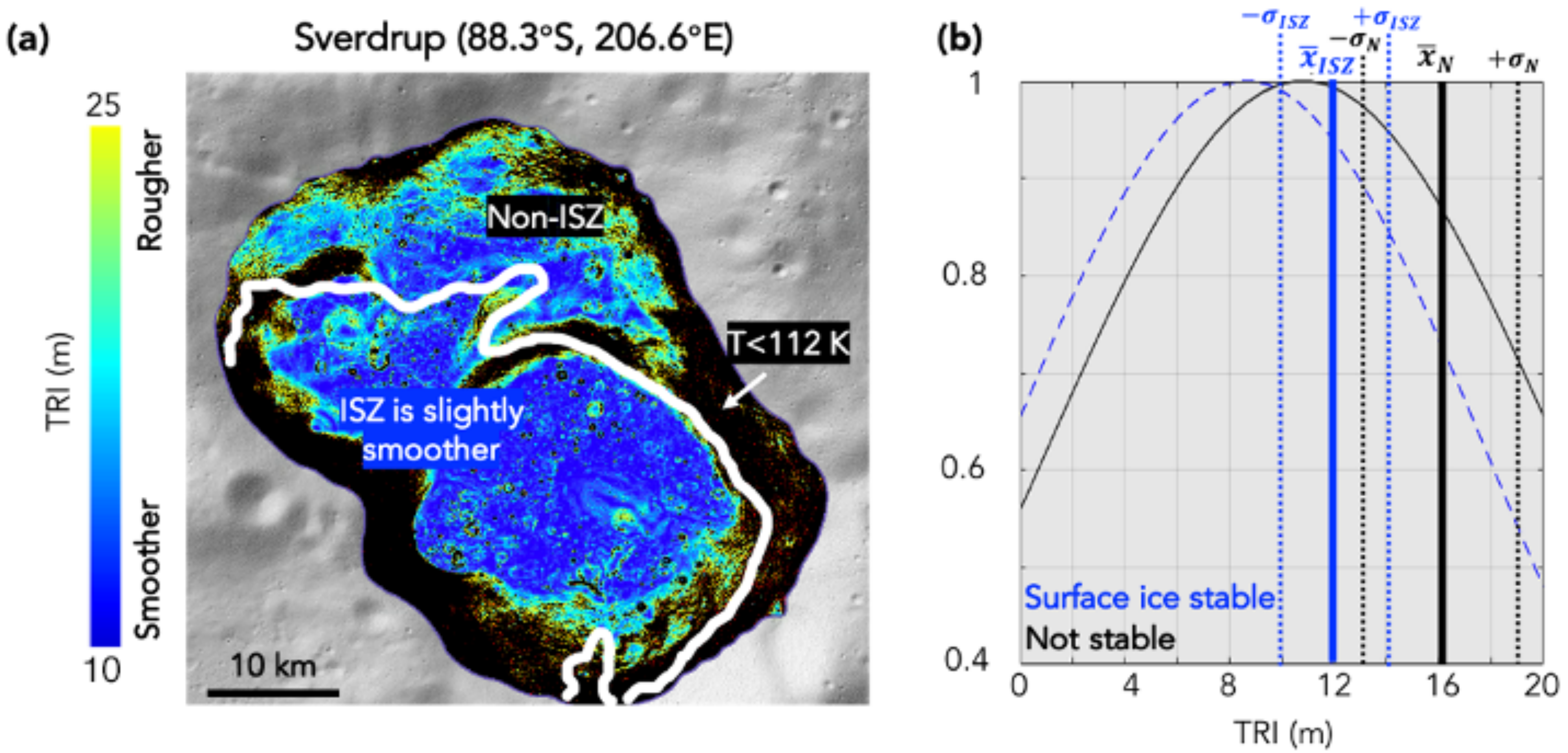
"Landforms inside two craters likely to host water ice are found to exhibit expressions of geologic processes…as yet **indistinguishable from non-ice-bearing craters**. Differences in wall slopes are attributed to typical crater variability. Additionally, **we found no definitive evidence of permafrost-like landforms or features suggestive of surface frost"**

Brown et al. 2020

"Finally, we closely examined HORUS images of all AoI PSRs for evidence of surface frost or ice, such as e.g. bright patches or lenses, although **we could not find any such evidence**"

Bickel et al., in press

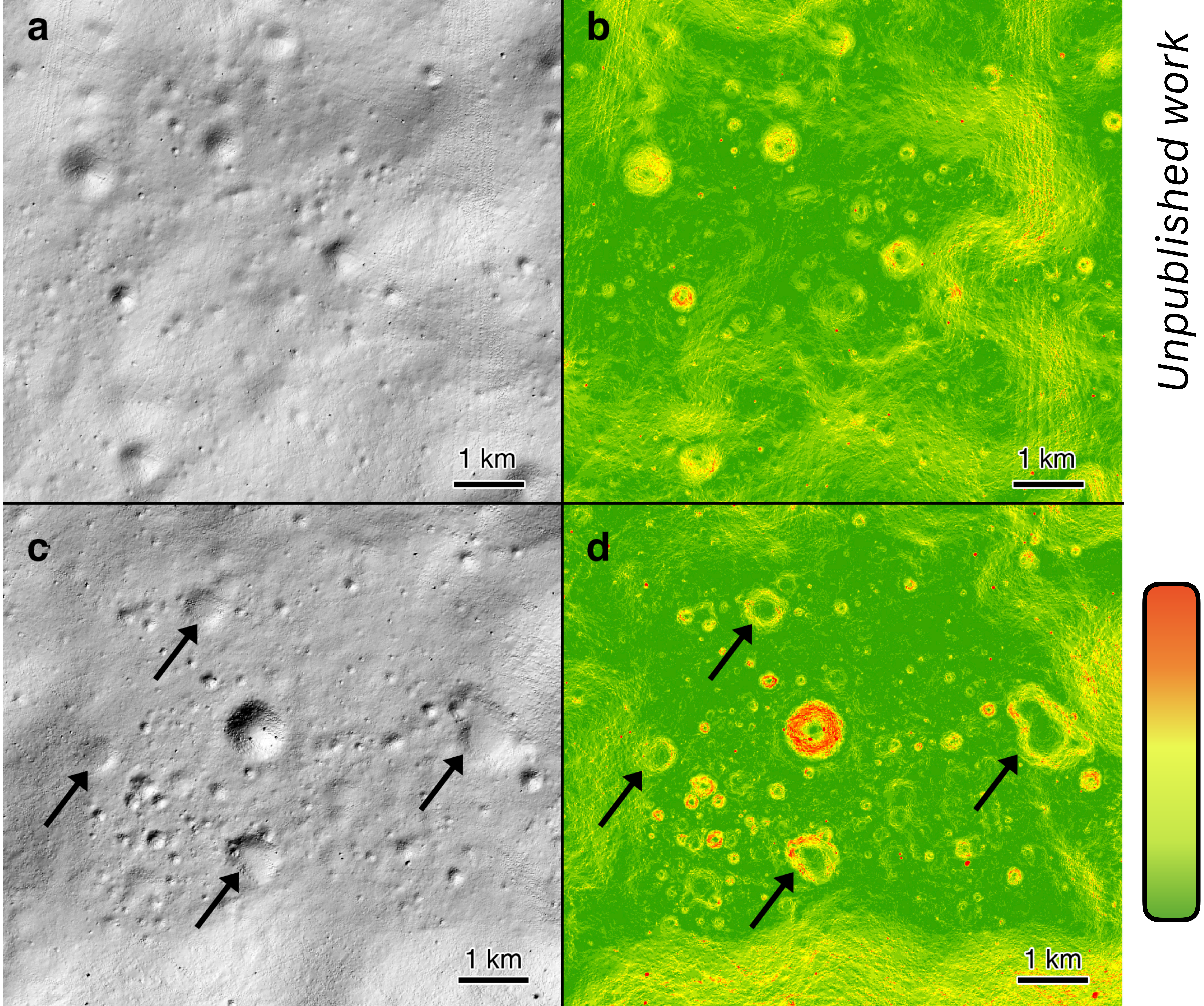




From Deutsch et al. *under review*

Warmer region

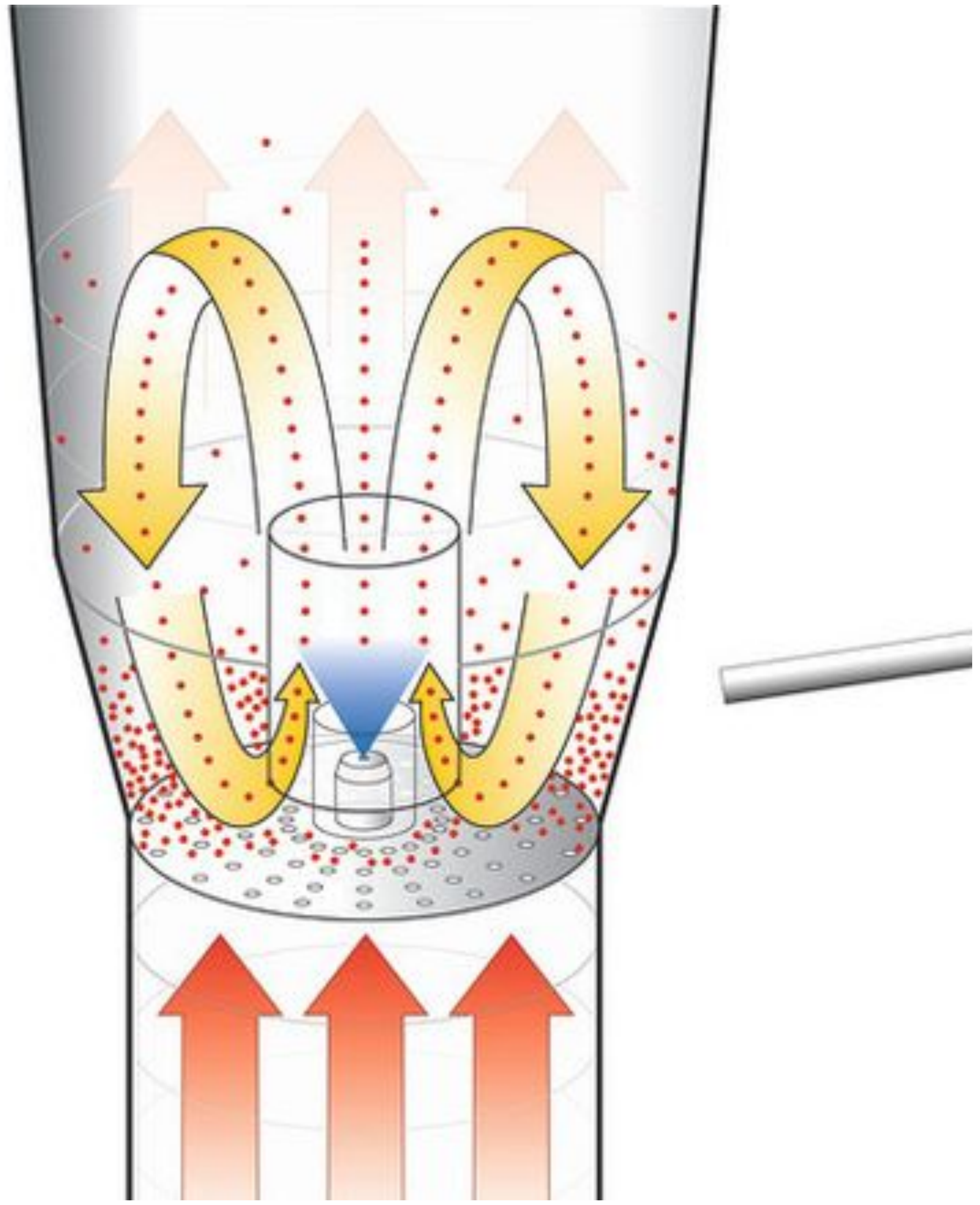
Colder region



Unpublished work

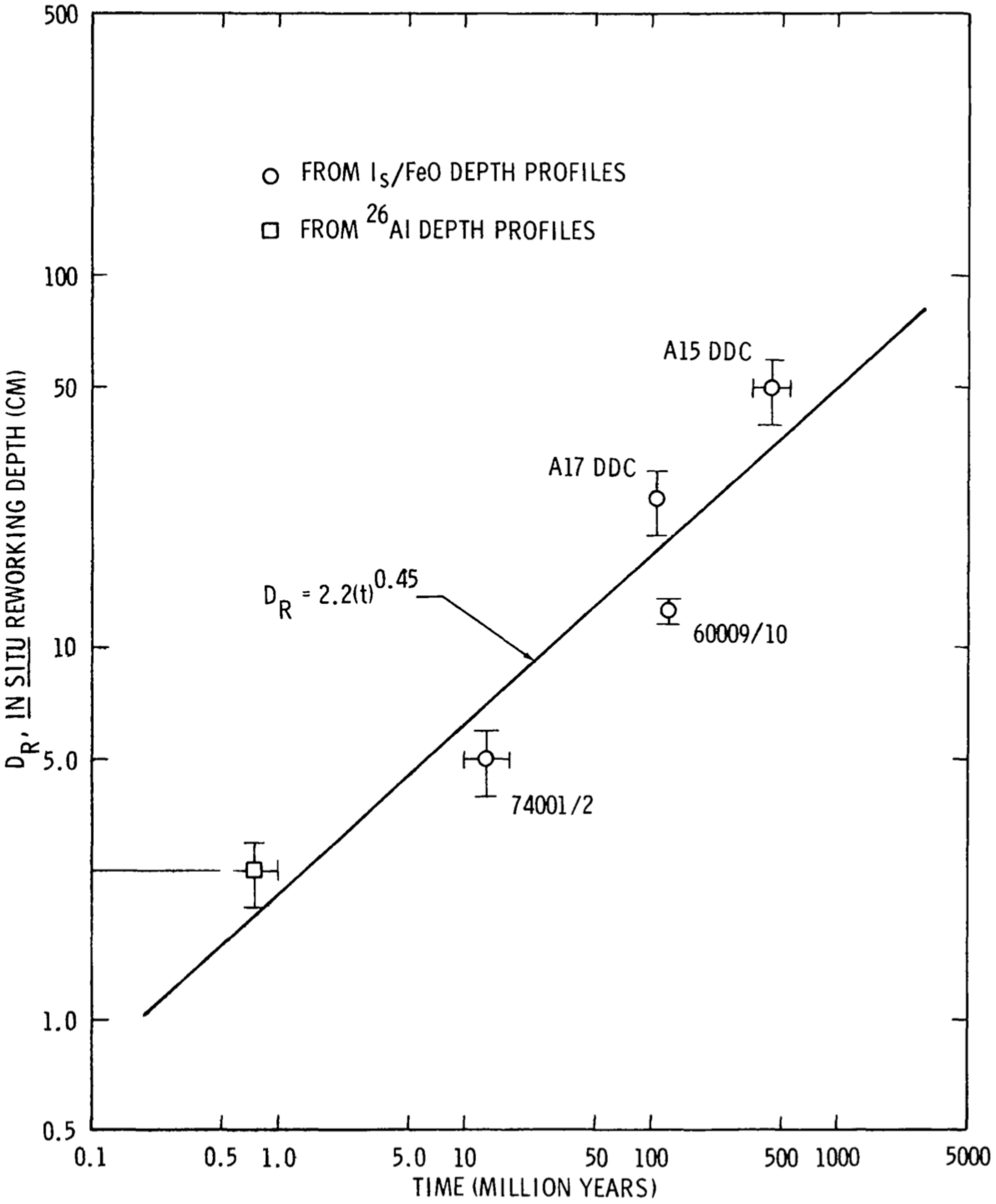

Thin, very patchy transient frost, not enough to even be visible in imagery
10 µm
Surface ice
Shallow ice
Desiccated zone 10s of cm thick
Perhaps up to 1 wt.% disseminated in the regolith
1 m
Deep ice
Potential for thick, relatively pure subsurface layers meters to 10s of meters beneath the surface
>10 m


Micrometeroid vaporization
Sublimation
Micrometeroid ejection of icy grains
Solar wind sputtering



These effects only penetrate millimeters deep, so how does a thick desiccated layer form?

Impact gardening churns the regolith like a *fluidized bed*: each chunk of regolith is brought up near the surface in time where it gets charbroiled.

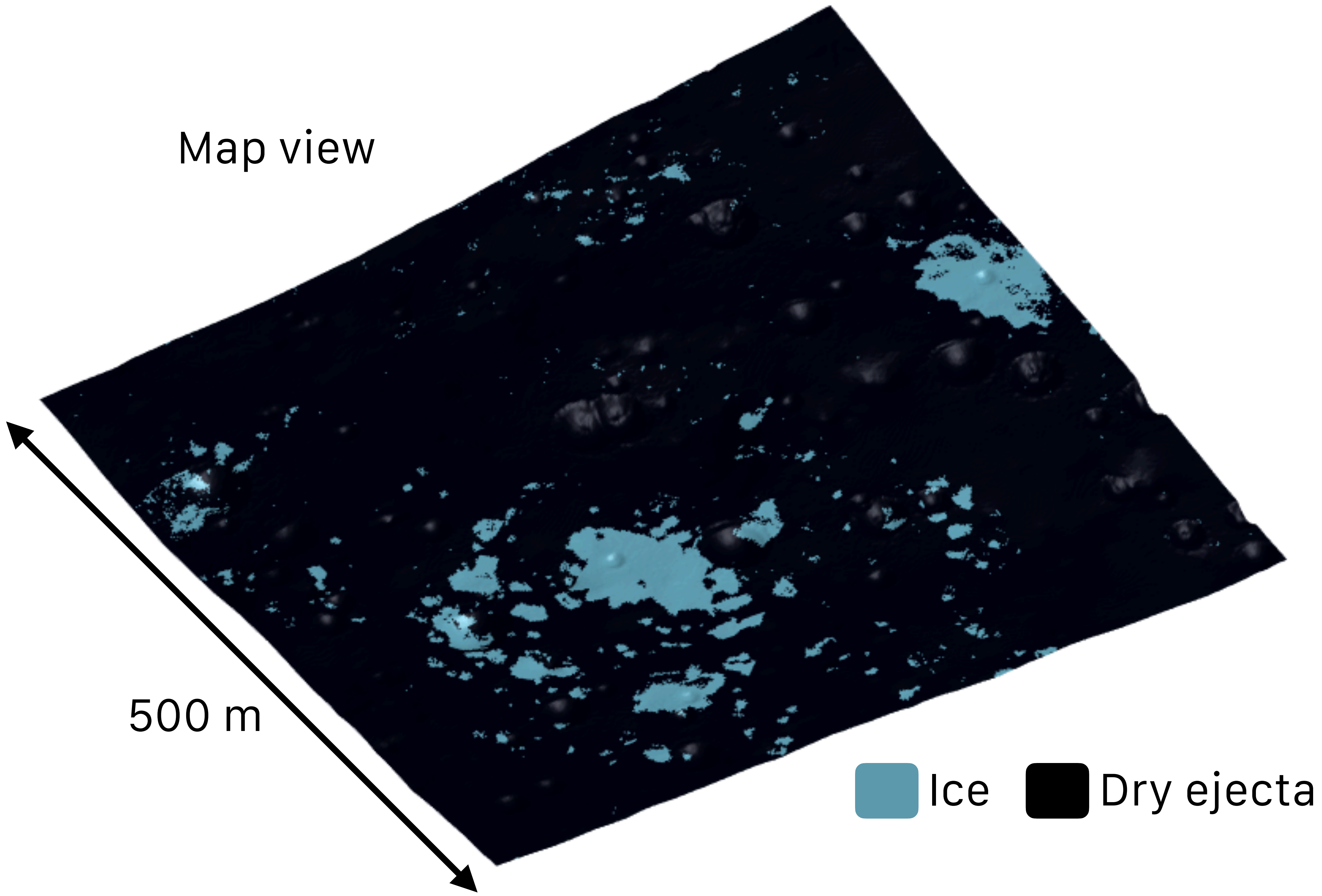


From Morris et al. 1978

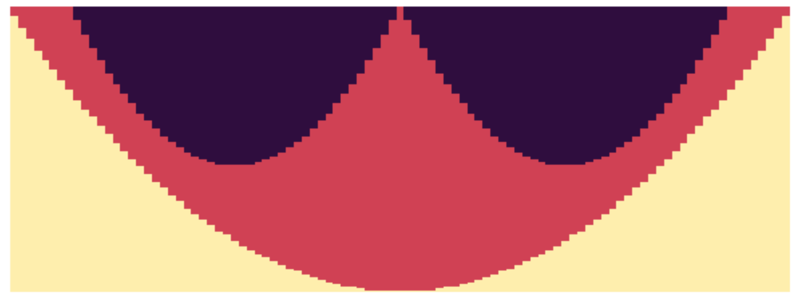
These processes have been well established going back to the Apollo era.

They are well behaved too!

At left: growth of the *in situ reworking depth* over time from Apollo core data.



Cross section



Impact crater template
Purple = ejecta
Red = final crater parabola

ICESTACK: A fully 3D, stochastic ice deposition and impact gardening model

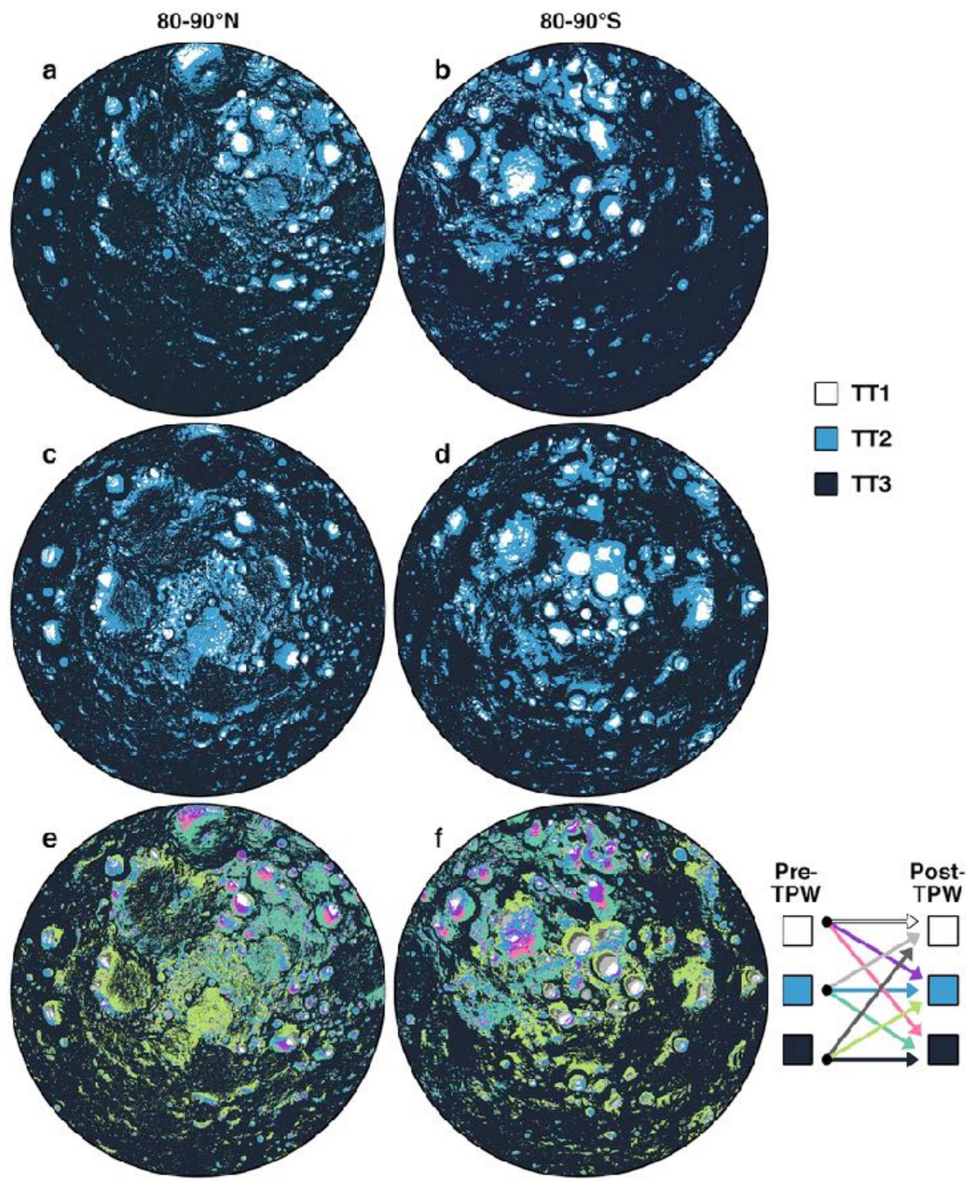
Newly added features:

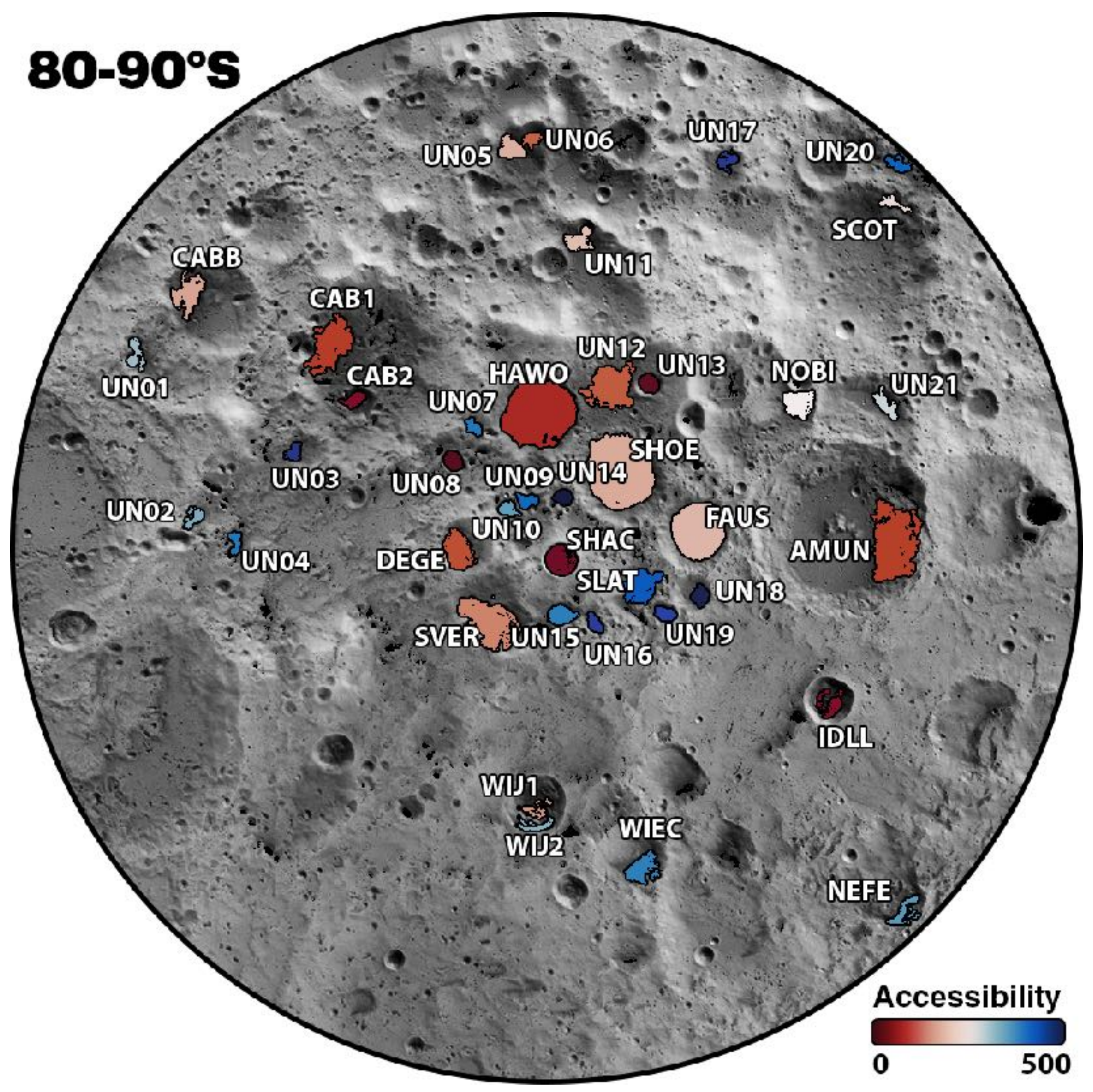
- Tracks ice concentration & ice properties (source, chemistry, δ18O, etc.) simultaneously

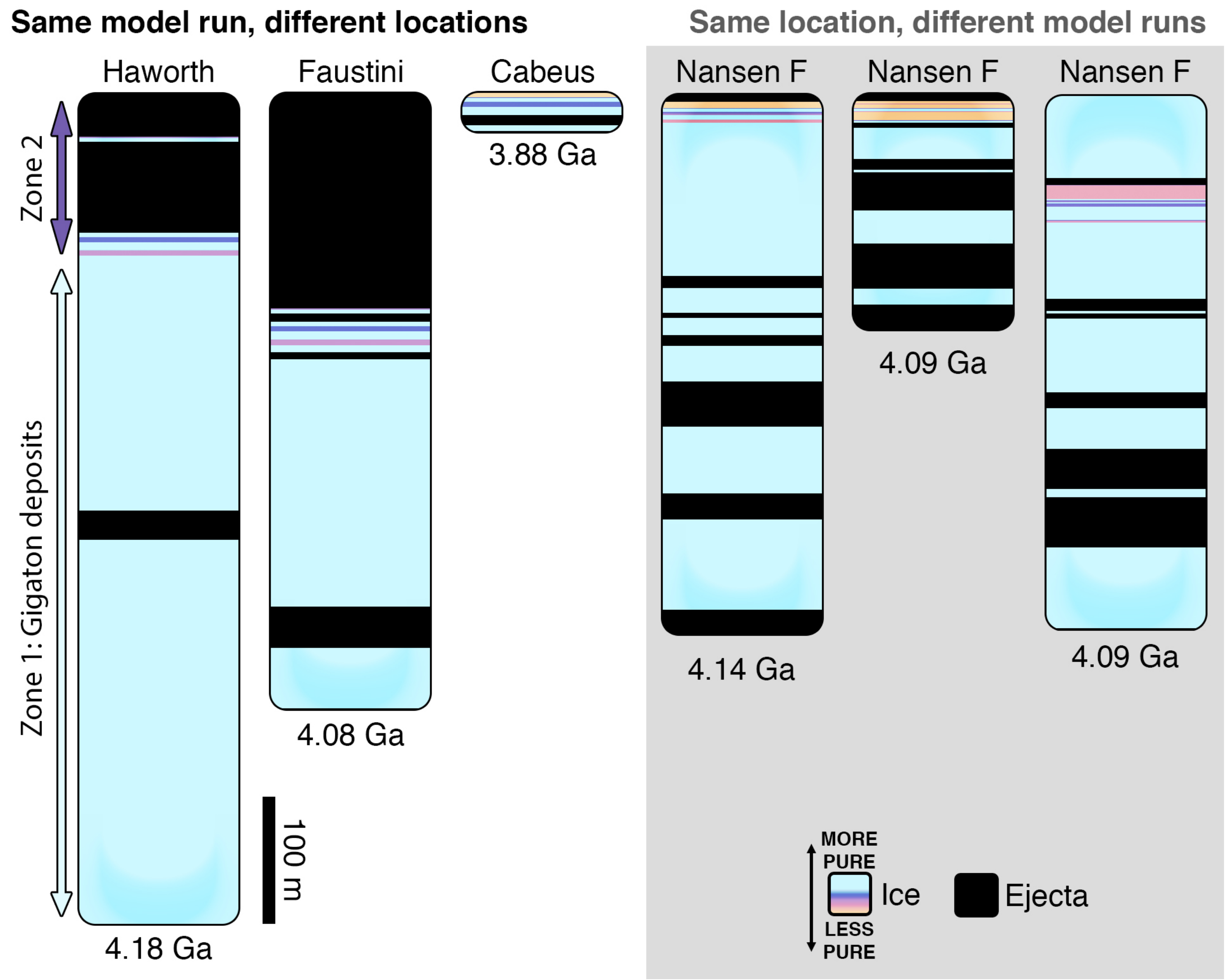
- Takes in ice stability depth maps as inputs

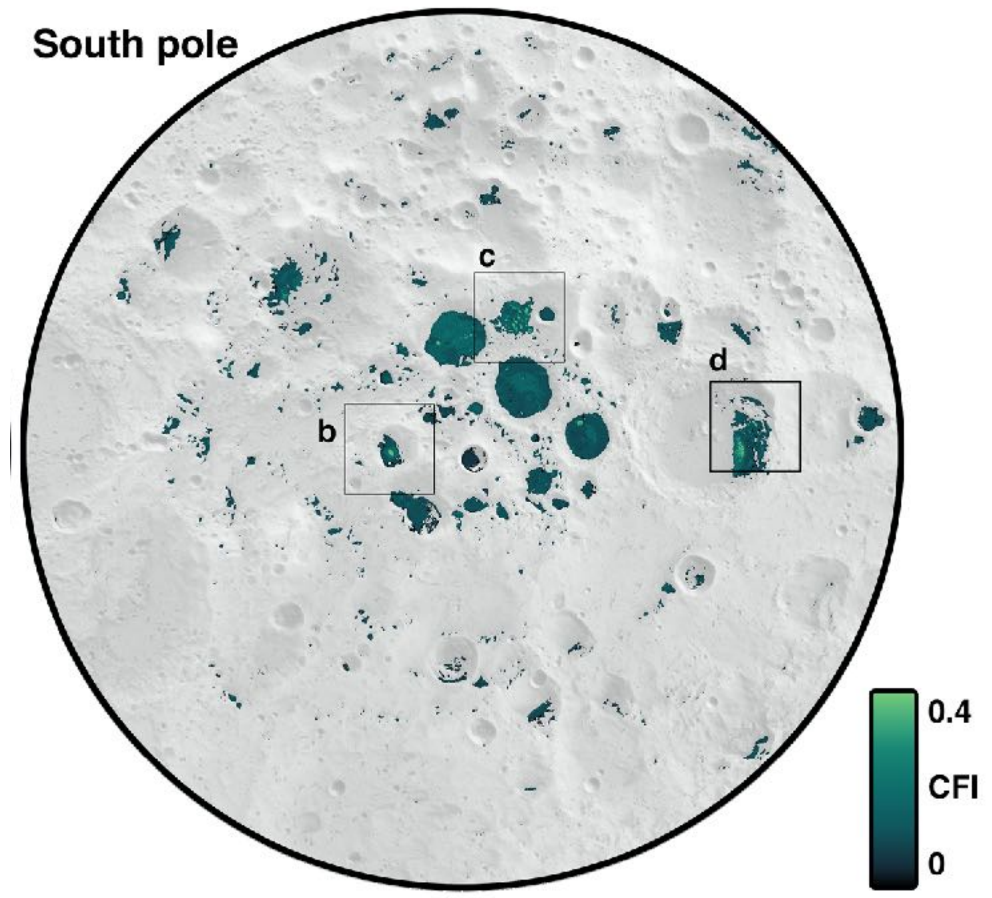
- Improved handling of surface ice erosion

- 3D topography & erosion









[Cannon and Britt 2020, A Geologic Model for Lunar Ice Deposits at Mining Scales, *Icarus*]

[Cannon and Britt 2020, Accessibility Data Set for Large Permanent Cold Traps at the Lunar Poles, *Earth and Space Science*]

[Cannon et al. 2020, Stratigraphy of Ice and Ejecta Deposits at the Lunar Poles, *Geophysical Research Letters*]

[Cannon 2021, Accessible Carbon on the Moon, *arXiv [preprint]*]

Is polar water ice an oasis or mirage?

1. Remote sensing data and geologic understanding *do not* suggest economic concentrations of ice exist in the upper meter.

2. There could be significant reservoirs deeper down, but the evidence is indirect.

3. New approaches are likely needed both for prospecting deep ice, and accessing it. If these prove too difficult, oxygen from regolith may be a better alternative for propellant production.

PTMSS Planetary & Terrestrial Mining Sciences Symposium & Space Resources Roundtable

Hosted by the Canadian Minerals and Metals Plan Secretariat

The Canadian Minerals and Metals Plan / Le Plan canadien pour les minéraux et les métaux

Financé par Ressources naturelles Canada / Funded by Natural Resources Canada

Canada

Virtual 2021

Asteroids/Simulants

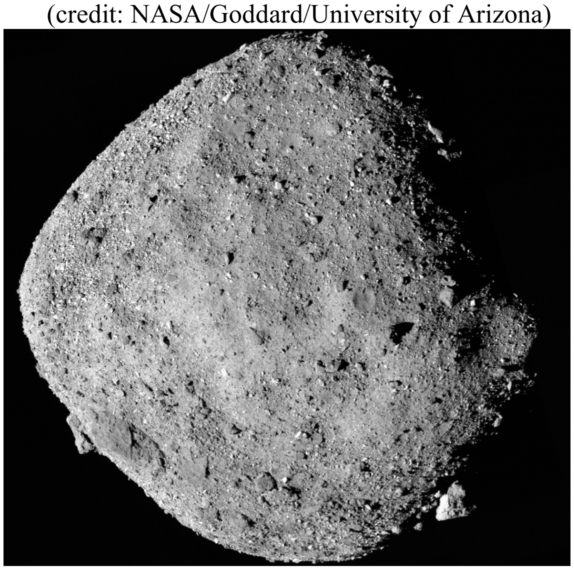
ASTEROID BENNU: THE FIRST AND BEST TARGET FOR AN ASTEROID MINING DEMONSTRATION MISSION. C. S. Dickinson[1], A. T. Polit[2] and D. S. Lauretta[3], [1]MDA 4700 Airport Rd., Brampton, Ontario, L6S 4J3, Canada, cameron.dickinson@mdacorporation.com. [2]University of Arizona, 1415 N 6th Ave, Tucson, AZ 85705, United States, anjani@orex.lpl.arizona.edu. [3]University of Arizona, 1415 N 6th Ave, Tucson, AZ 85705, United States, lauretta@orex.lpl.arizona.edu.

Introduction: With NASA's decision to return to the Moon by the mid-2020s, the need for supporting cis-lunar infrastructure (between Earth and the Moon) will move to the forefront — specifically, the need for low-cost, high-volume consumables, such as water and rocket propellant. Such infrastructure would unlock not only cis-lunar opportunities, but lower the cost of delivering essential supplies to Earth and lunar orbits, as well as facilitate future lunar and Martian surface opportunities. The opportunity to service cis-lunar space is not limited to governments, as private industries, such as SpaceX, have publically indicated their plans to provide interplanetary services.

Several recent developments indicate that such resources could be derived from near-Earth asteroids (NEAs) in an economically viable manner. These include existing asteroid missions, to upcoming resource-extraction demonstration missions. With over 20,000 NEAs available to be mined, the potential for growth could quickly exceed that of Earth's easily accessible minerals.

Initial efforts will almost certainly focus on the extraction of water, as it can be used for human consumption, rocket propellant, energy storage (fuel cells), radiation shielding, and more exotic applications like space agriculture.

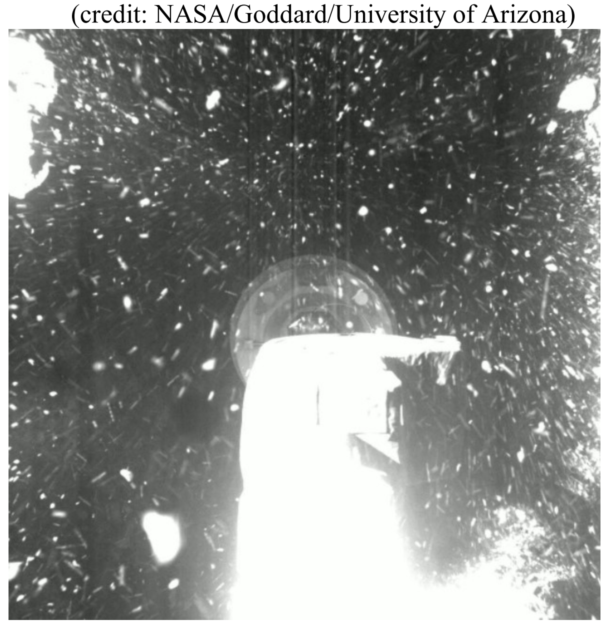
Figure 1. Asteroid Bennu, as observed by the OSIRIS-REx spacecraft
(credit: NASA/Goddard/University of Arizona)



The OSIRIS-REx Mission: NASA's Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft was launched in September of 2016 and rendezvoused with its target, the carbonaceous NEA (101955) Bennu (Figure 1), on December 3, 2018. A comprehensive survey campaign was undertaken for the following 22 months, culminating in the successful acquisition of ~400 g of sample [1]. Of the discoveries made by the mission, at least three are relevant to the extraction of space resources:

Water. The presence of hydrated minerals on Bennu was predicted [2] and later detected via spectrometers aboard the OSIRIS-REx spacecraft [3]. The presence of hydrated minerals will be confirmed when the sample is returned to Earth, but their spectral signatures were observed in the sampling area prior to acquisition [1]. Meteorites with similar spectroscopic features have been found to have compositions of hydrated minerals (silicates) of >55%.

Figure 2. The sample acquisition mechanism making contact with the surface of Bennu
(credit: NASA/Goddard/University of Arizona)



Regolith Physical Properties. Ultimately, the composition of the sample will be determined by Earth-based methods; however, what is known from the sample acquisition operation is that the surface of Bennu is composed of loose regolith that "responded like compliant, viscous fluid" to contact from the spacecraft [1]. The head of the sampling mechanism reached a depth of (more than) 50 cm [1] (owing to a combination of spacecraft inertia and the nitrogen-driven sample acquisition mechanism, shown in Figure 2), indicating little or no resistance. Spectral data show that much of Bennu has a similar composition [3], making materials easily extractable.

Surface Topography. Bennu was surveyed using a scanning laser altimeter [4], which globally surveyed the surface to resolutions of better than 10 cm. Bennu has a wide range of boulder sizes ranging from tens of meters down to less than a meter [5], and thus a variety of extraction strategies could be formulated and tested as part of a demonstration mission.

Economics of Bennu: When determining whether to collect water on asteroids or the Moon, plentiful hydrated asteroids with a large size are favorably accessible in terms of delta-v. It has been estimated, primarily on the basis of mass and spectral properties, that Bennu contains ~$670M worth of retrievable minerals, with an estimated profit of ~$185M [6].

Conclusion: Bennu offers an attractive target for a demonstration mission and/or technology demonstration for water extraction from a carbonaceous asteroid. The asteroid has a favorable delta-v, it has been well characterized, and the returned sample will provide a wealth of information on the mineral composition and physical properties. The fact that the surface of the asteroid has been extremely well surveyed provides an excellent reference for the development of a mineral extraction concept of operations, as well as the follow-on technological development.

Acknowledgments: We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible. OLA and funding for the Canadian authors were provided by the Canadian Space Agency. This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program.

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[6] http://www.asterank.com/

An Asteroid Regolith Database for ISRU.

Amara L. Graps [1,2,3] , Karlis Slumba[2], and Marta Vaivode[2], [1]amara@balticsinspace.eu [2]karlis.slumba@gmail.com [1]Baltics in Space, A. Caka iela, 96-31, Riga, Latvia LV-1011; [2]University of Latvia, Jelgavas 3, Riga, Latvia LV-1004; [3]Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, Arizona, USA.

Abstract: We have developed the first database of asteroid regolith properties: "ARD": one hundred asteroids so far, to aid space resource utilisation workers. The physical parameters: grain density, grain size, near surface bulk density and porosity are provided of a collection of the asteroids. The strength of our method is that it combines three types of information: 1) spacecraft-based, in-situ data, 2) laboratory-based meteorite samples, and 3) telescopic, remote data, such as from polarization-- the joint usage which amplifies the success and the probability of gaining new information. The database is also uniquely robust, due to its large number of crosschecks for the database's regolith parameters. Theoretical and laboratory studies provide additional crosschecks. See Figure 1.

Introduction: In-space resource utilization will provide an extension of our SpaceShip Earth to include space infrastructures for, and of, our robots that are orbiting the Earth and traveling beyond. With such space resources, we can service, recycle, or build anew, without the limitations of carrying the resources from the Earth. Telecommunications, Earth observations, planetary research, extraterrestrial life explorations, are just a few examples, which can be implemented cheaper and more efficiently using resources in space.

Despite the asteroid mining industry's shift to smaller companies since 2018, it is no longer a question of 'if' but of 'when'. The endeavor of the in-space utilization of asteroid resources have several attractive features over their lunar and Martian counterparts, in that their low gravity, large quantities, and tiny sizes lead to different legal regimes [1] for their utilization. The continuing spacecraft miniaturization and drop in the cost of rocket launches support a variety of low-cost asteroid mission philosophies (pg. 56-60 of [2]). The asteroid mining community continues to build successes [3] and there is an active, engaged, international community [2, 4, 5].

Database Strategy: The information detail for each asteroid is uneven. The most detailed-information is acquired from 1) spacecraft measurements –least number of asteroids, 2) laboratory meteorite measurements and 3) regolith simulations. The fewest details – and largest asteroid numbers, are acquired from surveys: radar and optical light curve. If a parameter is deemed necessary for a calculation for a regolith physical property, it is included. This strategy is the reason for the approximately 40 information fields available for each asteroid. We expect that the database format will be more sophisticated, as we grow the database and learn what is needed in the community. In the interest of open, scientific reproducibility and verification, the data format for ARD version 1.0 is a spreadsheet that includes the calculation, for example to derive solid (rock) density from radar albedo. Other notes about the database strategy:

- Most of the ARD information is manually extracted from tables in published research journal articles (and less from official archives). As the asteroid research progress moves quickly, scientific conference attendance with tracking the research through public social media platforms is mandatory.

- With asteroid regolith-related measurements dependent on other factors, we've adopted a strategy of including multiple rows, for each asteroid, to aid future processing and filtering and for determining errors. We provide an identical reference spreadsheet to look up that data source in the [row,column] cell.

- We track the spatial scales where the bulk density and porosity [6] of an asteroid is related to the average density and porosity of its constituent rocks, which is further distinguished from the average density of the mineral assemblages within the rocks.

Regolith Porosity: Due to planned and executed surface operations on the asteroid and the electrostatic risks to equipment, asteroid regolith *porosity* is one of the most important parameters that must be known as precisely as possible. The Hayabusa2 and OSIRIS-Rex sample return space missions are pointing to, not only a very loose, porous regolith, but to *regolith layers of different porosities*, as envisioned in Fig. 5 of [7]. See, e.g. [8] of the regolith before and after the sampling operation on asteroid Bennu. A new view of dust charging since 2016 is the particles' charge buildup in the regolith's porous cavities. The Patched Charge Model [9] shifts our view from the regolith surface to electrostatic charging *within* microstructures inside the regolith, where a negative charge buildup results in strong repulsive forces between the regolith particles, to cause their lofting or mobilization.

Meteorites as Proxies: Measurements of meteorite densities, porosities, thermal inertia, thermal conductivity, heat capacity, and light scattering can act as 'bridge' of ground truth between remote asteroid thermal, radar, and polarimetry measurements, thermal heat conduction models, and first guesses of the multi-layered [7] (or not) regolith physical properties. Meteorites acquired in fresh falls and in measurement conditions near vacuum pressures and at low temperatures are particularly helpful. The ARD v. 1 uses recent compilations by [10, 11] to bridge remote thermal inertia measurements [12,13], radar measurements [14, 15, 16], polarimetry measurements [17]. Empirical, laboratory-based thermal conductivity measurements that can indicate particle sizes [18] are rough, compared to particle sizes derived from theoretical heat conduction modeling [19]. Functional forms to fill in gaps in the data are used whenever possible. For example, upon rearranging the thermal inertia equation, $\rho = \Gamma^2 /(kc_p)$ and keeping track of scales (ρ_{rock} , ρ_{grain}, φ_{rock} , etc., for example: $\rho_{rock} = (1-\varphi_{rock})\rho_{grain}$ we can proceed with the sizes derived from the empirical fits in [20], and cross-check theoretical particle sizes from [19]. See the TREX website for the asteroid regolith database: https://trex.psi.edu/

Methodology: The derived products for the asteroid regolith properties are currently following this flowchart.

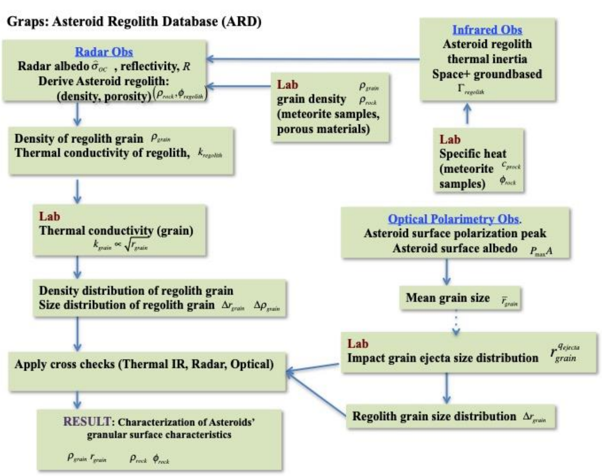

Figure 1: Flowchart of the methodology of the Asteroid Regolith Database.

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SPACE RESOURCES IN CHONDRITIC ASTEROIDS: INSIGHTS FROM CHONDRITE METEORITES.

C. M. Gilmour[1] and C. D. K. Herd[2], [1]Centre for Research in Earth and Space Science, York University, Toronto, ON, Canada. E-mail: cgilmour@yorku.ca, [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada.

Introduction: There is an abundance of precious resources contained within chondritic asteroids. Chondritic asteroids are thought to be the parent bodies of carbonaceous chondrites (carbonaceous 'C-type' asteroids) and ordinary chondrites (stony 'S-type' asteroids) [1]. Due to the aqueously altered nature of C-type asteroids, these bodies are rich in water and volatiles. In contrast, as ordinary chondrites contain Fe-Ni metal, their asteroid parent bodies are suitable for metal extraction. These three resources—water, volatiles, and metal—are essential to the future of space exploration. To assess the quantity of resources within chondritic asteroids, we have completed two comprehensive chondrite meteorite studies: 1) an evaluation of water abundances in pristine samples of the Tagish Lake carbonaceous chondrite via Thermogravimetric Analysis (TGA) [2] and 2) an investigation of Platinum Group Element (PGE) concentrations in ordinary chondrite metal with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) [3]. Here, we summarize our findings to provide insight into the resources that can potentially be mined from chondritic asteroids.

Water: Water is considered the most precious resource as it is essential for life support and is also fundamental for transportation (i.e., rocket fuel and radiation shielding) [4,5]. C-type asteroids are good targets for water extraction. Specifically, water in C-type asteroids is structurally bound in hydrous minerals (i.e., phyllosilicates) in the form of hydroxyl (-OH); the most aqueously altered carbonaceous chondrites contain up to 85 vol.% phyllosilicates [6-8]. Based on carbonaceous chondrite investigations, the most altered carbonaceous asteroid compositions (i.e., CI, CM, and Tagish Lake-like) could potentially yield between 8 and 23 wt.% water (-OH) [2, 9-11]. TGA of the Tagish Lake carbonaceous chondrite has revealed two temperature regions where water is released upon heating: 1) <200°C and 2) 400 to 700°C (Fig. 1). Included in Fig. 1 is the derivative thermogravimetric (DTG) curve which corresponds to the peak temperatures at which the decomposition reaction of minerals and organics occur (refer to [2] for more information). At temperatures <200°C, adsorbed water is released (Fig. 1); however, this water is terrestrial in origin and therefore has no significance for space resource utilization.

The water that has the greatest economic significance is released between 400 and 700°C. Our TGA

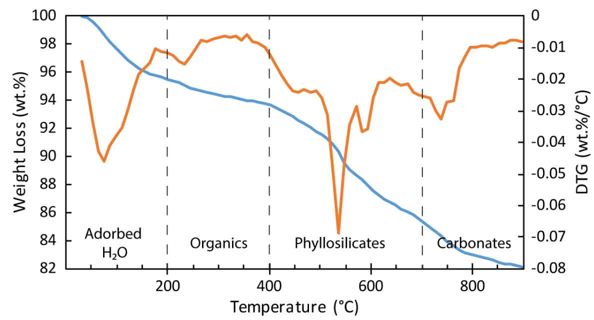

Fig. 1. TGA (blue line) and DTG (orange line) for one Tagish Lake specimen (TL11i). Adapted from [2].

results reveal that dehydroxylation of phyllosilicates occurs within this temperature range (Fig. 1); however other TGA studies of carbonaceous chondrites suggest phyllosilicate dehydroxylation occurs between 300 and 800°C [11,12]. Based on these investigations, heating the carbonaceous material up to 800°C is necessary for extraction of water (-OH).

It is important to note that dehydroxylation of hydroxide minerals has been reported to occur between 200 and 400°C [11,12]; however, the pristine samples of Tagish Lake do not contain hydroxides [2,13]. As hydroxides are believed to be terrestrial weathering products [14], the weight loss between 200 and 400°C is believed to be due to the decomposition of organics (see below), at least in the case of Tagish Lake [2].

Volatiles: C-type asteroids are also potentially rich sources of volatiles, including those essential for life (C, H, N, O, P, and S), as well as NH_3, CO_2, and hydrocarbons [4,5]. However, the amount of volatiles that could be extracted is not well defined. Due to the high abundance of carbon in C-type asteroids, heating the carbonaceous material can result in the autoreduction of magnetite (Fe_3O_4) to Fe-Ni metal [5,15]. It has been stated by [5] and [15] that the autoreduction process can produce ~40 to 45 wt.% of volatiles. However, carbonaceous chondrite TGA results suggest otherwise. Heating carbonaceous chondrites between 200 and 1000°C results in a total weight loss up to 22 wt.%, with the majority of weight loss occurring between 300 and 800°C [2,11,12] (Fig. 1). TGA of Murchison (CM2) insoluble organic matter (IOM) reveals decomposition between 200 and 420°C [2]. Therefore, any weight loss between 200 and ~400°C corresponds to the breakdown of organic material. The amount of weight lost due to the release of organic matter in

Tagish Lake corresponds to ~2 wt.% [2].

It is also important to consider that decomposition of Fe-sulphide minerals can occur between 200 and 700°C [e.g., 11]; however, weight loss related to the release of sulphur is expected to be minor given the relatively low abundance of sulphides in carbonaceous chondrites [6-8]. Furthermore, decarbonation of carbonates releasing CO_2 occurs between 700 and 900°C constituting a weight loss of ~2 to 4 wt.% (Fig. 1, [2], [11]) although [12] suggest that carbonates begin to break down at 600°C.

Based on the observations from TGA investigations [2,11,12], only ~6 wt.% of volatiles from C-type asteroids is expected. However, it is important to note that the TGA analytical conditions are likely not sufficient to properly induce autoreduction. Therefore, a thorough investigation of the autoreduction process in carbonaceous chondrites is needed to confirm the amount of volatiles that could be extracted from C-type asteroids.

Metal: Fe-Ni metal is a fundamental resource for construction material in space [5] and the processing of Fe-Ni metal can provide valuable byproducts such as PGEs. Metallic asteroids are a potentially rich source for metal resources; however, the material processing of these bodies will be difficult given that iron meteorites typically have a crushing strength of 3600 bars [5,16]. Instead, we should consider mining the metal from stony asteroids. Ordinary chondrites have material crushing strengths between 60 and 2600 bars [16], and therefore their parent bodies should be more cost effective and energy efficient to process than metallic asteroids. Furthermore, since ordinary chondrite parent bodies are undifferentiated, they are expected to contain PGE concentrations greater than what is found in the richest deposits on Earth (e.g., Bushveld Complex).

Our study involved the analysis of the main metal phases (kamacite and taenite) in 14 ordinary chondrites via LA-ICP-MS in order to determine the concentrations of PGEs in the metal of chondritic asteroids [3]. Despite the differences in metal abundances among the ordinary chondrite groups (H > L > LL), we found that average PGE concentrations in ordinary chondrite metal are similar among the different groups, within uncertainty (Table 1). Additionally, we have discovered that the variability of PGEs decreases with increasing petrologic type (degree of secondary heating) due to intragrain homogenization during metamorphism [3].

To put into perspective the value of PGEs in ordinary chondrite metal, we can compare these concentrations to terrestrial PGE concentrations in Southern Africa where PGE production is greatest. PGE head grades for 6E PGEs (Pt + Pd + Rh + Ru + Ir + Au) from all South African mines (2010 to 2015) averaged between 3.17 and 3.75 g/t (ppm) [17]. Taking into consideration the metal abundance in ordinary chondrites defined by [18] and the fractions of taenite and kamacite in each ordinary chondrite group from [3], we have found that the average 6E PGE grades in ordinary chondrite metal are 3.56 ppm, 3.26 ppm, and 1.45 ppm for H, L, and LL chondrites, respectively. Therefore, it is apparent that the PGE concentrations in H and L ordinary chondrite metal is comparable—not greater as originally predicted—to the richest terrestrial deposits.

	H		**L**		**LL**	
ppm	**Km**	**Tn**	**Km**	**Tn***	**Km**	**Tn**
Ru	3.3 (0.9)	n.d.	2.9 (1.4)	8.3 [0.9]	n.d.	12.1 (3.9)
Rh	0.95 (0.26)	n.d.	0.93 (0.44)	2.0 [0.2]	n.d.	3.3 (1.2)
Pd	2.7 (0.4)	n.d.	2.8 (0.6)	13 [0.8]	n.d.	15 (1.9)
Os	2.4 (0.7)	n.d.	2.2 (1.4)	6.0 [0.4]	n.d.	6.9 (3.0)
Ir	2.2 (0.7)	n.d.	2.0 (1.4)	4.8 [0.3]	n.d.	6.6 (2.7)
Pt	4.3 (1.2)	n.d.	4.0 (2.3)	9.4 [0.9]	n.d.	15.1 (5.9)
Au	1.0 (0.1)	n.d.	1.1 (0.4)	3.9 [0.5]	n.d.	4.5 (1.0)

Table 1. Average PGE + Au concentrations (ppm) in ordinary chondrite kamacite (Km) and taenite (Tn) from [3]. SD = parenthesis and SE = square brackets. *From a single measurement (BhT-1). n.d. = no data.

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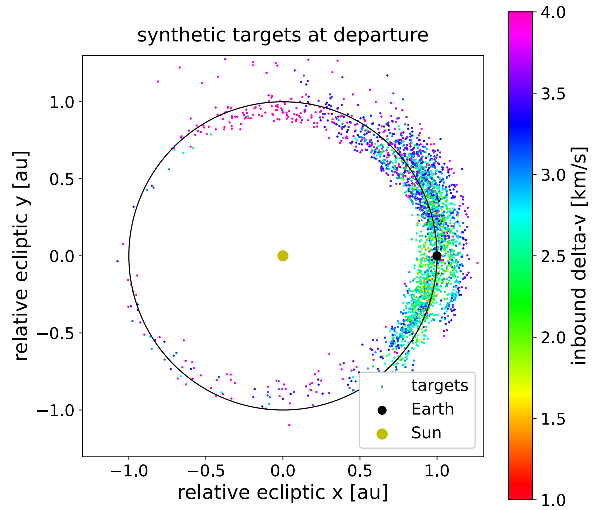
OPTIMISED LOW-THRUST ROUND-TRIP TRAJECTORIES TO THOUSANDS OF ULTRA-LOW DELTA-V ISRU TARGETS. R. Jedicke[1], P. Hermosin[2], J. Sercel[3], S. Centuori[2], M. Sciarra[2], Á. Cano[2] and C. Peterson[3], [1]Institute for Astronomy, University of Hawai`i, 2680 Woodlawn Drive, Honolulu, HI 96822, USA (jedicke@hawaii.edu), [2]Deimos elecnor group, Ronda de Poniente 19, 28760 Tres Cantos, Madrid, Spain (pablo.hermosin@deimos-space.com, simone.centuori@deimos-space.com, marcello.sciarra@deimos-space.com, alvaro.canot@deimos-space.com) , [3]TransAstra Corporation, 11404 Camaloa Avenue, Lake View Terrace, CA, 91342, USA (sercel@transastracorp.com, craig@transastracorp.com).

Introduction: In recent years asteroids have become increasingly interesting due to a heightened awareness of their scientific, commercial, and hazardous properties. Scientifically, they continue to unveil precious details about the solar system's origin and ongoing evolution due to 1) technological advances that have improved their discovery and characterization rates by orders of magnitude and 2) the many spacecraft missions that have visited a growing list of these diverse objects. They are commercially valued at trillions of dollars once the technology has evolved to the point where mining is economically viable. Finally, the danger of asteroid impacts on Earth has become fully appreciated only in the past half century and dedicated efforts to identify the most dangerous km-scale asteroids have already reduced the risk of an unknown impact by more than 90%. Even so, the residual risk remains significant and justifies continued investment in identifying smaller, but still hazardous, objects.

The Problem: Irrespective of whether the motivation is scientific investigation, deflection for planetary defense, or the profit margin of an asteroid mining company, there is a growing need for rapid cost evaluation of asteroid mission scenarios that requires novel optimisation tools and techniques. The identification of the most interesting or profitable targets may require screening trajectories for thousands of objects over long time scales of up to a hundred years to identify optimal candidates. Potentially millions of trajectories may need to be calculated to provide a consistent comparison, especially for round-trip sample return or mining missions. The problem's complexity is reduced with the use of high-thrust, pseudo-impulsive chemical propulsion but explodes in the case of more realistic continuous, low-thrust missions that e.g. use less fuel and are therefore more profitable.

The Solution: We describe our method to solve the problem based on combining a fast but low fidelity optimiser (SESWIC; an in-house tool developed by Deimos) with a high-fidelity trajectory design [1] to provide quick and robust trajectories. We applied our algorithm to optimise round-trip low-thrust missions to a catalogue of more than 4,000 synthetic but realistic ultra-low Δv near Earth objects [2] over the course of the next 100 years. In this case, the customer, TransAstra Corporation, plans to extract water from the asteroids, use some of the extracted water as fuel for the return trip to the Earth-Moon system, and then sell the remaining water to customers in high Earth orbit or e.g. at NASA's Lunar Gateway [3]. Our tools allow the company to maximize their profit margin by minimizing the use of fuel/water over multiple launch, rendezvous time spans, and return opportunities to each target over the course of the century.



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ASTEROID PROVIDED IN-SITU SUPPLIES (APIS ™) MISSION ARCHITECTURE AND PROGRESS

Joel C. Sercel[1] , Philip Wahl, and Craig Peterson, [1]TransAstronautica Corporation, 10276 Foothill Blvd. Lake View Terrace, CA 91342, sercel@transastracorp.com, philip@transastracorp.com, craig@transastracorp.com

Introduction: In 2015 the first Phase 1 NIAC proposal for the Apis™ architecture quoted the NASA Advisory Council Committee on Human Exploration and Operations, "The mismatch between NASA's aspirations for human spaceflight and its budget for human spaceflight is the most serious problem facing the Agency". This is still the key problem facing NASA. NASA has not yet embraced the innovations needed to enable its great mission ambitions. Apis™ (Asteroid provided in-situ supplies) is a breakthrough mission and flight system architecture that solves this problem by providing all major consumable materials including rocket propellant, radiation shielding, consumable water, and oxygen, thereby collapsing the cost of NASA human exploration of deep space and later the industrialization and human settlement beyond Earth. NIAC was created to solve exactly this type of major strategic problem.

The Patent Pending Apis™ spacecraft concept and mission architecture with Optical Mining™ was invented by the PI in 2013 and advanced to TRL 3-4. Current work has been funded for a ground demonstration model of the Mini Bee™ (The initial version of Apis™ for validation and demonstration in LEO) which will advance key technologies to TRL 4-5.

Key Apis™ innovations and inventions include:

- **Optical Mining™ to extract resources from asteroids using highly concentrated sunlight**. An Optical Mining™ Test Bed (OMTB) has been developed and is currently targeting various test materials including heat resistant bricks and CI type asteroid simulants. Simulants have been developed replicating a range of

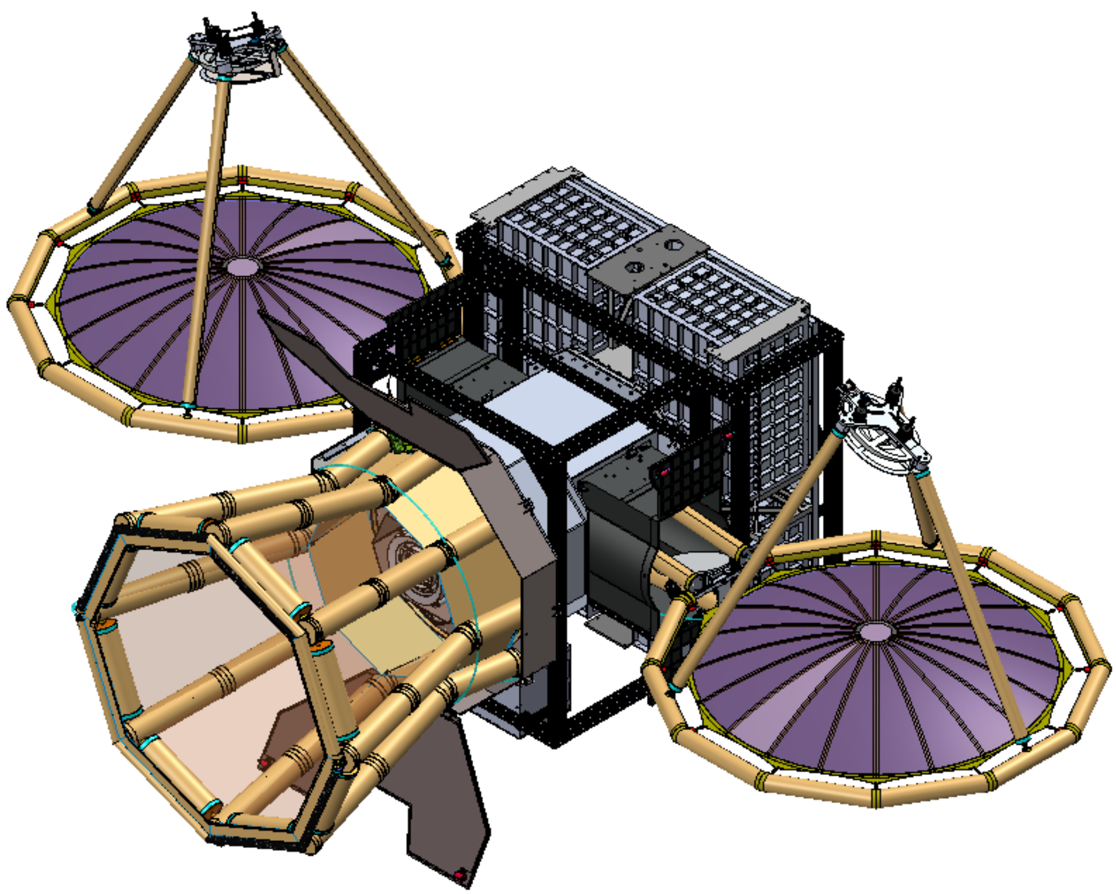

Figure 1= Mini Bee™ Spacecraft

solid form asteroid and regolith types including representatives of both CM and CI materials.

- **The Omnivore™ thruster** is a breakthrough technology which uses asteroid-extracted volatile liquids such as unprocessed water as a propellant.

- **The Apis™ spacecraft architecture** based on Optical Mining, thin film solar reflectors, asteroid capture systems, and water based propulsion is core to the Mini Bee technology demonstrator, the Honey Bee 100 MT ice return system, Worker Bee™ Orbital Transfer Vehicles (OTVs), and the Queen Bee multi thousand ton ice return system.

- **The Apis™ commercial transportation network design** which includes a combination of cargo vehicles and chemically propelled spacecraft for crewed transport with all consumables supplied by Optical Mining™.

Mission and business analysis funded by a combination of private, NIAC, Office of Emerging Space, and NASA SBIR sources has been peer reviewed and published, clearly showing that a Public Private Partnership (PPP) can be applied with the Apis™ architecture promising ~$300B in savings for a NASA HEOMD program over 20 years with human missions to the Moon, asteroids, and Mars. This savings enables affordable cis-lunar tourism and commercial infrastructure for space industrialization and settlement.

CURRENT RESEARCH IN SOIL SEALS, WATER STABILITY, AND SIMULANT BEHAVIOR. Diane L. Linne[1], Fransua Thomas[1], John E. Gruener[2], Douglas L. Rickman[3], and Beau M. Compton[1], [1]NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135 (diane.l.linne@nasa.gov, fransua.thomas-1@nasa.gov, beau.m.compton@nasa.gov), [2]NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058 (john.e.gruener@nasa.gov), [3]Jacobs Space Exploration Group, 620 Discovery Drive Northwest, Huntsville, AL 35806 (douglas.l.rickman@nasa.gov)

Introduction: The past few years have seen an exciting increase in visibility for the use of in-situ resources to achieve sustainability at the Moon and Mars. This visibility and inclusion in the mission architectures has led to an explosion in the research and development of mining and processing of regolith at the Moon. However, there are still many fundamental issues regarding digging, transporting, and processing of lunar and Mars regolith that may slow the progress by multiple teams who need to undertand these issues before proceeding with hardware development. The objective of this project is to utilize the same team of soil and thermal experts and unique facilities to allow for efficient and fast generation of fundamental data and dissemination of critical results to the larger community. The capability gaps being addressed include how to dig up hard, frozen resources, transport to the processing site, lifting/depositing into a hopper or reactor, and extracting the water, all without losing the primary product to the environment.

Soil Seals: Much attention has been focused on the challenges with regolith inlet/outlet valves that must seal in process gases after being repeatedly exposed to abrasive regolith and dust particles. One possible solution that has been proposed is to design the inlet hopper or duct such that the bulk of regolith provides sufficient sealing of the reactor. Tests are planned to parametrically measure the maximum delta-pressure that can be maintained across a column of soil before 'blow-out' occurs. Variables to be examined include column height and width, simulant type, and compaction.

Soil Transport: The water that has been identified in the permanently shadowed regions of the Moon's poles has spurred significant research for feasible and optimal methods of mining and extracting it for propellants and life support. Prospecting missions are planned to better determine the spatial and vertical distribution of the water. The current prevailing theory is that the top centimeters of regolith are desiccated due to impact gardening and long-term exposure to hard vacuum [1]. Several test campaigns conducted in the NASA Glenn Research Center vertical dirty thermal vacuum chamber has measured significant drying of the top centimeters of water-doped simulant in an 11-inch liquid-nitrogen chilled simulant bin after several days exposure to vacuum levels on the order of 1×10^{-6} Torr [2]. In addition, icy simulant brought to the surface in those tests on the flutes of an auger and brushed into a sample container experienced 50 percent or greater water loss after only a few minutes of exposure. All of this raises questions of how much water will be lost during excavation and transport of the raw resource before it can be processed in a controlled manner. Tests are being designed to parametrically measure the amount of water lost in various size transport bins as a function of transport time, agitation, etc.

Highland Simulant Behavior: During the past two decades of research in excavation and regolith processing it has been well-recognized that using appropriate simulants is critical to designing hardware and conducting tests that produce relevant results. The plans to explore near the polar regions has resulted in taking a new look at the mineral and chemical makeup of lunar highlands regolith and developing simulants that more closely mimic those properties. Recent tests with the new Greenspar highland simulant in a carbothermal reactor has highlighted the significant differences in melt viscosity which can have significant consequences on processing methods that have to-date been mostly tested with mare simulants. A brief discussion on the key composition differences that are driving this viscosity change will be discussed and demonstrated.

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THERMAL PROPERTIES OF LUNAR MATERIAL IN PERMANENTLY SHADOWED REGIONS
R. J. Macke[1], C. P. Opeil[2], D. T. Britt[3], and G. J. Consolmagno[1]; [1]Vatican Observatory, V-00120 Vatican City-State, rmacke@specola.va; [2]Boston College Dept of Physics, 140 Commonwealth Ave, Chestnut Hill MA 02467, opeil@bc.edu; [3]University of Central Florida Dept of Physics/ Center for Lunar and Asteroid Surface Science, 4111 Libra Dr., Orlando FL 32816, britt@physics.ucf.edu.

Introduction: Thermal emission data from the Lunar Reconnaissance Orbiter Diviner Lunar Radiometer Experiment indicate that permanently shadowed regions of the Lunar surface, such as those near crater rims in the extreme polar regions, may have temperatures as low as roughly 20 K [1,2]. Given that these regions are also candidates for reservoirs of permanently frozen water, understanding the thermal properties of Lunar materials at comparably low temperatures may be vital for Lunar resource utilization.

To date, thermal properties measurements on Lunar materials and analog Lunar materials has been mostly limited to the temperature range 100-350 K. Woods-Robinson et al. [3] have developed semiempirical theoretical models for Lunar thermal properties at lower temperatures, but there have not been any systematic studies of actual Lunar materials at temperatures below about 100 K.

We have measured heat capacity, thermal conductivity, the coefficient of thermal expansion, thermal inertia, and thermal diffusivity for six Lunar meteorites from Northwest Africa [NWA]. These include Lunar feldspathic breccias (NWA 5000, NWA 10678, NWA 11421, and NWA 11474), a gabbro (NWA 6950) and a troctolite (NWA 8687). Heat capacity data are supplemented by a further nine specimens collected from African desert regions.

Measurement: All thermal measurements were conducted using a Quantum Design Physical Properties Measurement System (QD-PPMS) at Boston College. The measurement procedure is described in detail in [4]. Meteorite specimens are cut to parallelapipeds a few mm per side (exact size varies depending on the particular measurement). The device uses liquid He coolant to precisely control the temperature over a range 5 - 300(+) K, enabling the measurement of thermal properties as a function of temperature.

Thermal diffusivity and thermal inertia were calculated from heat capacity, thermal conductivity, and meteorite bulk density. Thermal diffusivity is $D_T = \kappa\, \rho^{-1}\, c_p^{-1}$, where κ is the thermal conductivity, c_p is specific heat capacity, and ρ is bulk denity. Thermal inertia (Γ) is calculated $\Gamma = (\rho\, c_p\, \kappa)^{1/2}$.

Results and Discussion: Our results are summarized in Figures 1-5. Heat capacity is a strong function of temperature over the range 5 – 300 K. Thermal conductivity is a weak function of temperature above about 100 K, but in the range 5 - 100 K temperature becomes very important. This is consistent with what we have observed for other meteorites [4,5].

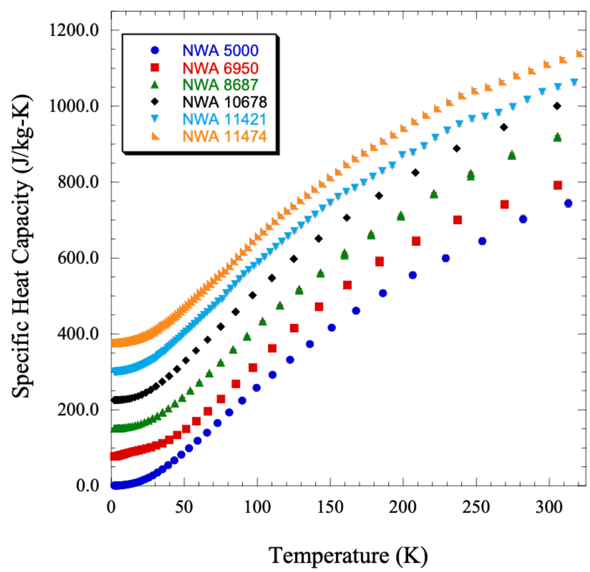


Figure 1: Heat Capacity as a function of temperature for the six specimens in this study. Plots are offset vertically by intervals of 75 J kg^{-1} K^{-1} to distinguish each meteorite.

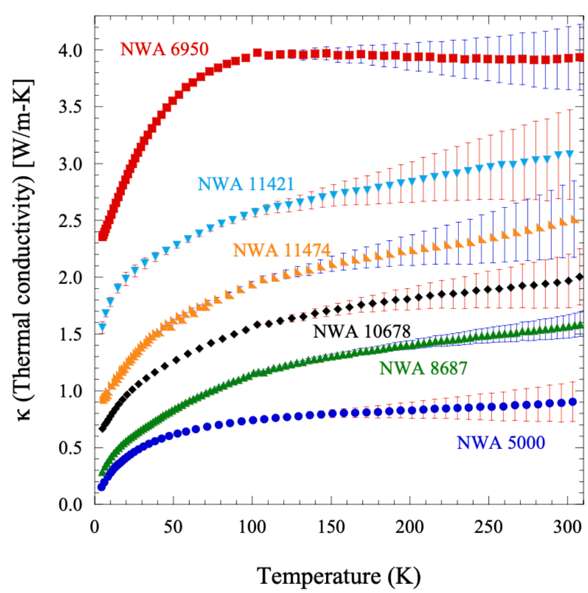


Figure 2: Thermal Conductivity as a function of temperature for the specimens in this study. Data are offset vertically by varying amounts to distinguish each meteorite. Note that κ varies lightly above 100 K but is a strong function of temperature below 100K.

In previous studies of CM2 carbonaceous chondrites, we observed a zone of negative thermal expansion centered at about 235 K, which we attribute to phyllosilicates [4]. Several of the lunar meteorites in this study also include a zone of negative thermal expansion centered at about 75-80 K. This negative thermal expansion (NTE) behavior in lunar samples differs from CM2, as it is caused by a different mineral component, most likely from the abundant lunar silicate mineralogy [6,7]. NTE in silicates has been observed by [8].

References: [1] Aye K.-M. et al. (2013) *LPSC XLIV* #3016. [2] Paige D. A., et al. (2010) *Science* 330, 479-482. [3] Woods-Robinson R. et al. (2019) *JGR Planets* 124, 1989-2011. [4] Opeil C. P. et al. (2020) *Meteoritics & Planet. Sci.* 55, E1-E20. [5] Opeil C. P. et al. (2012) *Meteoritics & Planet. Sci.47, 319-329.* [6] Lucey P. et al. (2006) *Rev. Mineral. & Geochem*. 60, 83-219. [7] Papike J. J. et al. (1998) "Lunar Samples" in *Planetary Materials*, chapter 5. [8] White G. K. (1973) *J. Phys. D: Appl. Phys.* 6, 2070-2078.

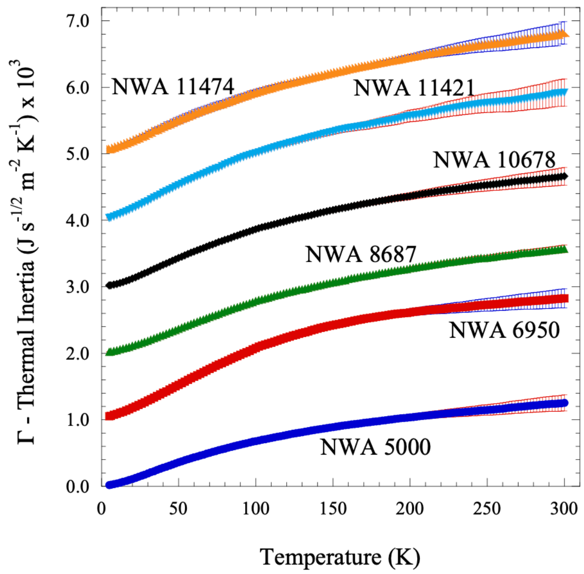


Figure 4: Thermal Inertia as a function of temperature for the specimens in this study. Data are offset vertically by intervals of 10^3 J $s^{-1/2}$ m^{-2} K^{-1} to distinguish the different meteorites.

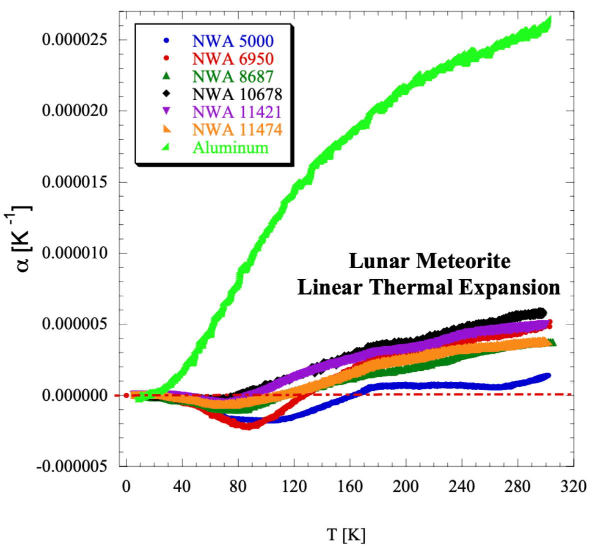


Figure 3: Coefficient of linear thermal expansion for the meteorites in this study. (Aluminum is included for comparison.) Note the range of negative thermal expansion for these specimens centered at about 80 K.

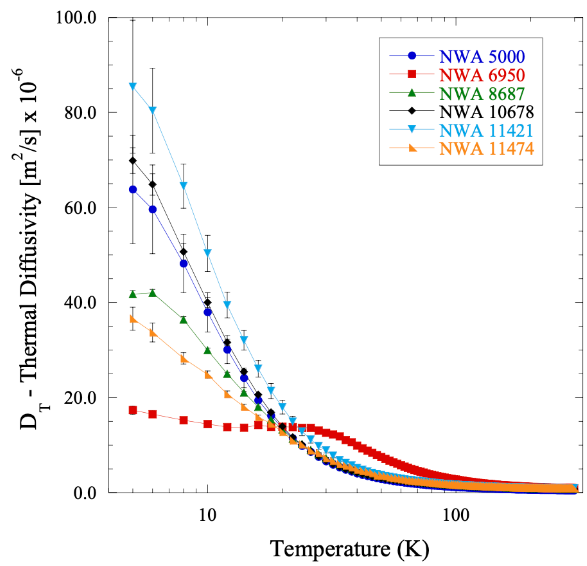


Figure 5: Thermal diffusivity as a function of temperature for the specimens in this study. Temperature is scaled logarithmically. Note the strong temperature dependence below 100K.

Space Resources in Chondritic Asteroids: Insights from Chondrite Meteorites

Cosette M. Gilmour & Christopher D. K. Herd

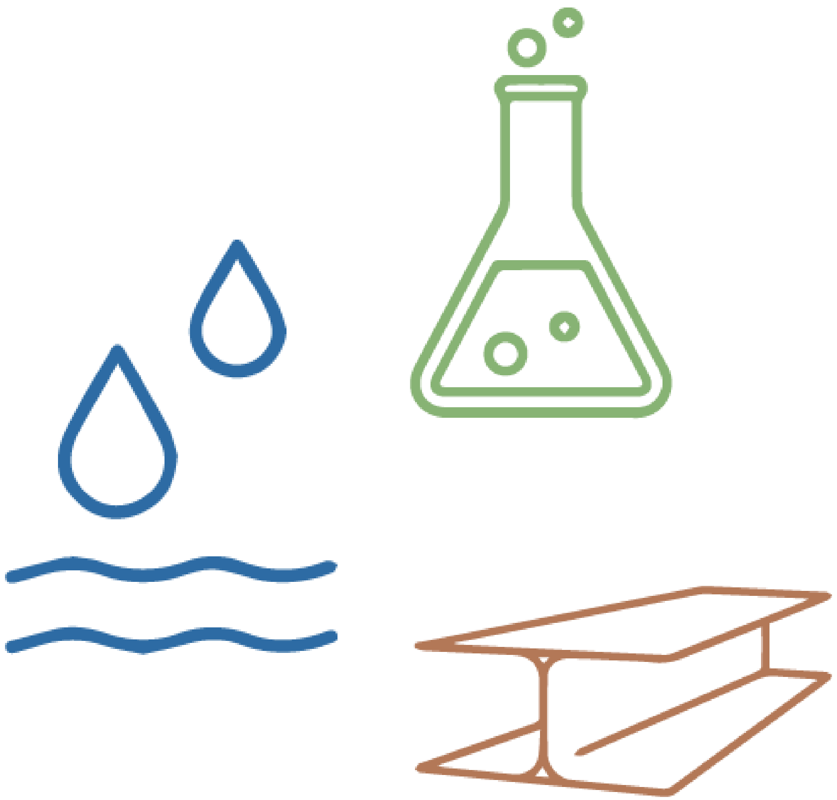
PTMSS 2021 – June 9, 2021

LASSONDE SCHOOL OF ENGINEERING
YORK U
UNIVERSITY OF ALBERTA

Introduction

- Chondritic asteroids are excellent targets for space resources (water, volatiles, and metal)
  - **Confirmed by chondritic meteorite studies**

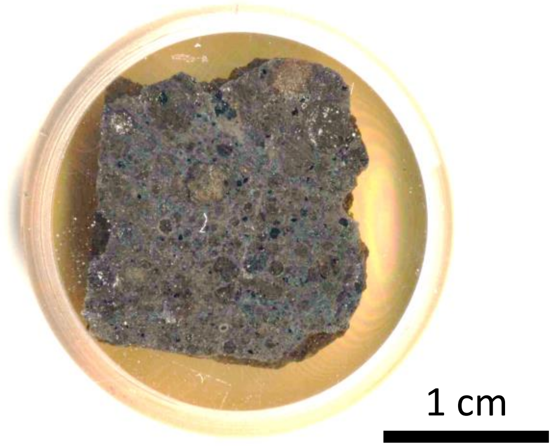
    (Rambaldi 1976, 1977; Kong et al. 1995; Kong and Ebihara 1996, 1997; Hsu et al. 1998; Campbell and Humayun 1999, 2003; Humayun and Campbell 2000, 2002; Garenne et al. 2014; King et al. 2015; Meftah et al. 2016; Gilmour et al. 2019; Gilmour and Herd 2020)
- Carbonaceous chondrites (C-type asteroids)
  - **Water and volatiles** (e.g., Nichols 1993; Ross 2001; Elvis 2014; Garenne et al. 2014; Lewis 2015; King et al. 2015; Gilmour et al. 2019)
- Ordinary chondrites (S-type asteroids)
  - **Fe-Ni metal** (e.g., Rambaldi 1976, 1977; Lewis 1992; Kargel 1994; Kong and Ebihara 1996; Campbell and Humayun 1999; Lewis 2015; Meftah et al. 2016; Gilmour and Herd 2020)



Meteorite Studies

- **Water and volatiles**: Thermogravimetric analysis (TGA) of pristine Tagish Lake carbonaceous chondrite samples for the investigation of water and volatile abundances (Gilmour et al. 2019)

- **Metal:** In situ analysis of Platinum Group Element (PGE) concentrations in ordinary chondrite kamacite and taenite metal with laser ablation ICP-MS (Gilmour and Herd 2020)



Water (C-type Asteroids)

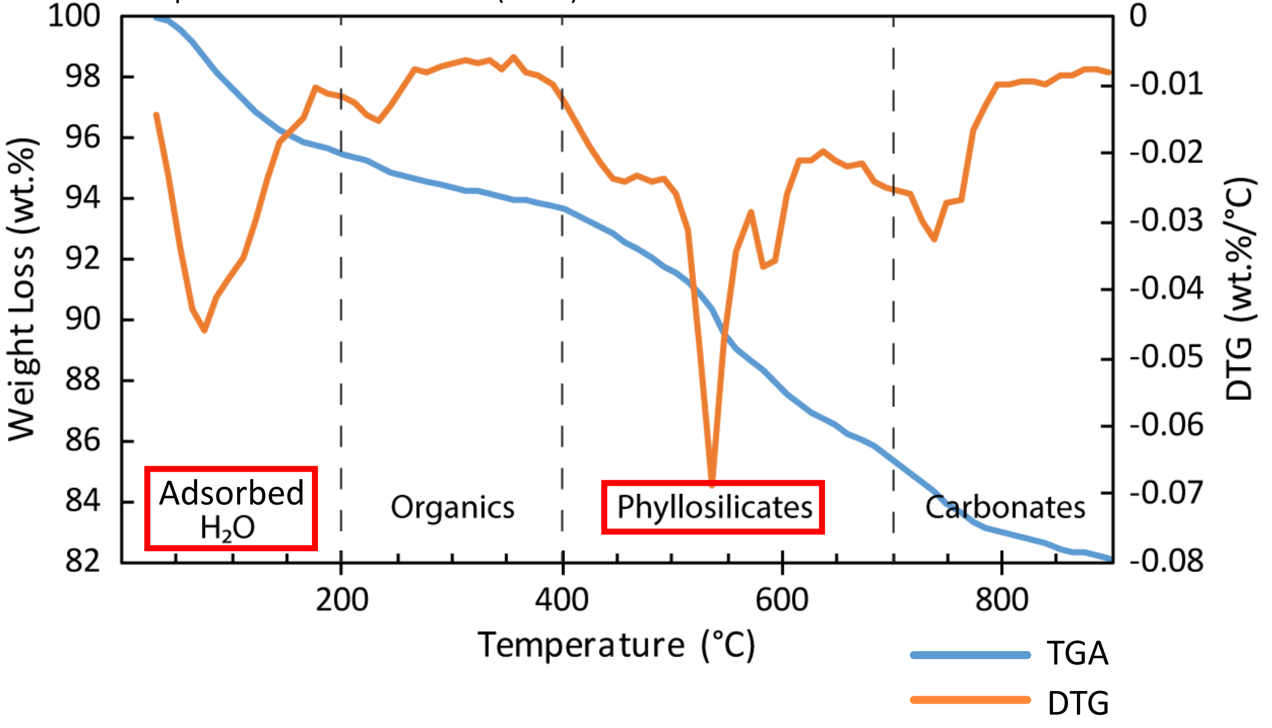
- Essential for life support, rocket propellant, and radiation shielding
- Water is bound in **hydrous minerals** (i.e., phyllosilicates) as **hydroxyl (-OH)**
- C-type asteroids can contain up to **85 vol.%** phyllosilicates (Howard et al. 2009, 2011; King et al. 2015)
  - CI, CM, and Tagish Lake-type asteroids → **8 to 23 wt.%** water (as -OH) (Alexander et al. 2012, 2013; Garenne et al. 2014; Gilmour et al. 2019)
- Gilmour et al. 2019 → Water abundance/form and changes to material from heating

Water: Tagish Lake TGA

- Water: < 200°C (adsorbed) and **400°C to 700°C (-OH)**
  - ~6 to 10 wt.% -OH
- Other studies suggest -OH is released between 300°C and 800°C (Garenne et al. 2014; King et al. 2015), so heating **up to 800°C** would be required for extraction
- Hydroxide minerals have been reported to break down between 200°C and 400°C (Garenne et al. 2014; King et al. 2015)
  - Tagish Lake does not have hydroxides
  - Hydroxides likely weathering products (Bland et al. 2006)
- For Tagish Lake, 200°C to 400°C range is likely **organics**

TGA of Tagish Lake

Adapted from Gilmour et al. (2019).



Volatiles (C-type Asteroids)

- C-type asteroids are potentially rich sources of volatiles
  - Elements of life (CHNOPS), NH_3, CO_2, hydrocarbons
  - Total amount of volatiles not well-defined

- TGA results from Tagish Lake suggest ~6 wt.% release of volatiles (not including OH) from heating

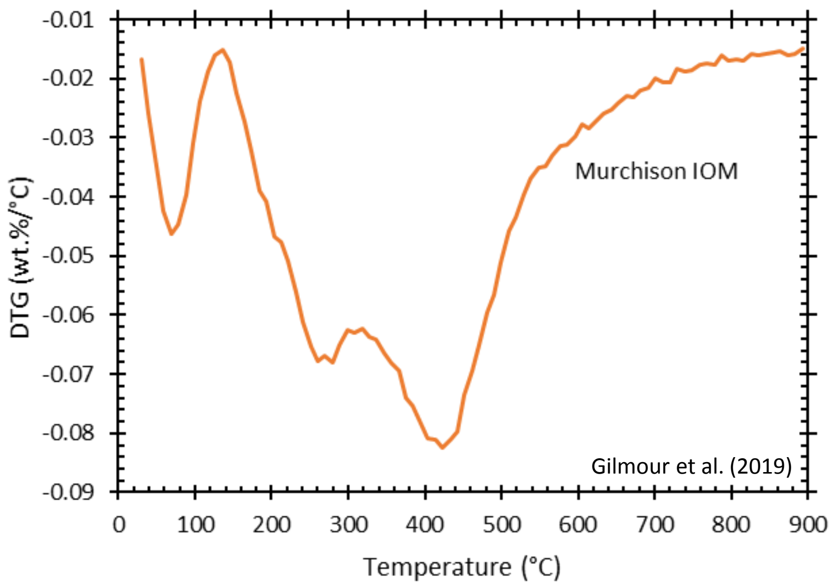
- Autoreduction of magnetite (Fe_3O_4) with organic matter
  - Process expected to produce ~40 to 45 wt.% volatiles (Lewis and Hutson 1993; Lewis, 2015)

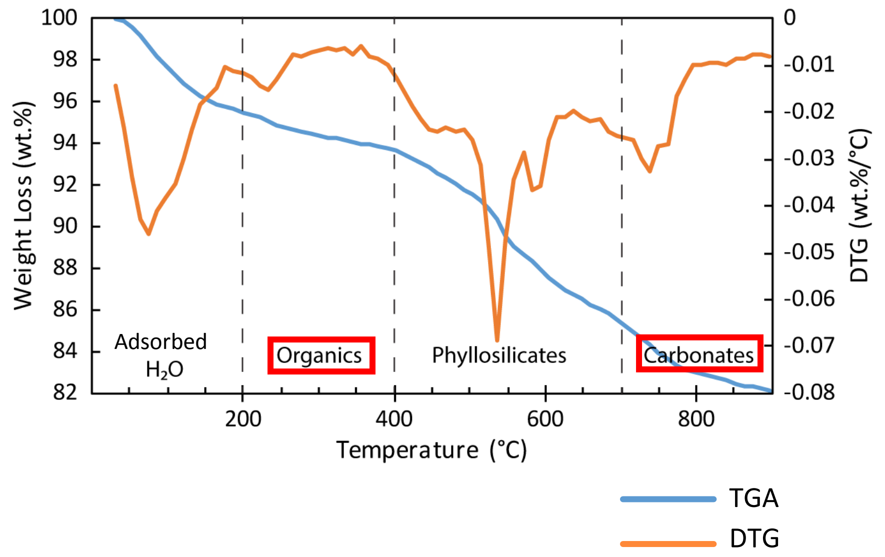
Volatiles: TGA Insight

- Murchison (CM2) insoluble organic matter (IOM) breaks down between **200°C and 420°C**

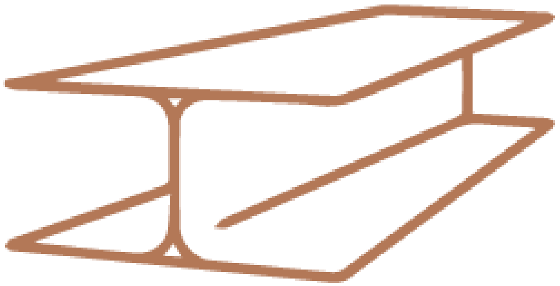
- Tagish Lake (6 wt.% total)
  - Organic material breaks down between 200°C to 400°C
    - **~2 wt.% loss**
  - Decarbonation of carbonates between 700°C to 900°C
    - **~4 wt.% loss**

- Mineral reactions during TGA are not sufficient to induce autoreduction (i.e., 40 to 45 wt.% volatiles)
  - Autoreduction warrants further study





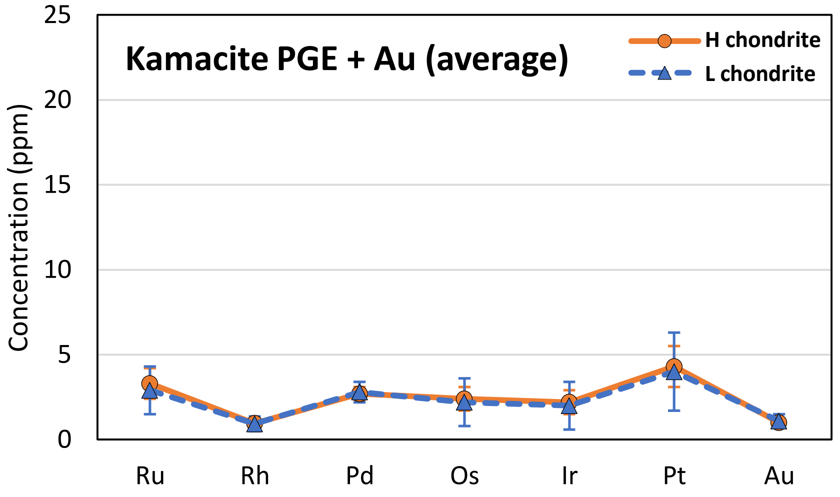
Metal (S-type Asteroids)

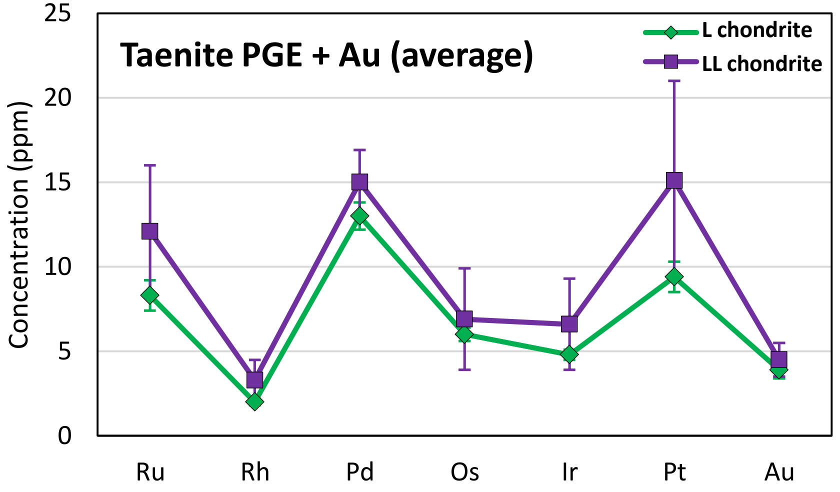


- Fe-Ni metal fundamental for construction material
- S-type vs. Metallic asteroids
  - Metallic asteroids likely rich sources, but processing is more difficult (crushing strength of iron meteorites > ordinary chondrites) (Lewis 1992; Lewis 2015)
  - ∴ S-type asteroids are more cost effective and energy efficient to process
- Processing of Fe-Ni metal can provide PGE byproducts
- Previous estimates suggest that PGE concentrations in S-type asteroids are equivalent or greater than the richest deposits on Earth (e.g., Bushveld) (Rambaldi 1976, 1977; Kargel 1994; Kong and Ebihara 1997)

Ordinary Chondrite (OC) Metal: PGEs

- PGE concentrations in **kamacite** (low-Ni) and **taenite** (high-Ni) analyzed in situ via LA-ICP-MS in 14 OCs
- Metal abundances → **H > L > LL**
  - Kamacite → **H > L > LL**
  - Taenite → **H < L < LL**
- Bulk metal studies suggest PGE concentrations **H < L < LL** (Rambaldi 1976, 1977; Kong and Ebihara 1997)
- Our study (**Gilmour and Herd 2020**):
  - PGE concentrations are higher in taenite
  - Kamacite average PGE concentrations are similar for H and L groups
  - Taenite average PGE concentrations are similar for L and LL groups





OCs vs. Terrestrial Deposits (6E PGEs)

- PGE production is greatest in South Africa
- **6E PGE** grades (Pt, Pd, Rh, Ru, Ir, Au) from all South African mines averaged between **3.17 and 3.75 g/t** (2010 to 2015) (Thormann et al. 2017)
- 6E PGE grades in OC metal based on published metal fractions and averaged PGE concentrations in kamacite and taenite:
  - H chondrites: **3.56 g/t**
  - L chondrites: **3.26 g/t**
  - LL chondrites: **1.45 g/t**… interesting! (PGEs ↑ in taenite)

Conclusions

Water

- Could possibly extract up to 23 wt.% water from carbonaceous asteroids
- CM, CI, and Tagish Lake-type asteroids are most water rich

Volatiles

- Tagish Lake study suggests 6 wt.% volatiles
- Mineralogy of carbonaceous asteroids may not be conducive to autoreduction for volatile extraction
- More studies of other carbonaceous chondrites are needed

Metal

- H and L ordinary chondrite PGE grades are comparable to the richest terrestrial deposits

Gilmour C. M. and Herd C. D. K. (2020) In situ analysis of platinum group elements in equilibrated ordinary chondrite kamacite and taenite. *M&PS*, 55:679-702.

Gilmour C. M et al. (2019) Water abundance in the Tagish Lake meteorite from TGA and IR spectroscopy: Evaluation of aqueous alteration. *M&PS,*

NIAC Phase 3 Apis Demonstration Model Project

PI: Joel C. Sercel, PhD.
SE: Craig Peterson
Eng. Director: Philip Wahl
June, 2021

Project Purpose

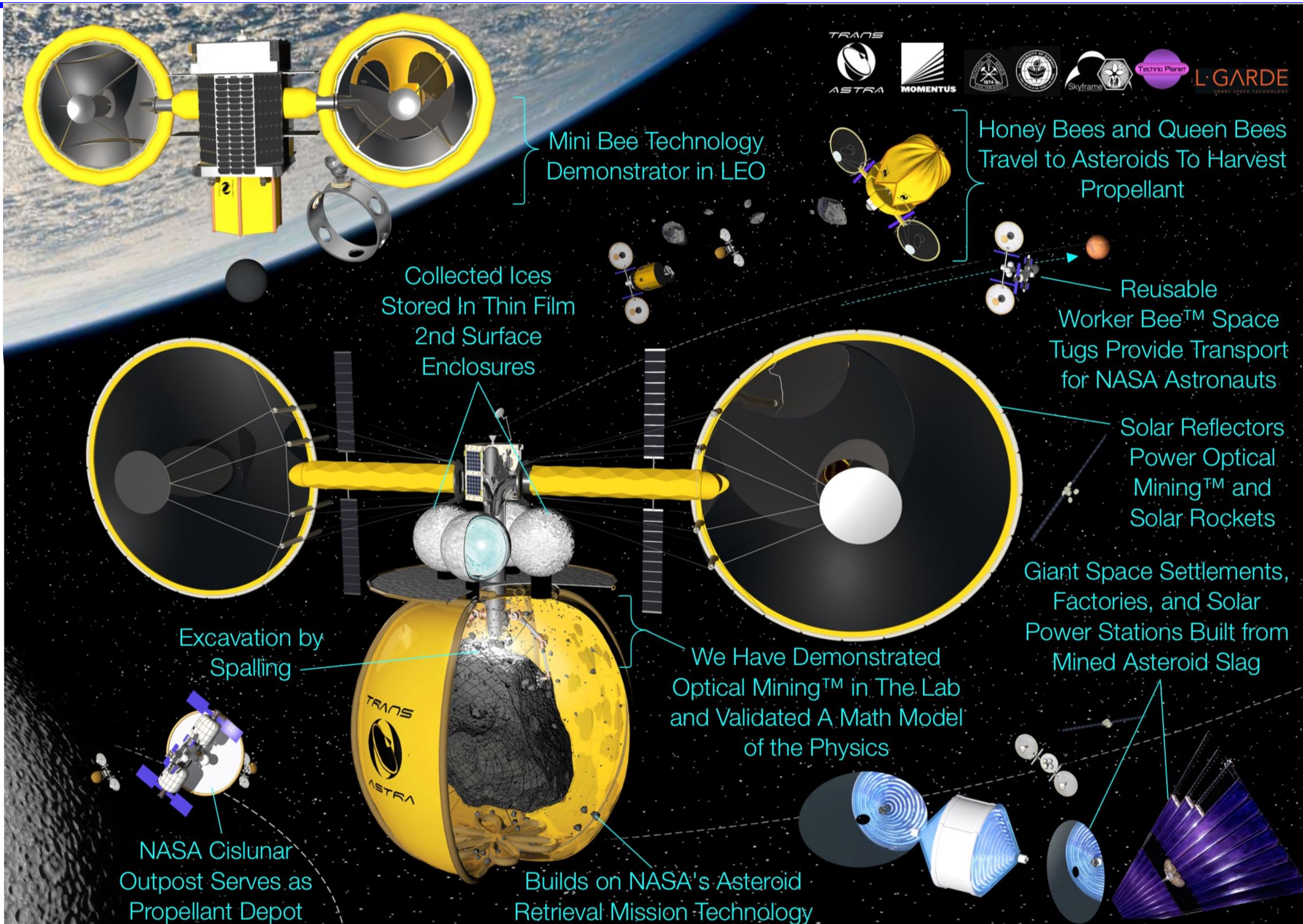
- Close gaps in technical maturity (advancing to TRL 4/5) of Apis architecture to enable Mini Bee™ flight demonstration.

- Mini Bee™ mission will establish the technical feasibility of Apis and advance all critical systems to TRL 6-7.

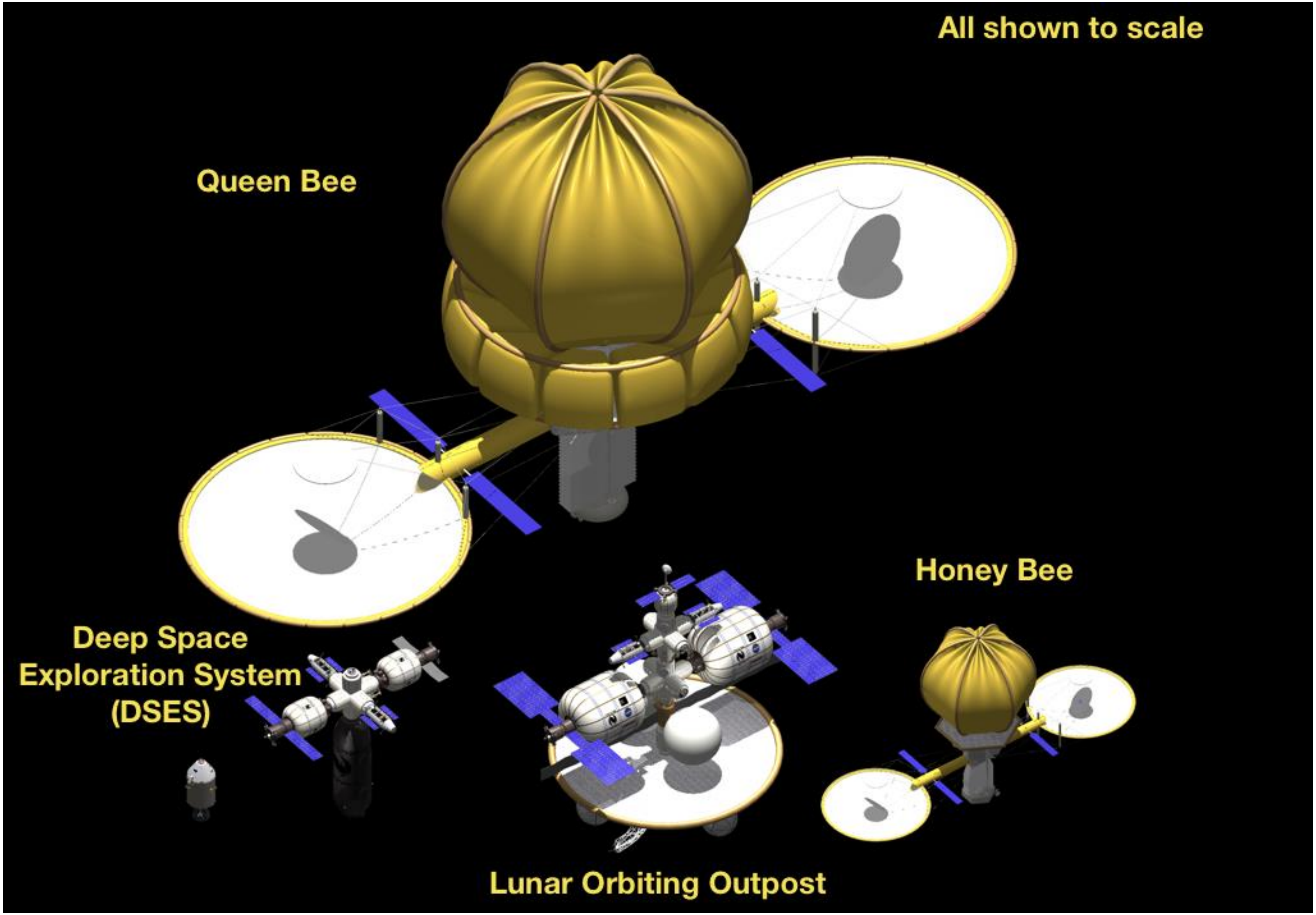
Introduction to Apis™

- 2015 NIAC Phase 1 study "APIS (Asteroid Provided In-Situ Supplies): 100MT Of Water from a Single Falcon 9"
  - -focused primarily on Honey Bee™ 10 m design.
- 2016 Economic Research for Space Development Grant for "Stepping Stones: Economic Analysis of Space Transportation Supplied From NEO Resources"
  - -Focused on economics of applying Honey Bee™ to extract asteroid resources to support exploration of Moon, asteroids, and Mars.
  - -Showed viability of creating a space resources business that would provide substantial savings ($300 billion over 20+ years) to NASA alone, with comparable benefit for other commercial space endeavors
- 2017 NIAC Phase 2 study "Optical Mining of Asteroids, Moons, and Planets to Enable Sustainable Human Exploration and Space Industrialization"
  - -Resulted in development of the Optical Mining Testbed (OMTB) at the Colorado School of Mines to explore the physics of Optical Mining on asteroid simulants.
- Reports available at https://www.nasa.gov/directorates/spacetech/niac/NIAC_funded_studies.html
- https://youtu.be/X5GKz9XLh70

Apis™ Mission Architecture Elements and Application



Apis™ Family



All shown to scale
Queen Bee
Honey Bee
Deep Space Exploration System (DSES)
Lunar Orbiting Outpost

Apis™ Family High Level MEL Comparison

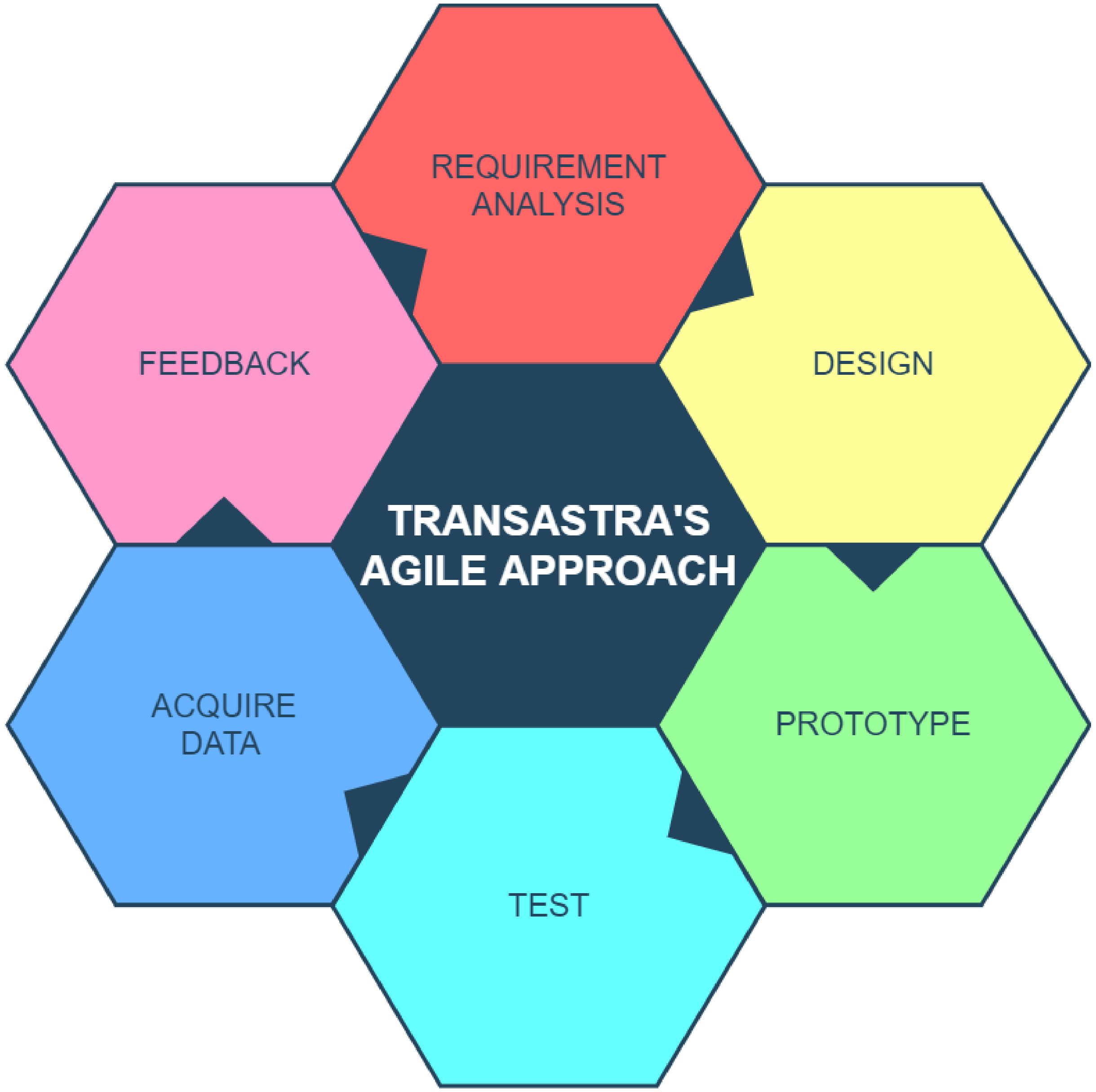
Apis™ Family	Mini-Bee (0.5 m)	Honey Bee™ (10 m)	Queen Bee™ (40 m)
Component	Mass (kg)	Mass (kg)	Mass (kg)
Wet (TOTAL) Mass	178	9,362	39,236
Propellant (water) for 700 m/sec ΔV (*except for Mini Bee)	2*	4,768	19,982
Spacecraft Dry Mass	176	4,594	19,254
Honey Bee™ Asteroid Capture and Extraction System	61	2,226	10,631
Instruments	5	35	35
Power	4	151	151
Inflatable Reflector System	33	189	849
Propulsion – STR (Omnivore™)	14	174	495
Propulsion – RCS	1	34	239
ADACS	2	44	44
C&DH	1	23	23
Comm	1	53	53
Thermal	1	84	84
Structures and Mechanisms	12	520	2,207

Design Philosophy

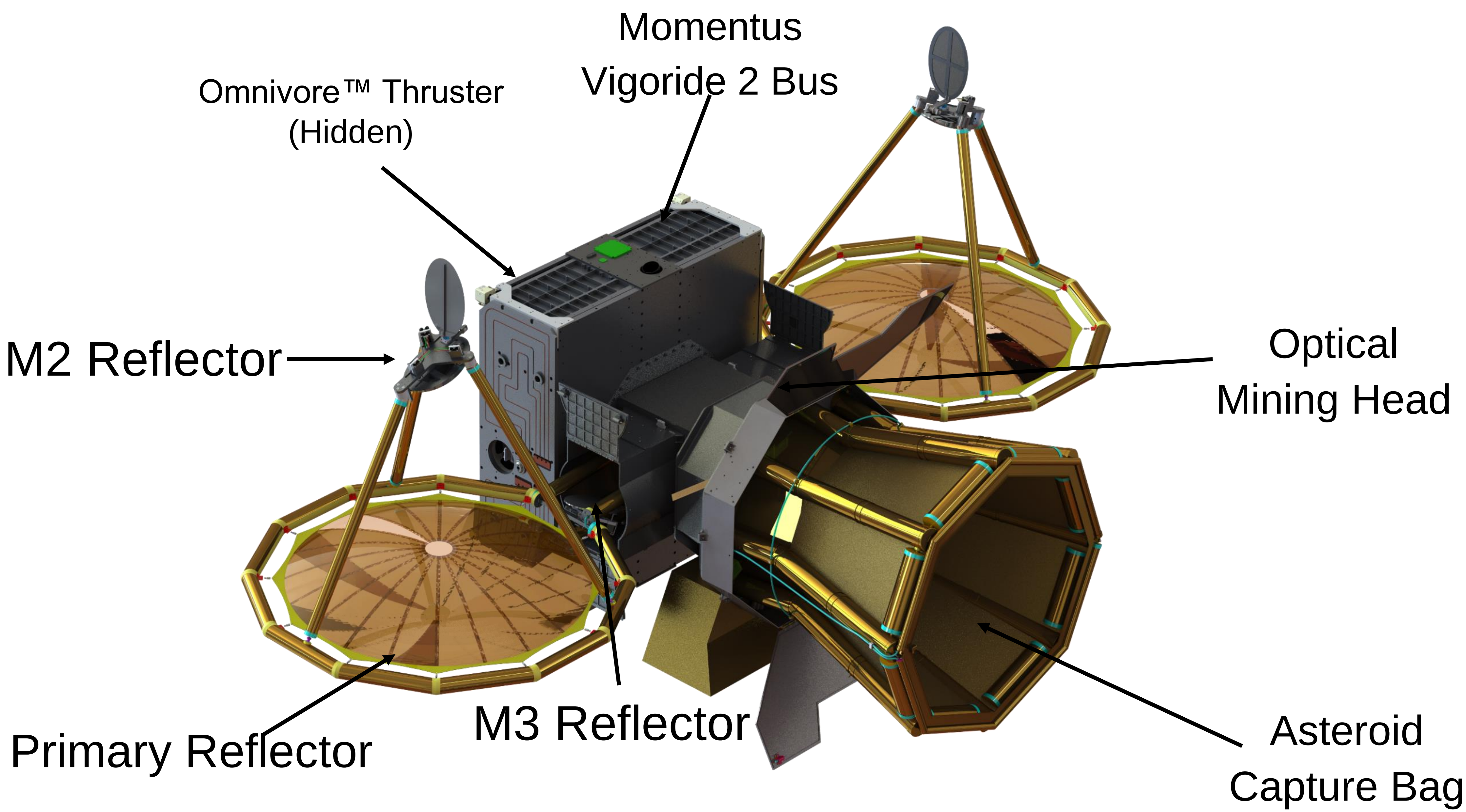
- Make the demonstration model as “flight-like” as possible.
- Use analysis where necessary to ensure that the compromises will not impact development of the flight Mini Bee™.
- Use of COTS parts as flight equivalents where feasible.

TransAstra Agile Engineering

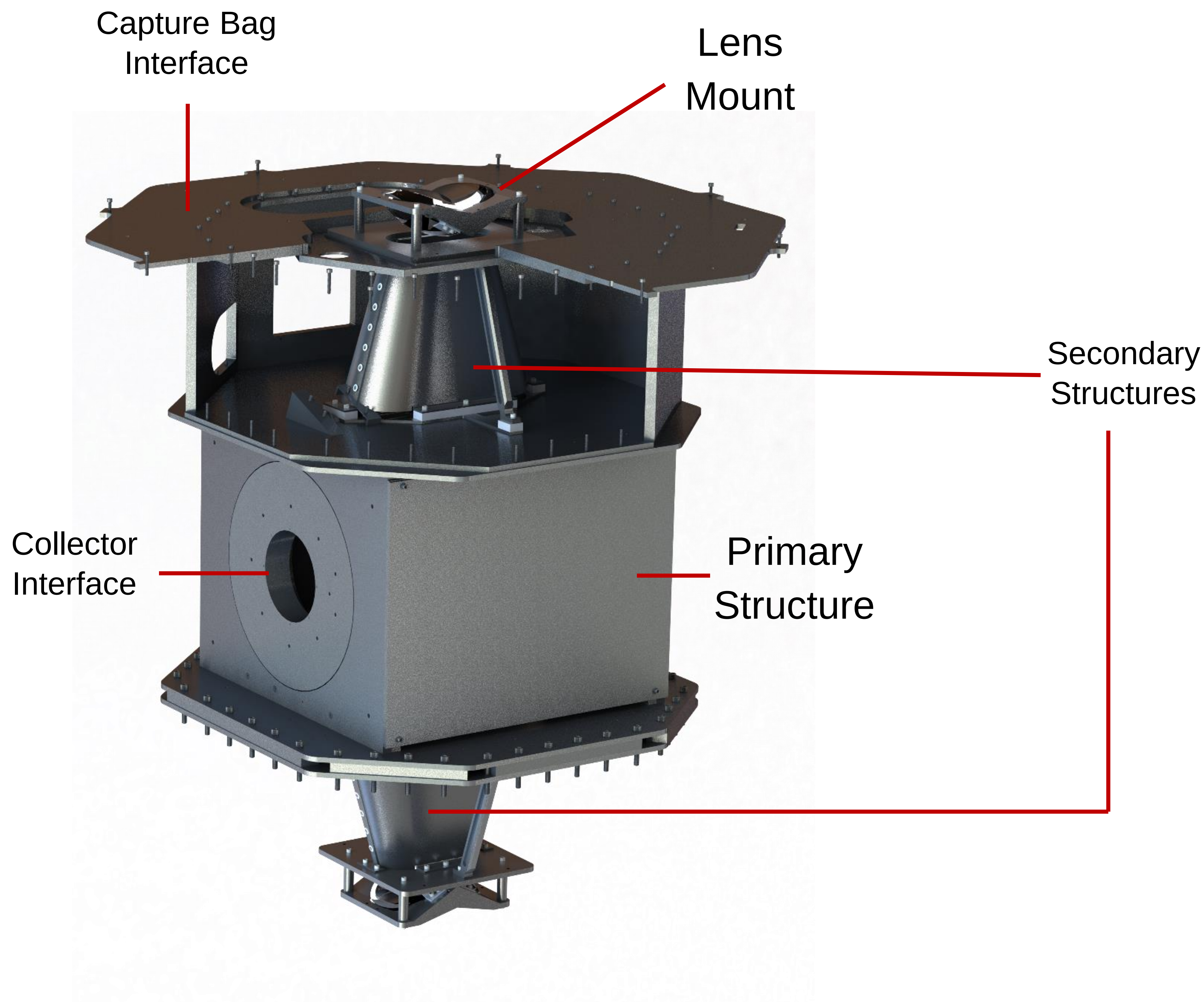
- Iterative design approach
  - Less upfront analysis during initial design phase
  - More information gained by prototyping, testing, and modifying accordingly
  - Extensive use of 3D printing in early stages
  - Faster and cheaper, more innovative (better)
- Not using waterfall systems engineering



Mini Bee Spacecraft Overview

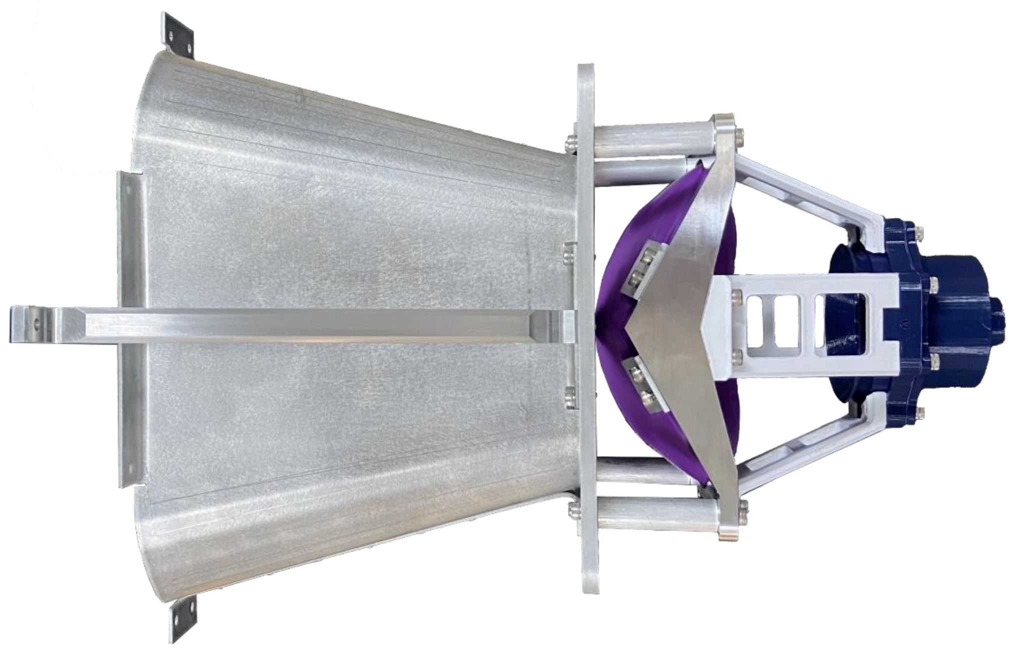


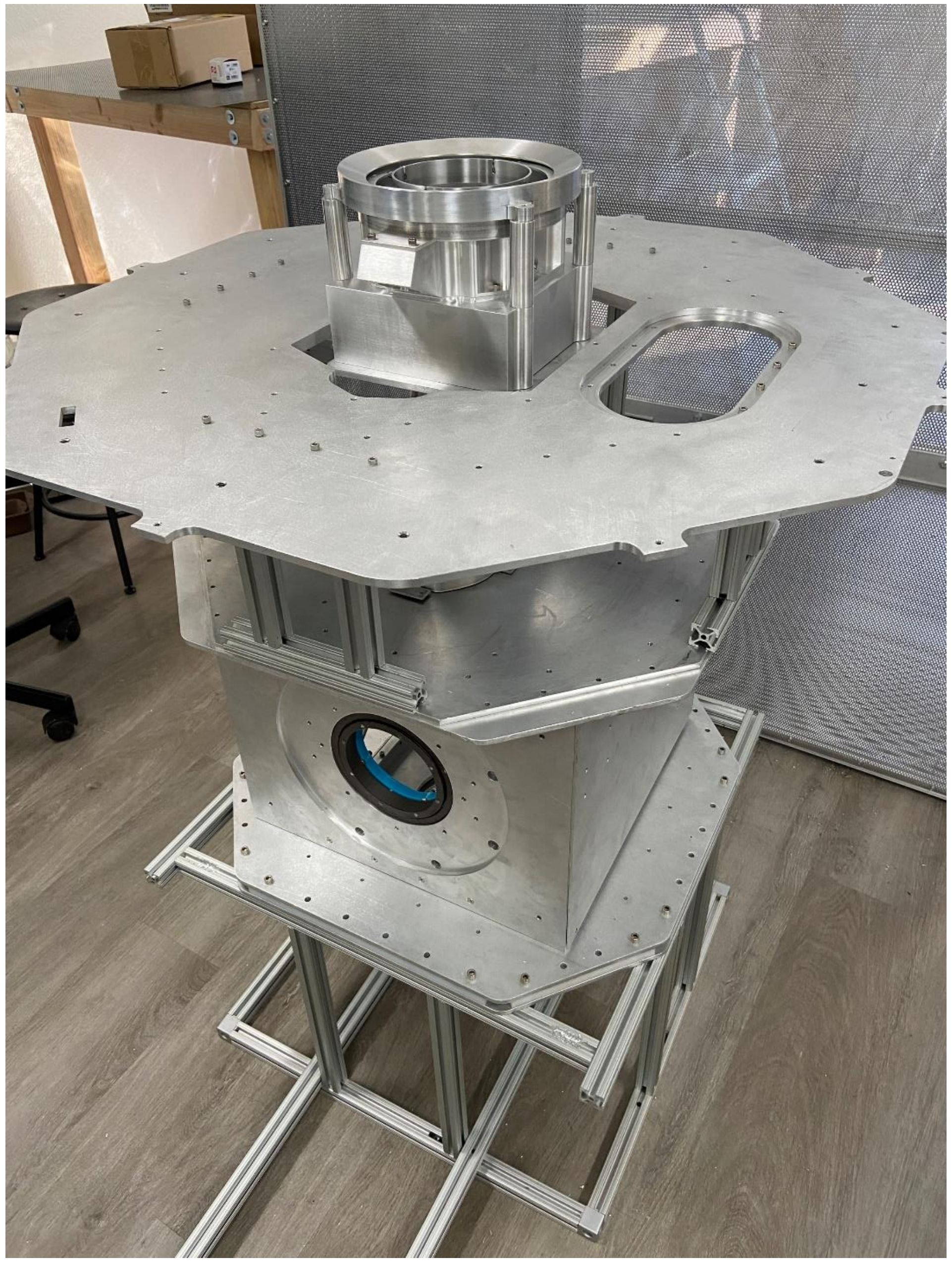
Mini Bee Selected Structures Overview



Mini Bee Structures Progress

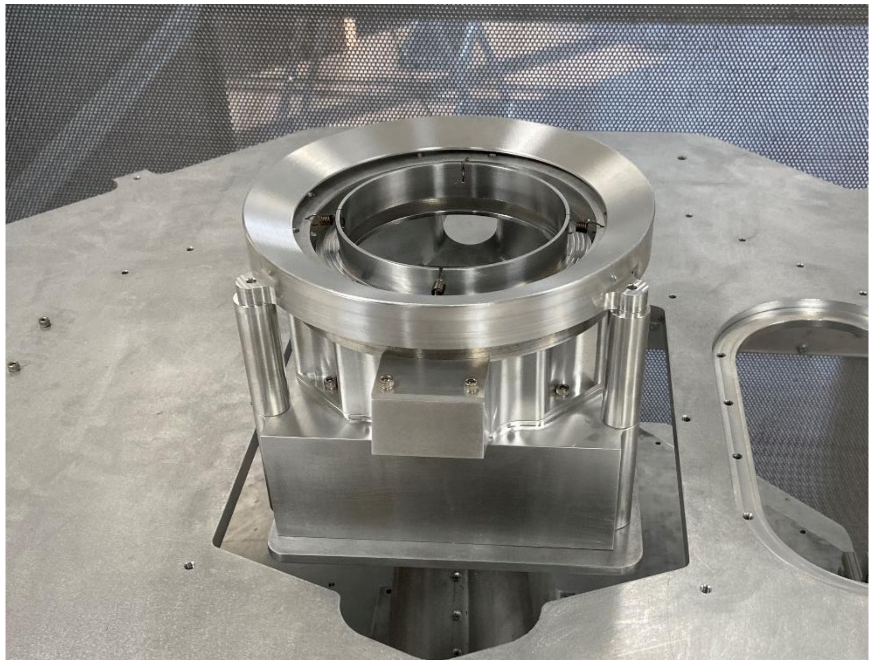
- Majority of parts fabricated and assembled
  - Currently integrating with collector, mining head and optical assemblies

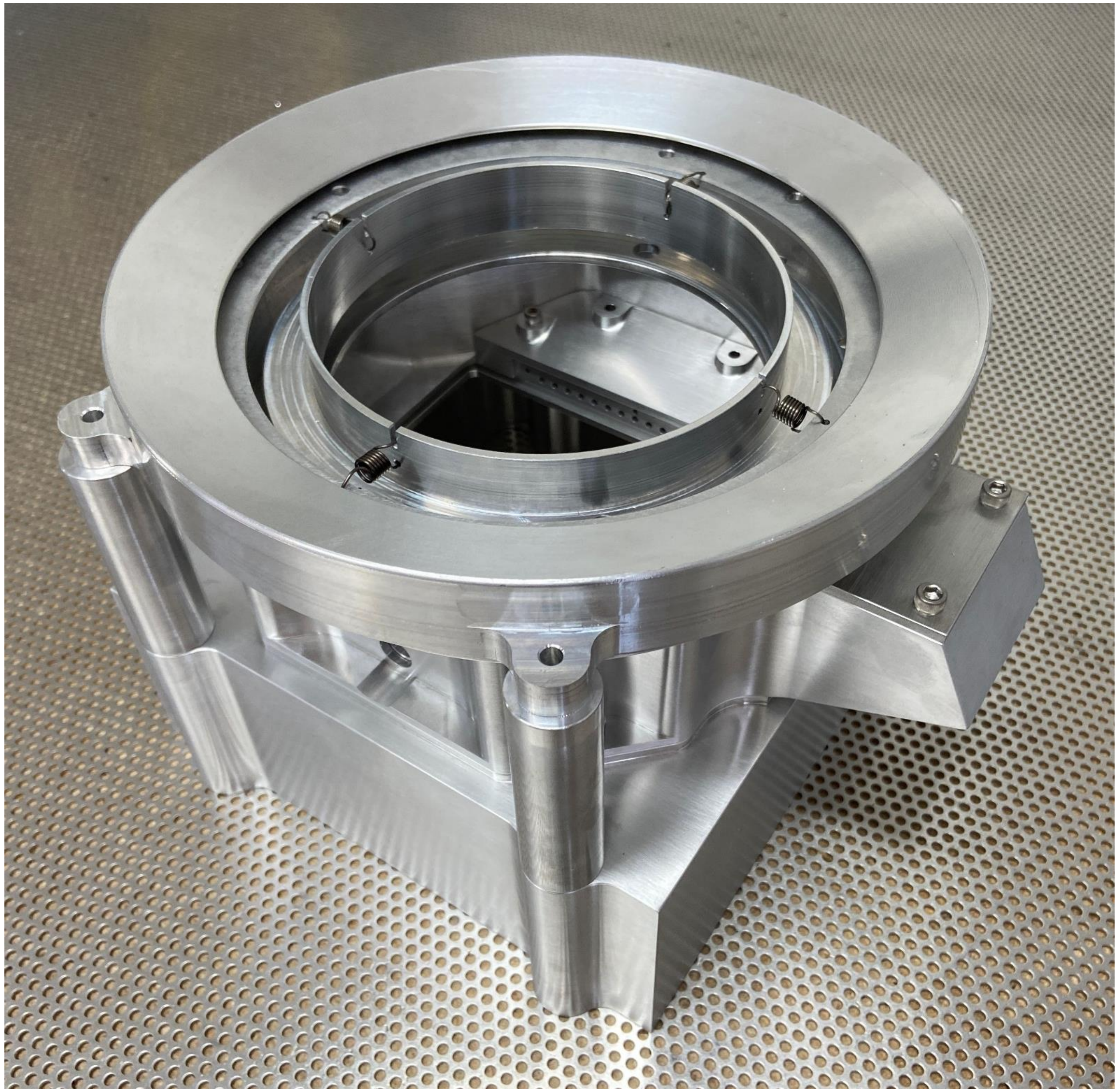




Optical Mining Head Hardware

- Optical Mining Boot ~90% Machined and assembled
  - Will be used to test optical mining and gas flush vent system in OMTB at Colorado School of Mines
    - OTMB variant currently being fabricated
  - Interfaces with Mini Bee secondary structure checked and validated

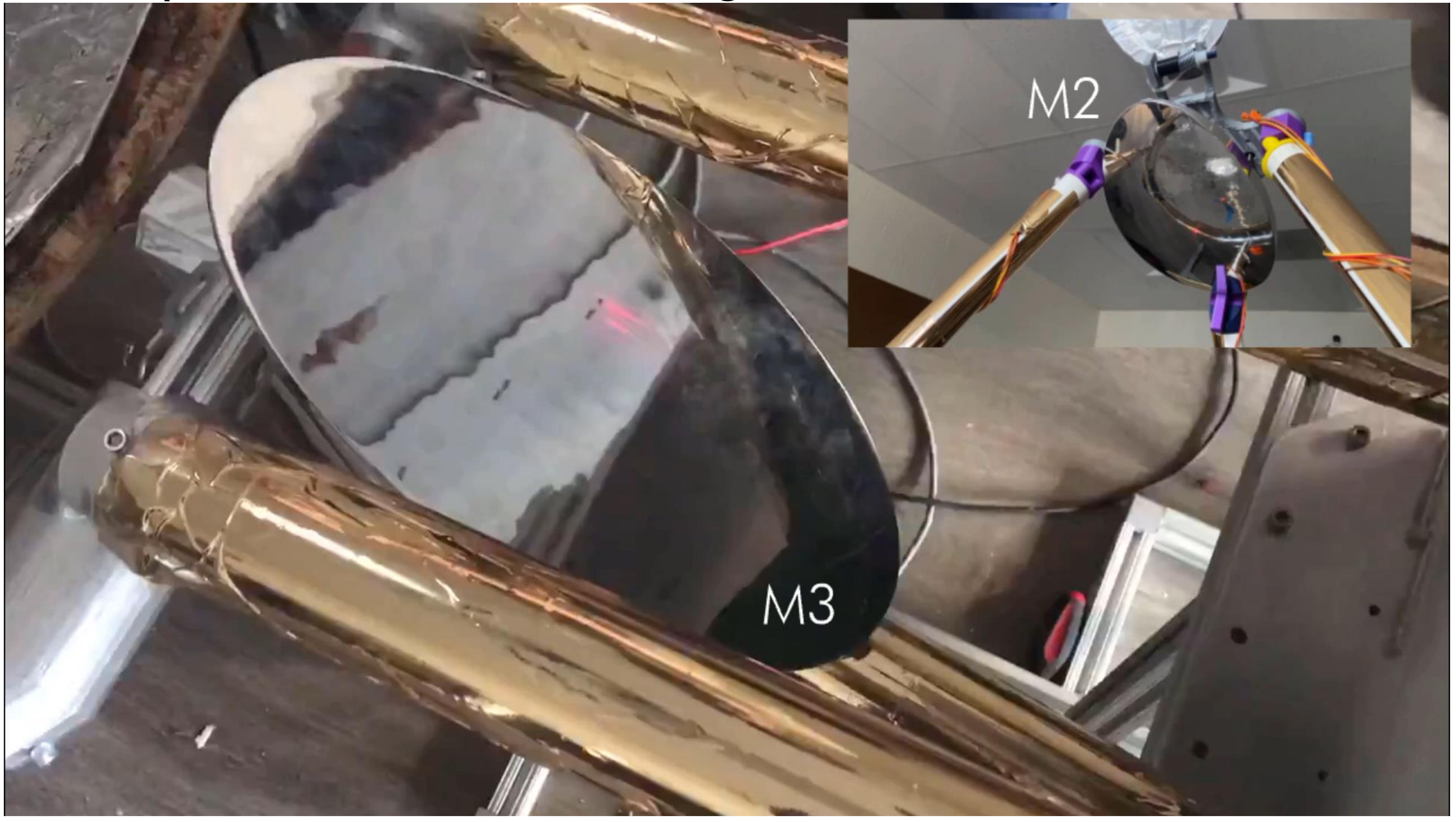




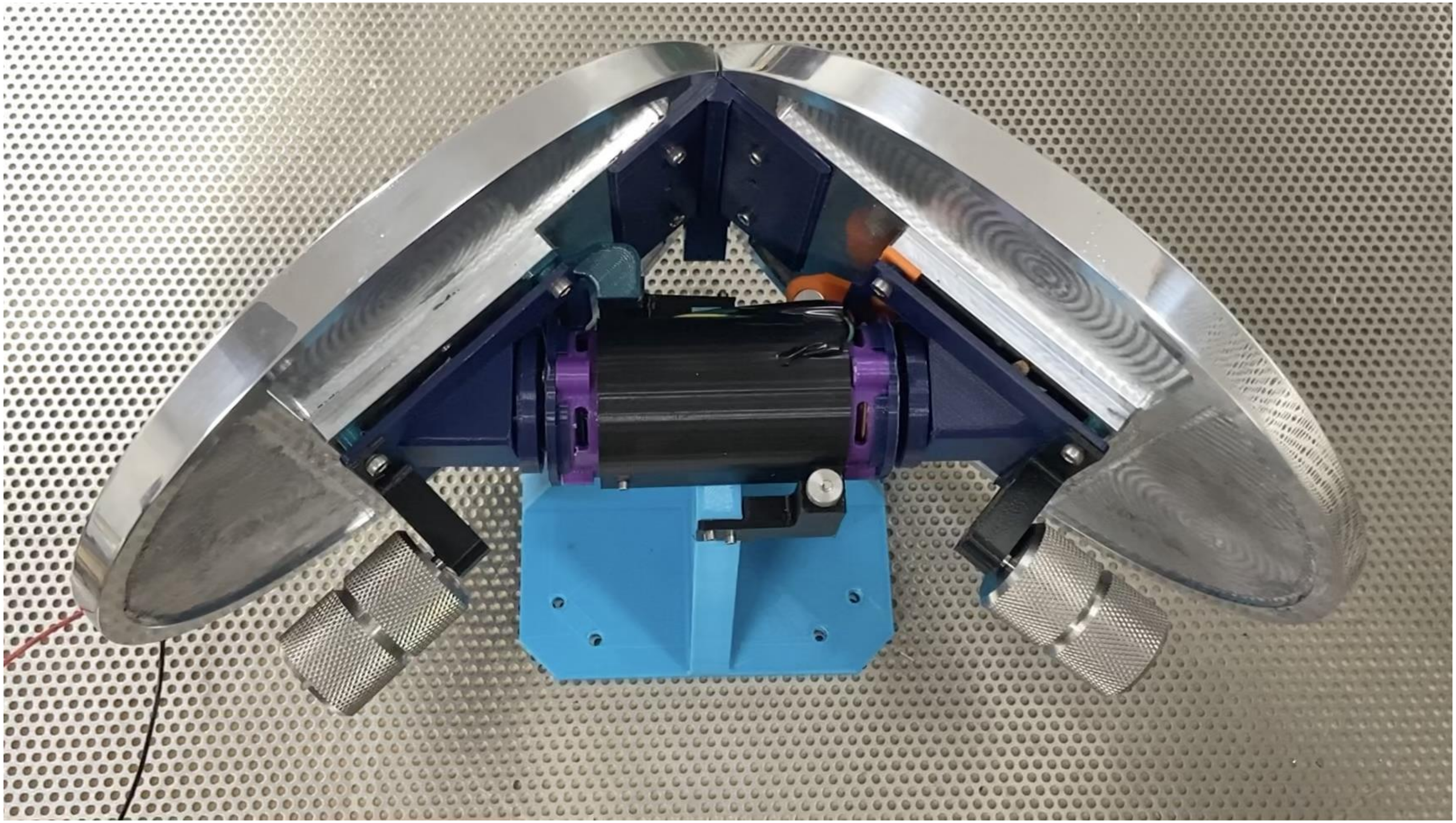
Optical Alignment Laser Test

- Laser reflected off M2, algorithm centers on M3
- Laser reflected off of M3, centered on M4

  -Aligned laser captured at mining head
- Next step is to test with solar light



Mini Bee Optics: M4 Actuation



Flight of the Mini Bee™

- https://youtu.be/rmavtBkVjSQ

Recent Discoveries in Simulant Behavior and Regolith Handling

Presented at the 11th Joint Meeting of the Space Resources Roundtable / Planetary and Terrestrial Mining and Sciences Symposium

June, 2021

Diane Linne/NASA GRC
John Gruener/NASA JSC
Doug Rickman/Jacobs/NASA MSFC

Background

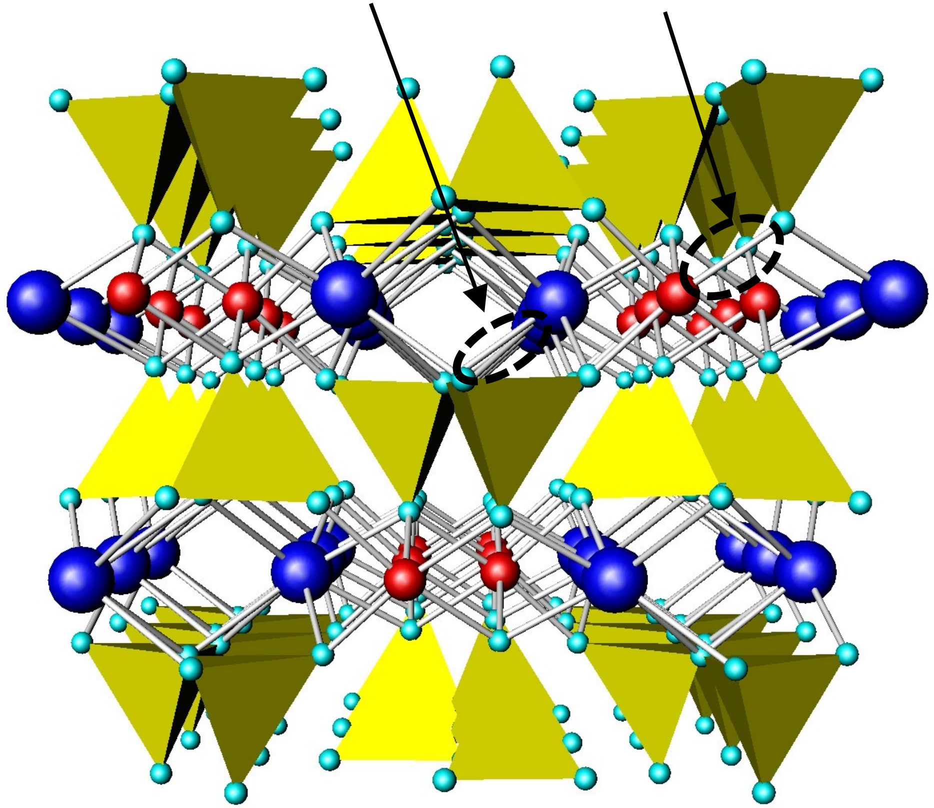
- NASA is taking a 2-prong approach for ISRU production of consumables
  - Water from permanently shadowed regions
  - Oxygen from mineral oxides
- Leading oxygen-from-regolith processes under development
  - Hydrogen reduction
  - Carbothermal reduction
  - Molten regolith electrolysis

Location Matters!

Even if you break these metal-oxygen bonds, the oxygen is <u>still</u> tightly bound in the silica tetrahedra

Hydrogen Reduction

- Iron oxides in the mare regions are predominantly contained in ilmenite, which can be reduced by reacting with hydrogen at ~900 °C
- Iron oxides in the highlands regions are predominantly contained in pyroxenes, which cannot be reduced by hydrogen

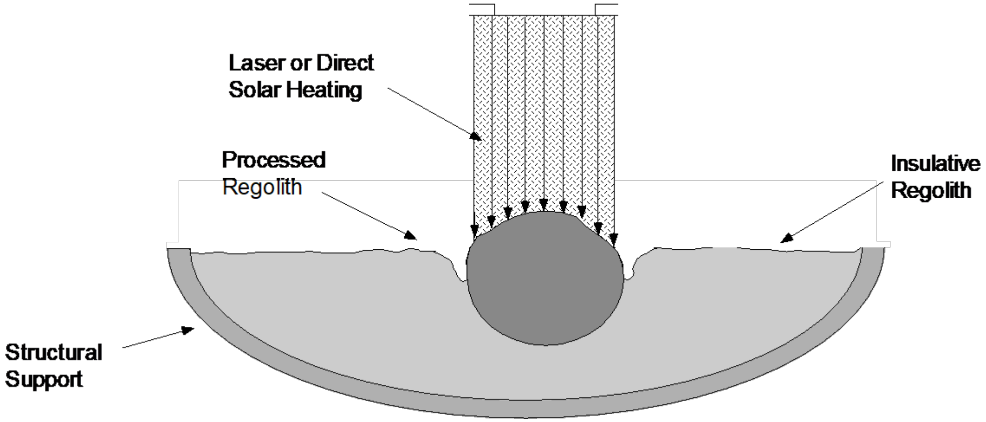


Crystalline structure of a typical pyroxene. Yellow SiO_4 tetrahedra, with light blue spheres representing oxygen atoms. Dark blue and red spheres represent metal cations such as calcium, magnesium, and iron

From Perkins, D., Introduction to Mineralogy, 2020, fig 6.69, https:/opengeology.org/

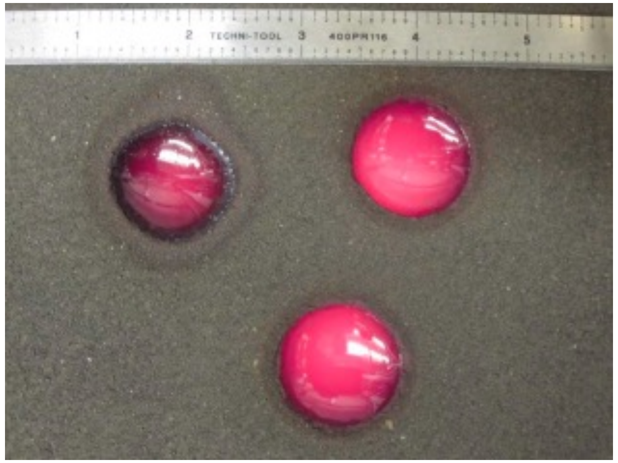
Next up: Carbothermal Reduction

- Regolith is melted to ~1800 °C and reacted with carbon to break the silicate bonds and extract oxygen in the form of carbon monoxide
- Process developed by Orbital Technologies (now owned by Sierra Nevada Corp (SNC)) in the 00’s created individual reaction zones in a bed of regolith
  - Carbon is added by cracking methane gas above the melts and allowing the carbon to mix into the molten region.
- Until recently, all of SNC’s testing was done with JSC-1A, a mare simulant



Direct heat process – the regolith becomes its own insulative ‘container’

Ref: Gustafson, R.J., White, B.C., Rice, E.E., and Gramer, D.J., “Carbothermal Lunar Regolith Processing System (CLRPS) Final Report, NASA Contract NAS9-03021, OTC-GS-131-FR-03-1, July 2003



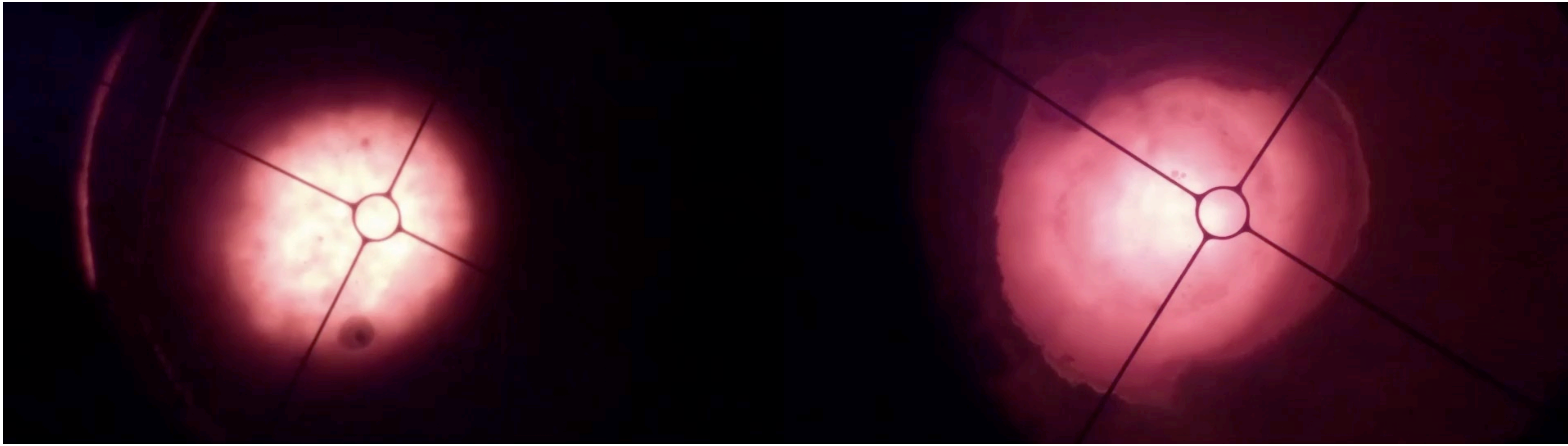
Regions of molten JSC-1A lunar regolith simulant

Ref: Gustafson, R.J., White, B.C., and Fidler, M.J., “2010 Field Demonstration of the Solar Carbothermal Regolith Reduction Process to Produce Oxygen,” AIAA 2011-434, Jan 2011

Location Matters!

Carbothermal

- Recent tests performed at Sierra Nevada Corporation (SNC) with JSC-1A and GreenSpar simulants observed significantly different melt behaviors
  - Higher viscosity of GreenSpar affects amount of carbon that can dissolve into melt, as visually observed by formation of carbon cap growing around edges



JSC-1A in methane environment

Greenspar in methane environment

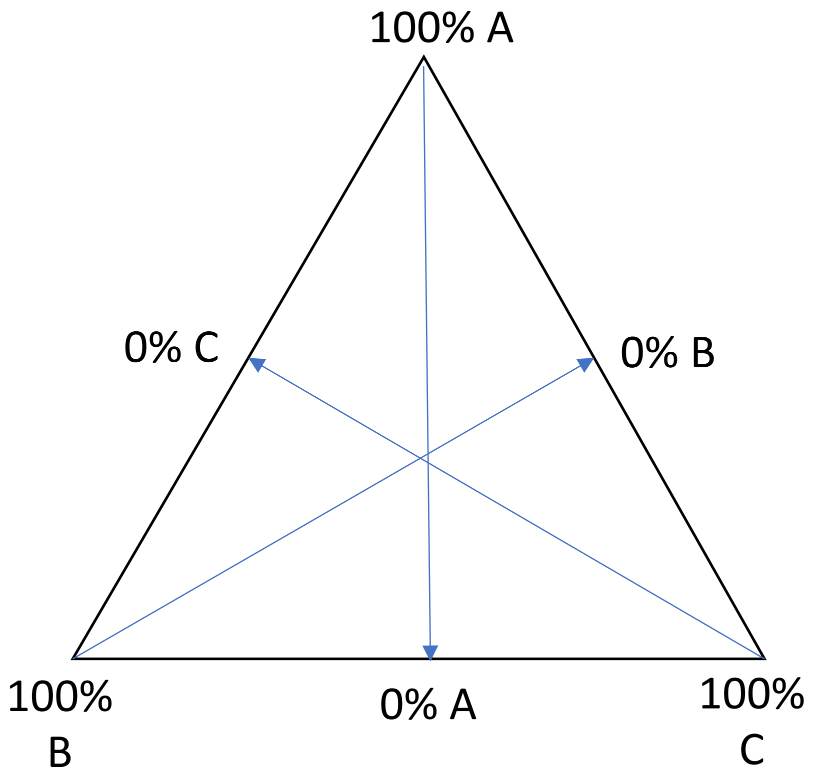
(Video used with permission from Sierra Nevada Corp)

Effects of Higher Viscosity on Carbothermal Process

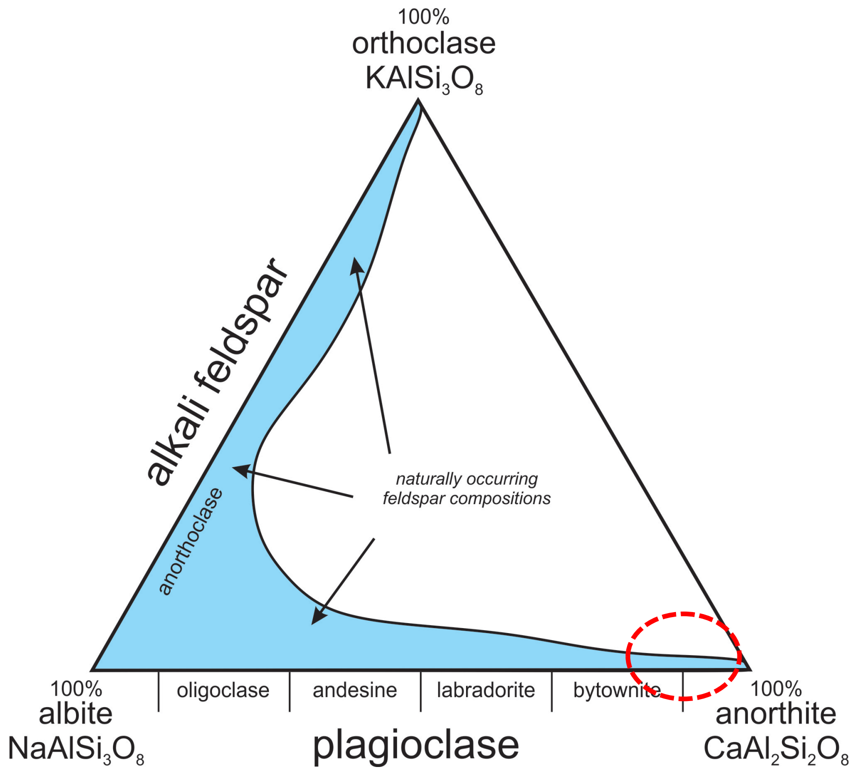
- Performance effects observed two ways
  - Oxygen Rate: reduced more than an order of magnitude due to inability to introduce enough carbon into full melt volume
  - Carbon Cap: inability of carbon to dissolve/mix into melt volume leaves too much at melt surface, forming cap which essentially halts the reaction
- Operating condition variations failed to recover performance (compared to JSC-1A)
  - Higher total power / heat flux into melt
  - Higher melt temperature
  - Methane concentration, absolute pressure in reactor chamber
  - Test duration
  - Mechanical vibration
  - Variable rate of methane introduction throughout test

The Explanation

- Mare regolith is predominantly basalts, which is the basis for the JSC-1A simulant
- Highland regolith (including the poles) is predominantly plagioclase, which is the basis for the NU-LHT-series and GreenSpar simulants
  - Plagioclase consists of sodium (Na) and calcium (Ca) components, but in varying ratios



Basic three-variable ternary plot, where any vertex represents a composition of 100% of that variable. The side of that triangle opposite of that vertex represents 0% of that variable.

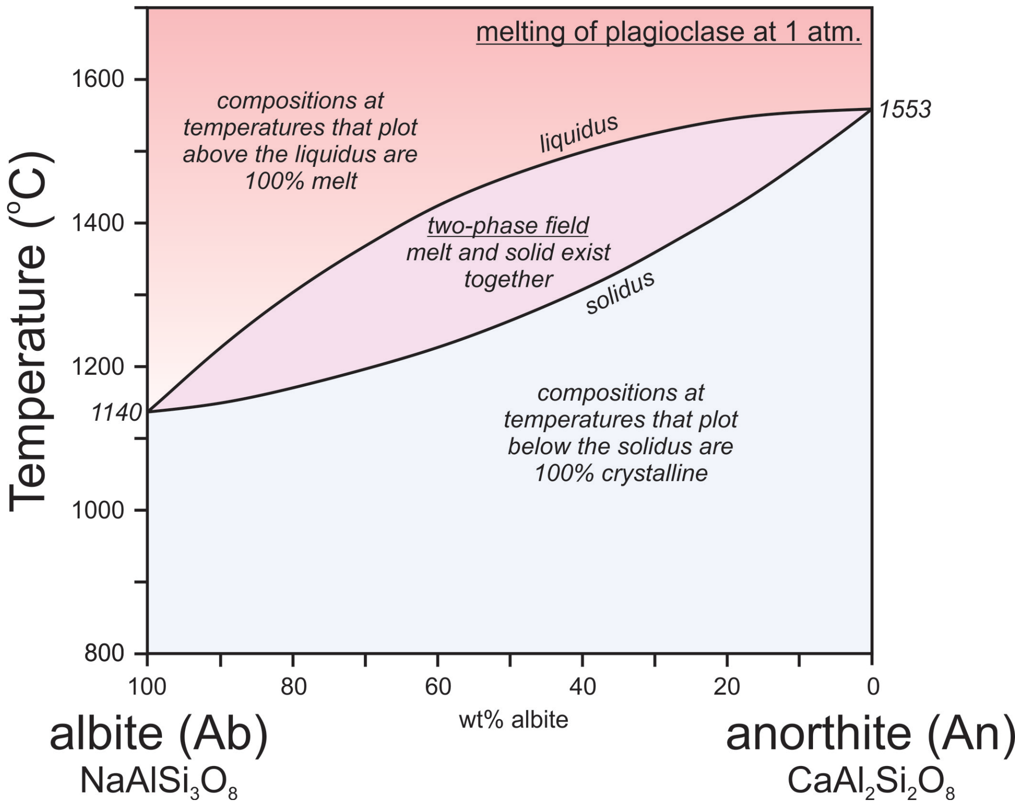


Feldspar mineral classification based on chemical make-up. Bottom base goes from high-sodium albite to high-calcium anorthite. Red dashed circle represents what we expect at the lunar south pole.

From Perkins, D., Introduction to Mineralogy, 2020, fig 6.34, https:/opengeology.org/

The Explanation (cont.)

- More Na will decrease the viscosity (i.e., make the melt more fluidic)
- More Ca will increase the viscosity (i.e., make the melt ‘thicker’)
- The An (Anorthite) number is the ratio of Ca / (Ca + Na)
  - Melt viscosity increases with increasing An number
- Increasing the An number will also increase the melting point temperature of the simulant
- Lunar plagioclase at the south pole is expected to have an An in the upper 80s to mid 90s



Plagioclase crystallization at 1 atm pressure. Full liquidus temperature increases from 1140 °C for albite (high-Na) to 1553 °C for anorthite (high-Ca)

From Perkins, D., Introduction to Mineralogy, 2020, fig 6.54, https:/opengeology.org/

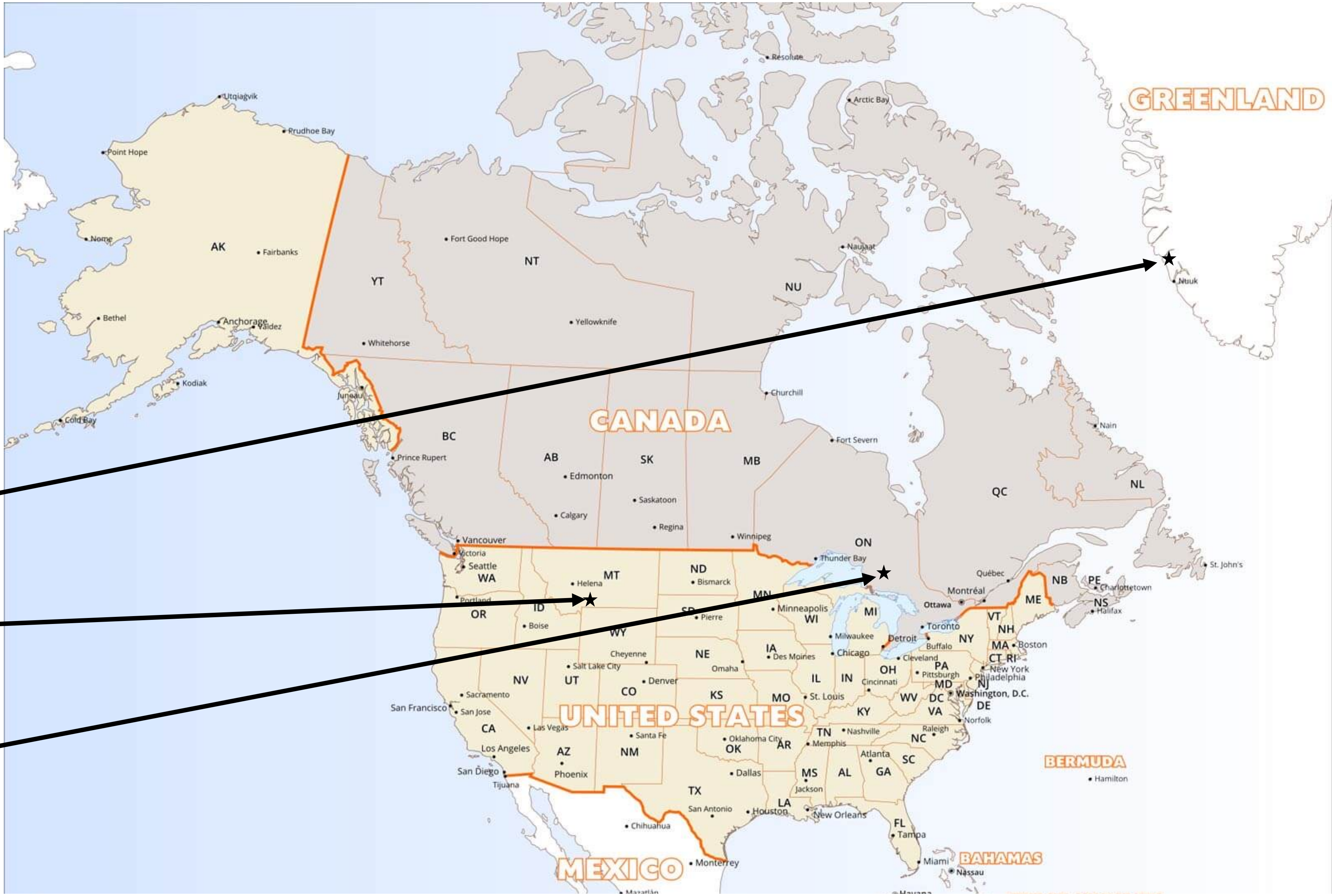
Sources for Simulant Feedstock

North American locations for large quantities of high-Ca Anorthosite

White Mountain

Stillwater

Shawmere



Map graphic from https://www.freeworldmaps.net/download/maps/northamerica/northamerica-map.jpg

Anorthosite Assessment

Deposit	Shawmere (OB-1, Chenobi)	Stillwater (NU-LHT-series)	White Mountain (GreenSpar)
Location	Near Foleyet, Ontario, Canada	Near Nye, MT, USA	Near Itivdleq, Greenland
Mining Co.	Various	Stillwater Mining Co.	Hudson Resources, Inc.
Mined for	Filler, plastics and paper production, cement and glass manufacture	Platinum	E-glass, paint, coating fillers, alumina, white cement
An content of plagioclase*	Average 78 (68-95, with areas of higher An content in rocks with lower plagioclase percentage)	75-88 (depends on the layer, An 70-80 are more common in Stillwater deposits)	78-86 (calculated as 87 based on analysis presented in Hudson Resources' presentation)
Trace phases (depends on proximity to alteration zones)	Apatite, zircon, hornblende, garnet, biotite, muscovite, calcite, epidote/clinozoisite, and chlorite	Biotite, olivine, pyroxene, chromite, augite, quartz, albite, zoisite, epidote, chlorite, amphibole, and calcite	Quartz, epidote/clinozoisite solid solution phases, muscovite, trace carbonate
Comments	The Shawmere Complex is not uniform – plagioclase content varies from 25-85% of the rock, various areas of metamorphism and alteration are present.	Note that Stillwater does not mine the anorthosite deposit. Geologists must pick rocks by hand for simulant feedstock.	Areas of metamorphism and alteration are present.

*An resources: Shawmere, Battler and Spray (2009) and Simmons et al. (1980); Stillwater, Page et al (1985), Meurer and Boudreau (1996); White Mountain, Polat et al. (2018), Hudson Resources Inc. presentation 6-16-20

Viscosity Summary

- Continue with the GreenSpar simulant
  - The high An number (ratio of Ca / (Ca+Na)) of lunar highland regolith will result in a highly viscous melt
  - Highlands simulants such as NU-LHT-series and GreenSpar all have high An numbers, although not as high as the lunar highland regolith
    - Should mimic melted viscosity as best as possible with current available simulants
    - Would be of interest to run a few baseline tests with multiple highland simulants and a synthetic plagioclase with matching An number (i.e., synthetic Anorthite)
  - Greenspar has the highest average An number of the available highland simulants, and is the most readily available for larger scale, destructive testing
- Molten Regolith Electrolysis developers should also evaluate whether the high melt viscosity will affect their performance or concept of operations

Note: Recent challenges regarding imperfect simulants further emphasizes the need for a demonstration on the lunar surface with real lunar highland regolith

Acknowledgements

- The authors would like to thank Brant White, Sierra Nevada Corp, for providing the videos of the molten simulants

THERMAL PROPERTIES OF LUNAR MATERIAL IN PERMANENTLY SHADOWED REGIONS

Vatican Observatory

- **Robert J Macke SJ**, Vatican Observatory
- **Cyril P Opeil SJ**, Boston College
- **Daniel T Britt**, Univ. Central Florida / Center for Lunar and Asteroid Surface Science
- **Guy J Consolmagno SJ**, Vatican Observatory

2021 Planetary & Terrestrial Mining Sciences Symposium / Space Resources Roundtable

Outline

- Introduction & Motivation
- Measuring Thermal Properties at Low T
- Results
- Summary / Conclusions

Introduction

- In-situ resource utilization of lunar materials requires knowledge of thermal properties at relevant temperatures.
- LRO Diviner Lunar Radiometer Experiment → Permanently shadowed regions of lunar surface have temperatures as low as 20K
- Existing data for thermal properties of lunar materials go as low as 100 K
- We need good data for thermal properties in the range 20 – 100 K.

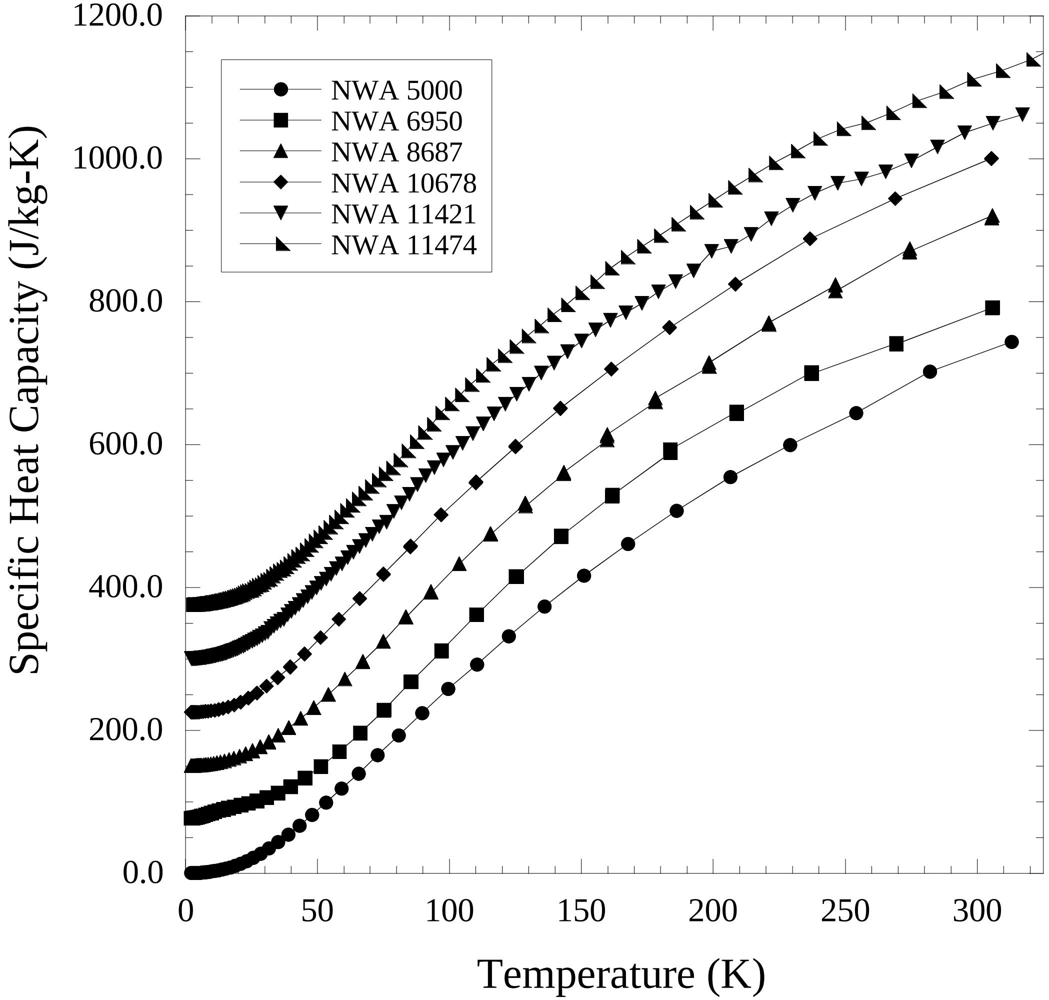
- We measured thermal properties
  - Specific Heat Capacity
  - Thermal Conductivity
  - Thermal Inertia
  - Thermal Diffusivity
  - Coefficient of Thermal Expansion
- For 6 lunar meteorites
  - 4 feldspathic breccias: NWA 5000, NWA 10678, NWA 11421, and NWA 11474
  - 1 gabbro: NWA 6950
  - 1 troctolite: NWA 8687
  - Plus specific heat capacity for 15 additional specimens

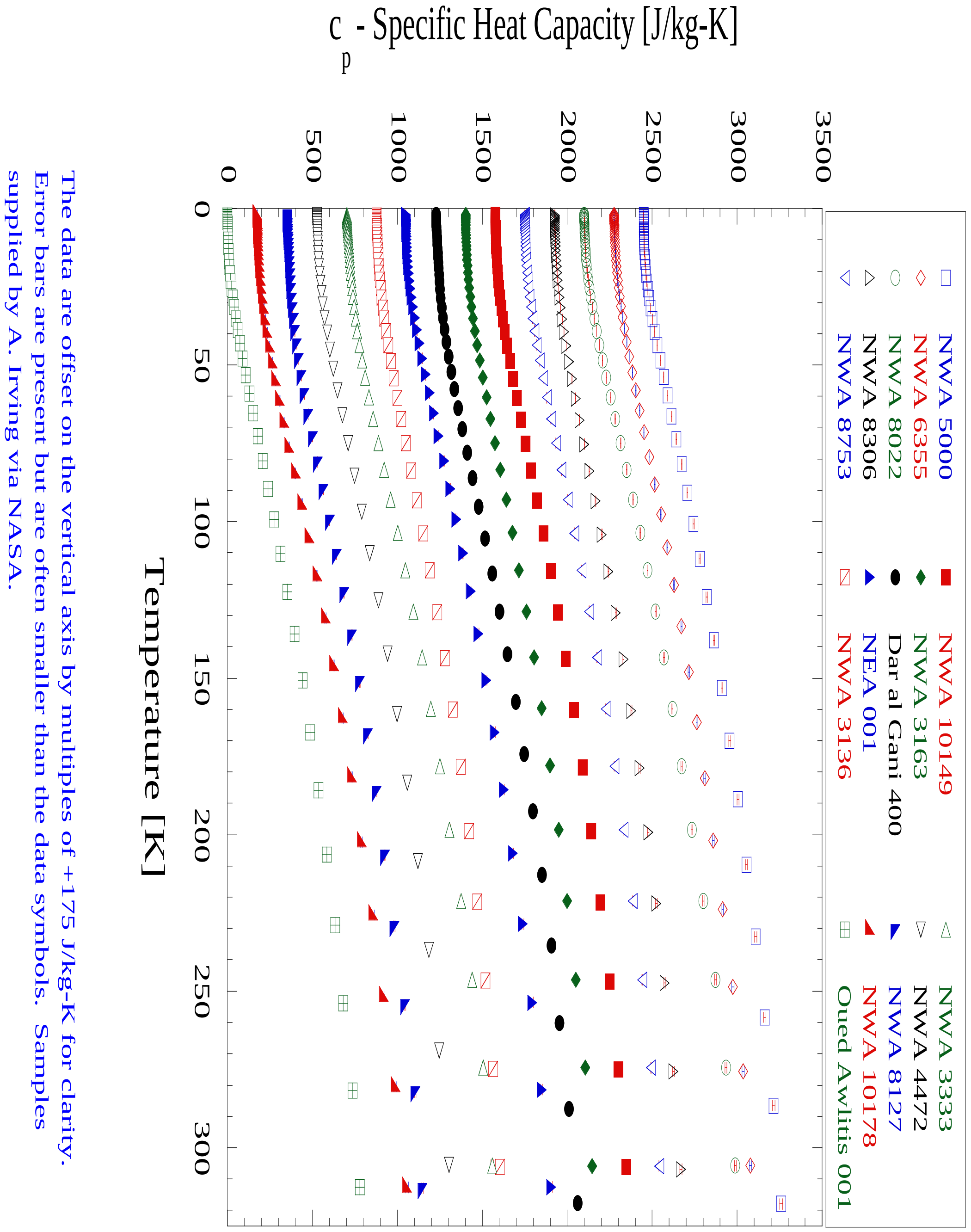
Measurement Techniques

- Measurements performed at Opeil laboratory at Boston College
- Quantum Design Physical Properties Measurement System (QD-PPMS)
- Measures thermal properties as f(T) between 2-300+ K.
- Bulk Density measured by Archimedean method
- Supplemented by density and porosity data (not same specimens) measured by Macke at Vatican Observatory

Results

Heat Capacity C_p





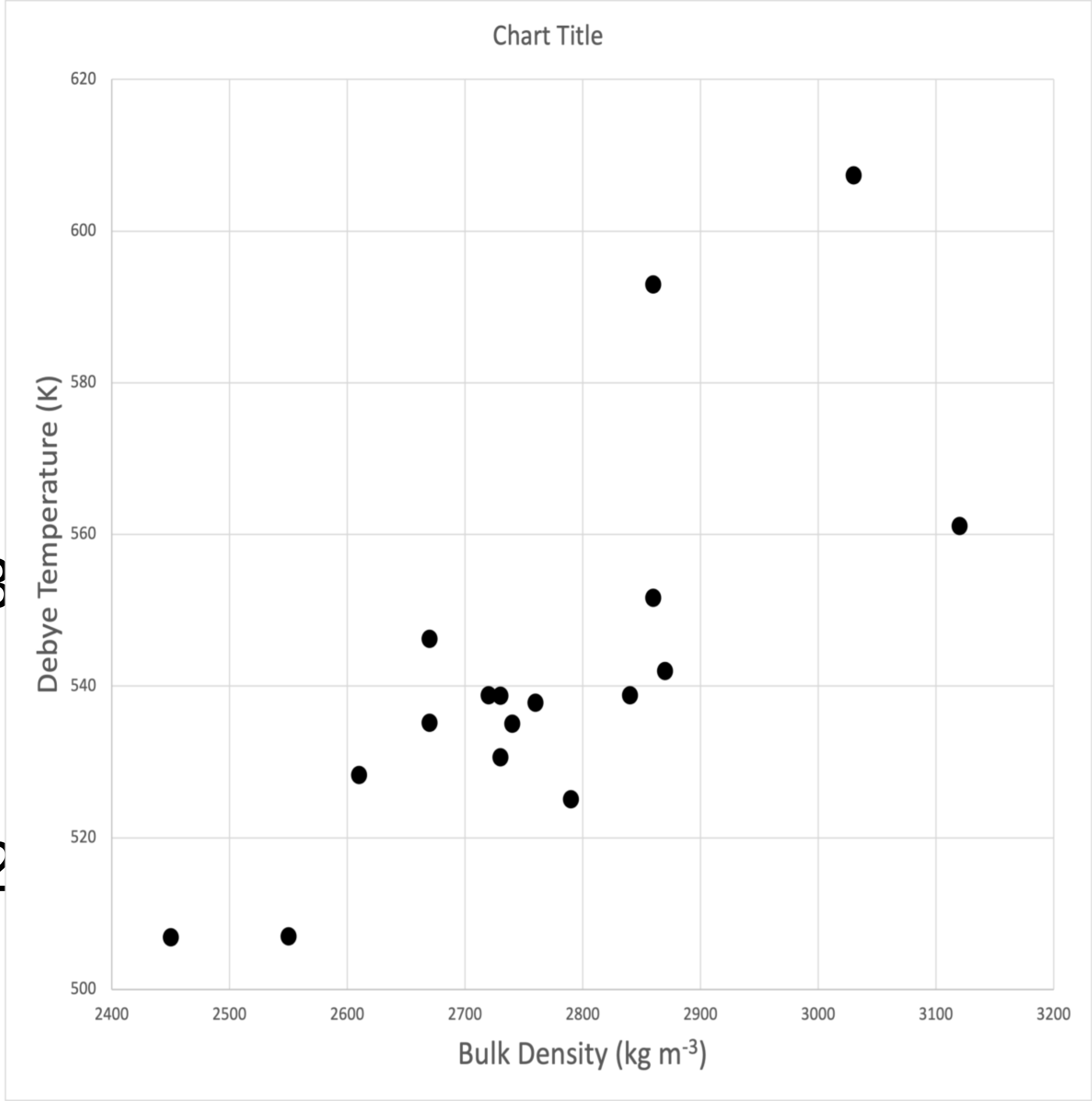
Heat Capacity C_p

- Debye Temperature Θ_D

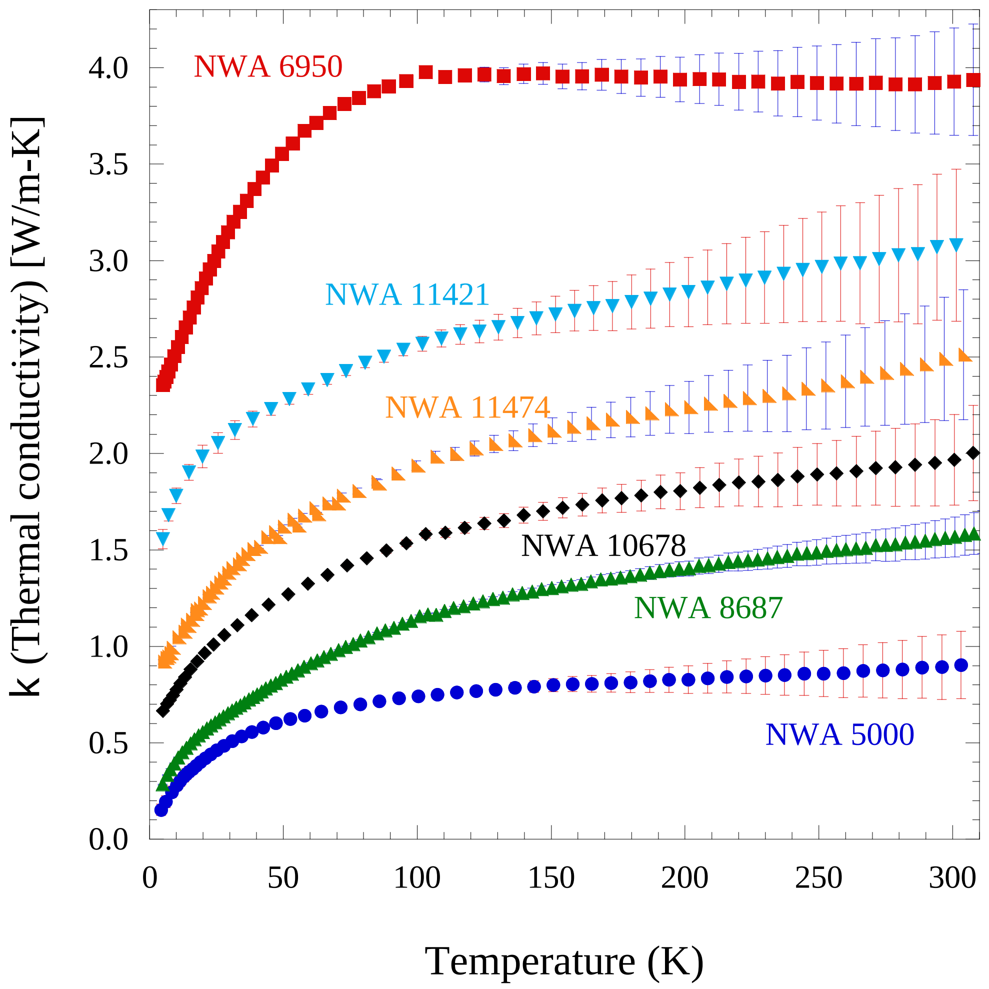
$$C_p(T) = \gamma T + 9Nk_b\left(\frac{T}{\Theta_D}\right)^3 \int_0^{\Theta_D/T} \frac{x^4 e^x}{(e^x - 1)^2}\,dx$$

- Average Debye Temperature: 543 K (stdev 29 K)

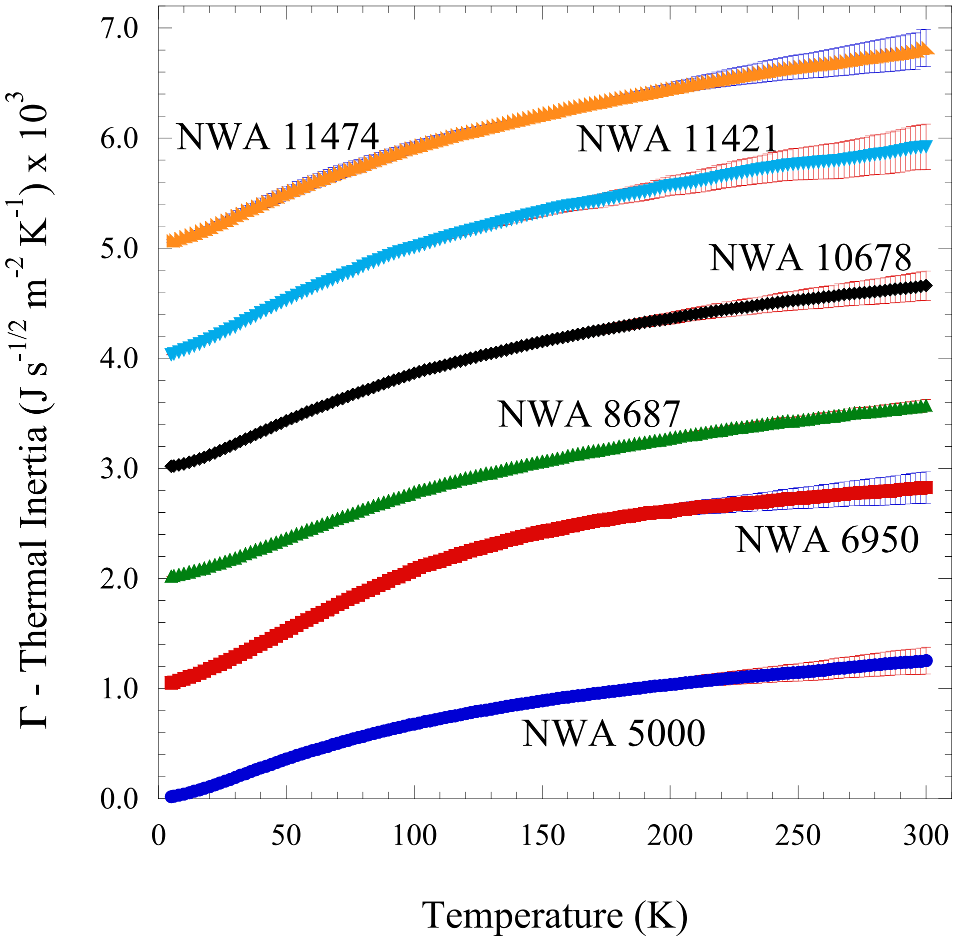
- For feldspathic breccias: 527 ± 52 K



Thermal Conductivity κ



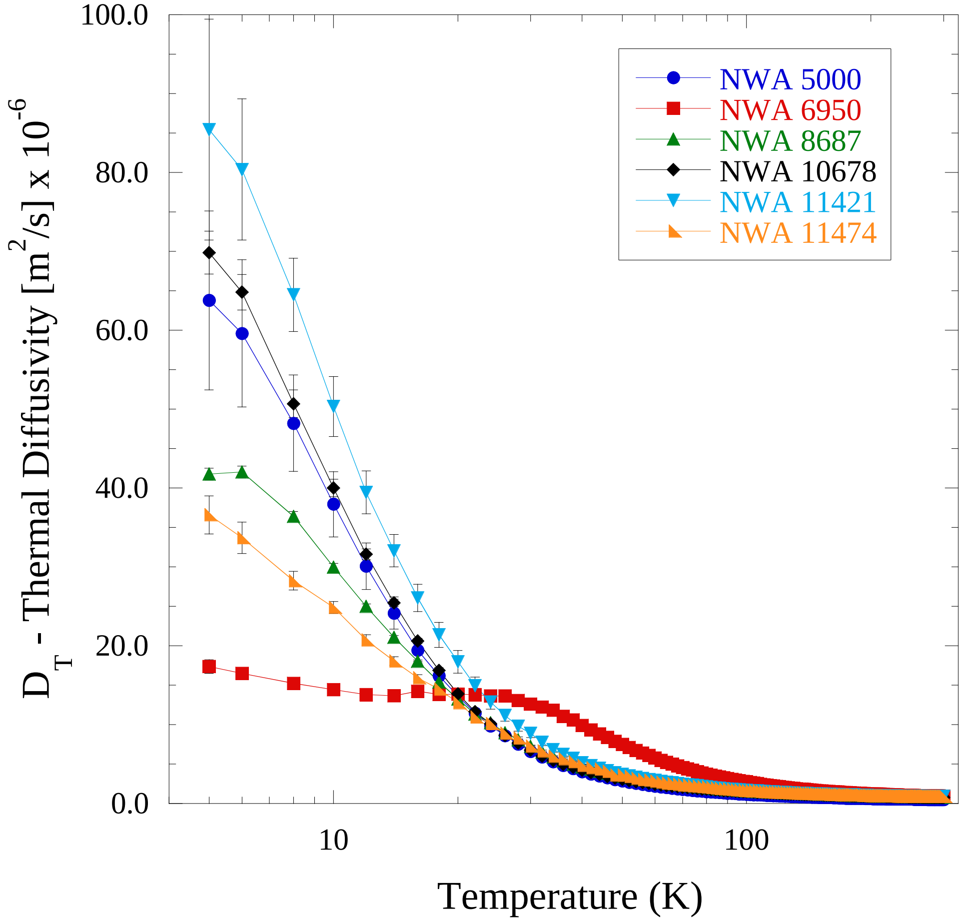
Thermal Inertia Γ



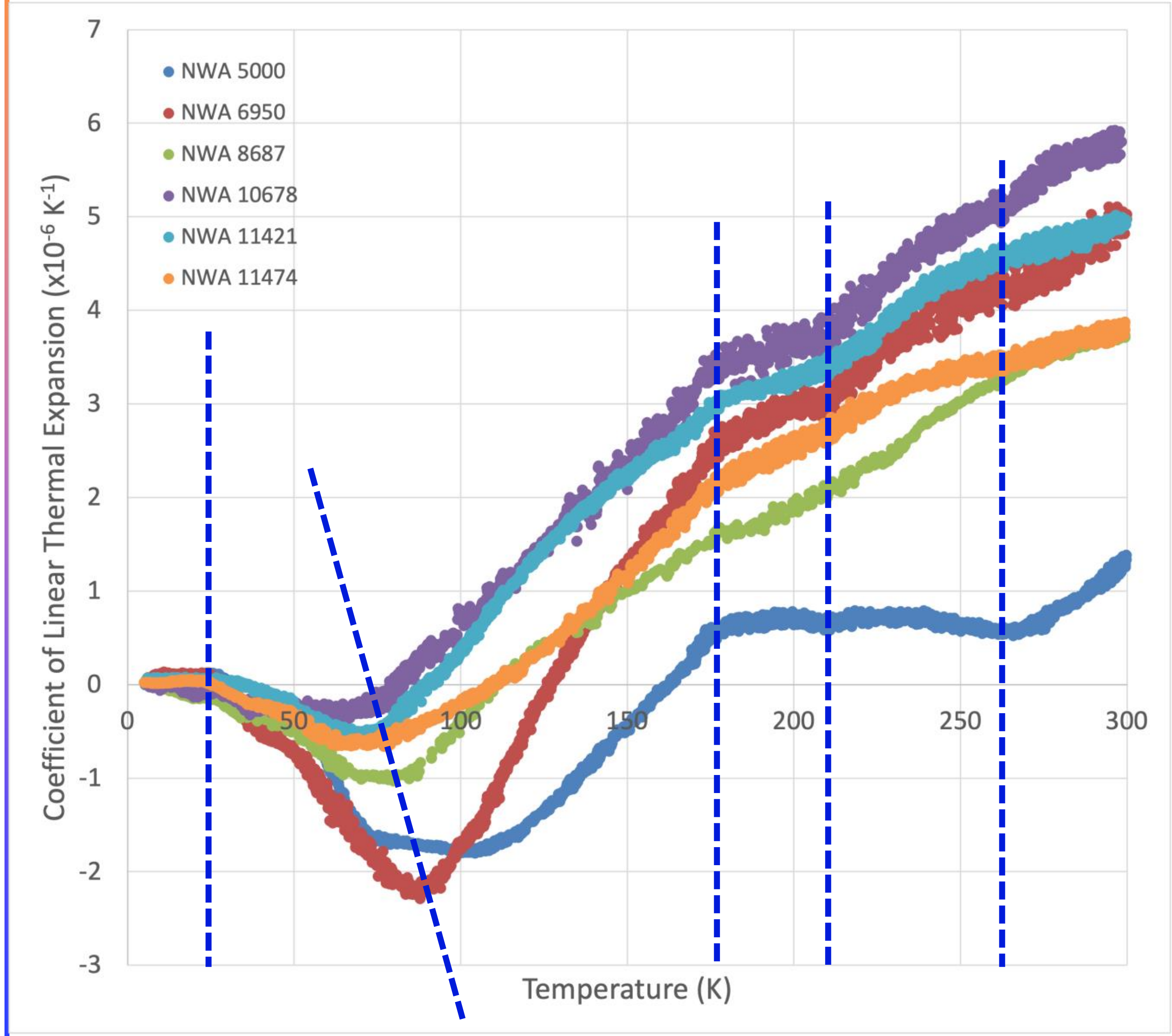
$$\Gamma(\mathrm{T}) = \sqrt{\kappa(T)\rho c_p(T)}$$

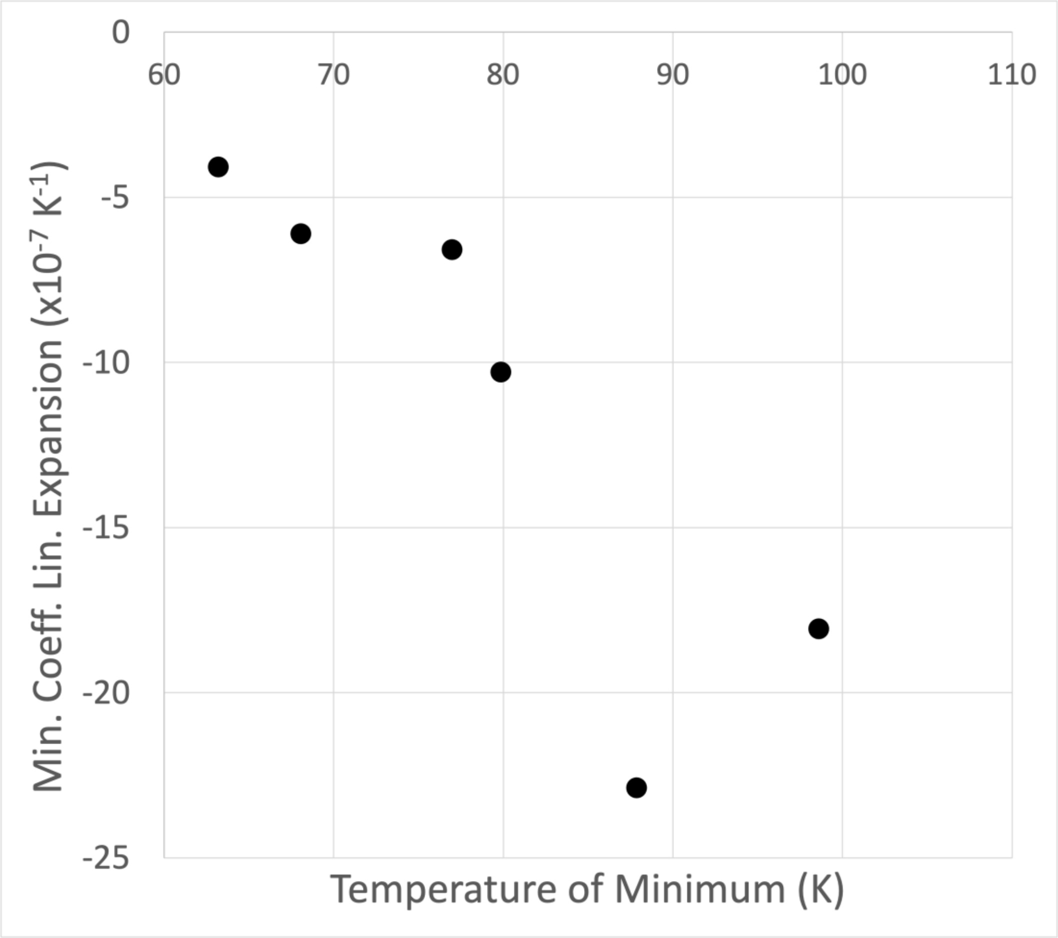
Thermal Diffusivity D_T

$$D_T = \kappa(T)/[\rho c_p(T)]$$



Coefficient of Thermal Expansion





Summary / Conclusion

- Thermal properties at low temperatures (<100K) are significantly different than at higher temperatures.
- Laboratory studies of meteorites can fill in this missing information.
- Lunar materials exhibit negative thermal expansion (NTE) near 25 K. This can increase thermal stress on materials exposed to these temperatures.

Virtual 2021

Simulants

NASA LSII LUNAR SIMULANT PROJECT. J. E. Gruener[1], [1]NASA Johnson Space Center, 2101 E NASA Parkway, Houston, Texas ,77058; john.e.gruener@nasa.gov.

Introduction: America has entered a new era of exploration. NASA's Artemis program will lead humanity forward to the Moon and prepare us for the next giant leap, the exploration of Mars [1]. To champion technologies needed to live on and explore the Moon, NASA's Space Technology Mission Directorate (STMD) established the Lunar Surface Innovation Initiative (LSII) [2]. LSII's technology development portfolio includes: Utilizing the Moon's resources; Establishing sustainable surface power; Building machinery and electronics that work in extreme environments, like super-chilly permanently shadowed craters; Mitigating lunar dust; Carrying out surface excavation, manufacturing and construction duties; and Extreme access which includes navigating and exploring the surface/subsurface. To support the development and testing of these technologies, LSII created the lunar simulant project, to create and/or acquire low-, medium- and high-fidelity lunar simulants to match the needs of STMD projects at all levels of technology readiness levels (TRL), as well as other NASA programs. There is not one bulk lunar simulant that will satisfy the needs of all projects.

NASA's Approach to Simulants: Just as LSII's activities are being implemented through a combination of unique NASA work and public-private partnerships, NASA will work with commercial simulant providers to acquire simulants that meet NASA's needs. If warranted, NASA will develop simulants using government agencies, as was done with the NASA/USGS Lunar Highlands Type (NU-LHT) series of lunar simulants [3]. NASA is also collaborating with the Johns Hopkins University Applied Physics Laboratory (JHUAPL) Lunar Surface Innovation Consortium (LSIC) in the development and characterization of lunar simulants [4]. Within NASA, a small team (< 10 people) is coordinating simulant activities across the agency, with team members located at several NASA centers. The overall objective of the project is to procure lunar simulants in sufficient amounts for earth-based testing of subsystems and systems in a variety of environments (i.e., laboratory, high-bay, thermal-vacuum chambers), required for Artemis missions to the Moon, as well as other missions carrying NASA lunar payloads, such as the Commercial Lunar Payload Services (CLPS) program [5].

Lunar Highlands Simulant: NASA's Artemis Program is targeting the lunar south pole region for initial human missions and the Artemis Base Camp. Hence, the LSII lunar simulant project is currently focusing on the mineralogy and properties of lunar highlands regolith [6 and 7]. Plagioclase-rich rocks (e.g., anorthosite, norite) are the dominant constituent in highlands simulants, with Shawmere, Stillwater, and White Mountain anorthosites being used in commercially available simulants. However, because these feedstocks are terrestrial in nature, they include hydrated minerals, carbon-bearing minerals, and other chemical signatures that are not present on the Moon, and these minor mineral assemblages need to be taken into account when trying to understand test procedures and results.

Glass Component: While much attention has been placed on the rock/mineral component of lunar simulants, glass is just as important when creating simulants. The glass component in lunar regoliths is often greater than 50% by volume [8]. This component includes impact melt glass, dark matrix breccias, and agglutinates. However, this component is difficult, time-consuming and expensive to make. Most lunar simulants, past and current, have relied on basaltic cinder as a feedstock for glass. Getting better glass components at a lower cost, particularly agglutinates and glass with an anorthositic composition is a near-term objective that the NASA simulant project is trying to address.

Characterization: It is extremely important for lunar simulants to be characterized by several analytical methods. Gruener et al. [9] and JHUAPL LSIC [10] conducted initial assessments of some of the commercially available simulants in 2019 and early 2020, before the global pandemic. Further analyses are needed to better quantify important parameters such as, modal mineralogy and glass content, particle shape, and particle size distribution. These quantified results can then be used in determining figures of merit (FOM) that show how well simulants compare to lunar regolith [11 and 12].

References:

[1] NASA (2020) https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf. [2] NASA (2020) https://www.nasa.gov/directorates/spacetech/game_changing_development/LSII. [3] Stoesser D. B. et al. (2010) NASA/TM-2010-216438. [4] JHUAPL (2021) http://lsic.jhuapl.edu/. [5] NASA (2021) https://www.nasa.gov/content/commercial-lunar-payload-services-overview. [6] Joliff, B. L. et al. (2006) Reviews in mineralogy & geochemistry, Vol. 60. [7] Korotev R. L. et al. (2003) *Geochim Cosmochim Acta* 67:4895-4923. [8] Heiken G. H. et al.

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REGOLITH SIMULANT REPORT CARDS: A USER FRIENDLY SIMULANT CERTIFICATION SYSTEM.

S. R. Deitrick[1,2] and K. M. Cannon[1], [1]Colorado School of Mines Center for Space Resources, 1500 Illinois St., Golden, CO 80401, srdeitrick@mymail.mines.edu, cannon@mines.edu, [2]Jacobs/NASA Johnson Space Center Astromaterials Research and Exploration Science Division, 2101 NASA Pkwy, Houston, TX 77058, sarah.r.deitrick@nasa.gov.

Introduction: As the nation prepares to return to the Moon, there is an increasing need for testing tools, instruments, and equipment in simulated lunar regolith to ensure successful operations during lunar missions. Because of this, it is important to use accurate lunar regolith simulants to prepare for these missions. To address this, we are building an objective certification and reporting system for regolith simulants to ensure suitable simulants are being used for the appropriate use cases. Previous systems like the Figures of Merit (FoM) [1] and the Lunar Regolith Simulant User's Guide fit-to-use matrices [2] for lunar simulants were not particularly user friendly. Some of the Figures of Merit were not clearly defined and did not include recommended baseline values of lunar regolith properties to compare simulants to, and the fit-to-use matrices are out of date and include simulants that are no longer in production and do not include simulants that have been developed since.

Certification System: Our simulant certification system takes in analytical data for a simulant and automatically generates a report card that emphasizes the most and least appropriate use cases for that specific simulant. We have defined a parsimonious set of five use cases that require testing with simulants: (1) Geotechnical, (2) Particle Bonding, (3) Particle-Surface Interactions, (4) Chemical Processing, and (5) Human Health. In the background our system takes in FoM values calculated for six properties of the simulant (bulk chemistry, modal mineralogy, particle size distribution, particle shape, grain density, and magnetic susceptibility) and outputs an overall score and suitability level for each of the five use cases. The front page of the simulant report card (Figure 2) summarizes the simulant suitability level for each use. case followed by appendices with analytical data for the six properties.

Weighting System. The overall scores are calculated based on a weighting system (Figure 1). The relevant properties for each use case are assigned a weight according to the significance of the property to the use case. For example in the Geotechnical use case, particle shape has the most significance and is therefore assigned the highest weight. If no data exist for a property, the weights will be re-normalized to account for the missing property. The FoM value for each property is then multiplied by its respective weight for each use case to give a property score, which are then summed to give an overall use case score. This score determines the suitability level of the simulant for the five use cases and clearly shows what the simulant is most suitable for.

Future Work: This system is currently being set up to automatically generate PDF report cards based on numerical input data, and the designs are being finalized before user testing. In the future we will produce a set of report cards for the most commonly used lunar simulants today, and report cards can be generated on an ongoing basis as new simulants are developed.

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	Property FoM per Use Case				
Properties	Geotechnical	Particle Bonding	Particle-Surface Interactions	Chemical Processing	Human Health
Chemistry		0.7		0.7	0.7
Mineralogy		0.94	0.94	0.94	0.94
Particle Shape	0.2	0.2	0.2		0.2
Particle Size Distribution	0.49	0.49	0.49		0.49
Particle Density	0.3	0.3	0.3		0.3
Magnetic susceptibility			0.04		

	Property Weight per Use Case				
Properties	Geotechnical	Particle Bonding	Particle-Surface Interactions	Chemical Processing	Human Health
Chemistry		20.00%		50.00%	25.00%
Mineralogy		20.00%	25.00%	50.00%	20.00%
Particle Shape	40.00%	20.00%	25.00%		25%
Particle Size Distribution	35.00%	20.00%	25.00%		25.00%
Particle Density	25.00%	20.00%	15.00%		5.00%
Magnetic susceptibility			10.00%		
	100.00%	**100.00%**	**100.00%**	**100.00%**	**100.00%**

	Use Case Score				
Properties	Geotechnical	Particle Bonding	Particle-Surface Interactions	Chemical Processing	Human Health
Chemistry	0	0.14	0	0.35	0.175
Mineralogy	0	0.188	0.235	0.47	0.188
Particle Shape	0.08	0.04	0.05	0	0.05
Particle Size Distribution	0.1715	0.098	0.1225	0	0.1225
Particle Density	0.075	0.06	0.045	0	0.015
Magnetic susceptibility	0	0	0.004	0	0
	0.3265	**0.526**	**0.4565**	**0.82**	**0.5505**
Most Suitable	**> 0.75**				
Suitable	**0.33 - 0.75**				
Less Suitable	**< 0.33**				

Figure 1. Weighing system using example values for FoMs and property weights to calculate use case scores.

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Regolith Simulant Report Card

Simulant Name CRH-1 **Developer** Colorado School of Mines

Simulant Batch Batch 1, created 01/31/2021 **Analysis Date** 04/07/2021

Use Case	Score	Suitability
Geotechnical Excavation, drilling, mobility, etc.	33	**Less Suitable** This simulant should give poor results that lack most characteristics of lunar regolith samples
Particle Bonding Sintering, 3D printing, regolith-based concrete, etc.	53	**Suitable** This simulant should give moderate results that lack some characteristics of lunar regolith samples
Particle-Surface Interactions Dust mitigation, plume-surface interactions, etc.	46	**Suitable** This simulant should give moderate results that lack some characteristics of lunar regolith samples
Chemical Processing Oxygen/volatile/metal production	82	**Most Suitable** This simulant should give highly accurate results that compare well to lunar regolith samples
Human Health Dust toxicity, respiratory, radiation shielding, etc.	55	**Suitable** This simulant should give moderate results that lack some characteristics of lunar regolith samples

	Mineralogy	Chemistry	Particle Size Distribution	Particle Shape	Grain Density	Magnetic Susceptibility
Figure of Merit Score	94	70	49	20	30	4

Signature

Date

Figure 2. Example of a regolith simulant report card main page. For the imaginary simulant CRH-1, it is clear that the simulant is most suitable for use in chemical processing tests.

Creation, Methodology, and Applications of High Fidelity Simulated Lunar Agglutinates. C. Sipe[1], P. Easter[1], Z. A. Landsman[1], L. Weber[1], D. T. Britt[1], J. M. Long-Fox[1], K. L. Donaldson-Hanna[1], B. Patterson[1], G. L. Schieber[1], and A. Metke[1].
[1]University of Central Florida, Orlando, FL, USA.

Introduction: Regolith simulants are used to test both spacecraft hardware and scientific processes in the absence of actual regolith samples. At the CLASS Exolith Lab, high fidelity regolith simulants are created to replicate both the Lunar Highlands (LHS-1) and Lunar Mare (LMS-1) regions of the Moon. These simulants aim to accurately represent the mineralogy and particle size distribution of Lunar regolith to provide a useful simulation tool for the scientific community. In the past, it has been difficult to accurately simulate certain features of the Lunar regolith. Agglutinates, welded glassy aggregates which are formed by high energy micrometeorite impacts on the Lunar surface [1, and references therein], are one of these features. The agglutinates themselves are products of high temperature and energy reactions. The Exolith Lab is now capable of adding agglutinates to small amounts of simulant, further increasing the fidelity and usefulness of our Lunar regolith simulants. This allows us to characterize our simulants in terms of maturity as well as glass content, which are essential factors of Lunar regolith.

Methodology: We have developed a time-and energy-efficient method to produce simulated agglutinates, which consist of a glassy matrix of melted regolith welded to unmelted grains. In the past, simulated agglutinates have been very cost and energy intensive to produce. However, using solar energy, the CLASS Exolith Lab now has the capability to mass produce these high fidelity simulated agglutinates for a lower price than past simulated agglutinates. These agglutinates are now available for purchase either by themselves or mixed in with their respective Lunar simulants and can be found at https://exolithsimulants.com. We have developed two different simulated agglutinate mixes: one for the Lunar Highlands and one for the Lunar Mare. For the Lunar Highlands agglutinate base, the mixture consists of 99% Anorthosite and 1% fine metallic iron by weight. For the Lunar Mare agglutinate base, the mixture consists of 99% LMS-1 and 1% fine metallic iron by weight. The metallic iron gives the simulant magnetic properties that are useful in scientific experiments as well as hardware testing. This mixture does not result in nanophase iron, as observed in the rims of grains in the Lunar Regolith as a result of space weathering [1].

After undergoing phase change, the resulting globular melt is left to anneal in the open air on a bed of the unmelted base material, which welds to the melt (Figure 1). The cooled aggregate is later crushed to an appropriate agglutinate size distribution. The soil dynamics and heat transfer of the process is currently being investigated.

Figure 1: Recently formed simulated aggregates during annealing process. Figure details both highlands (top) and mare (bottom) materials. These aggregates are later crushed to appropriate agglutinate sizes.

To study the internal structure of these aggregates, we obtained petrographic thin sections. The thin sections were analyzed in a petrographic microscope in reflected and transmitted light (both plane- and cross-polarized). An image of a simulated highlands agglutinate (Figure 2, left) shows unmelted plagioclase grains suspended in glassy matrix, which is dotted with voids from gas bubbles formed in the phase change reaction. Darker areas of the matrix are embedded with metallic iron. Comparison with an agglutinate from Apollo Lunar Highlands sample 68501* shows comparable internal structure.

* Image by Kurt Hollocher (http://minerva.union.edu/hollochk/moon_rocks/) from a sample included in the NASA Lunar Petrographic Thin Section Set (https://curator.jsc.nasa.gov/)

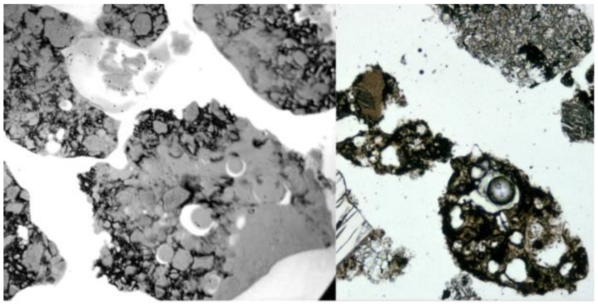

Figure 2: Microscopic image in transmitted, plane-polarized of a thin section of a simulated agglutinate (highlands composition, left) and an actual highlands Lunar agglutinate (right). Field width for left image is 1.5mm and field width for the right image is 1.6mm.

Relevance to ISRU and Applications: Regolith simulants are essential tools in the development of In-Situ Resource Utilization (ISRU) processes and evaluating and testing Lunar hardware.

ISRU technologies that are being developed to operate on the Lunar surface include molten regolith electrolysis, water extraction processes, dust mitigation systems, and construction of habitats and launch infrastructure. One such area of ISRU that can benefit from the agglutinates is magnetic beneficiation and magnetic dust separation. With the 1% metallic iron, the agglutinates make the simulated Lunar soil magnetic, which allows the simulant to be used for these types of experiments.

Lunar agglutinates are very sharp, which in turn makes the Lunar soil much more abrasive than soils here on Earth [3]. Adding simulated agglutinates to our regolith simulants serve to replicate the abrasiveness of the Lunar regolith, which can provide a closer result when testing spacecraft and mission hardware. Regolith flowability is an important factor to test as well, since having a quantified knowledge of flowability allows us to understand the mechanics of regolith more greatly. Agglutinates in the Lunar soil are angular, so they increase the amount of contact between the individual regolith particles, which in turn decreases the flowability. Adding agglutinates into the regolith simulants will provide a more accurate description of how different types of Lunar regolith flow.

Interaction with volatiles is another important attribute of Lunar regolith. In past studies, regolith simulants that did not have any agglutinates mixed in, i.e., JSC-1A, adsorbed water much better than Lunar regolith [4]. This was attributed to the Lunar regolith having agglutinates. This is advantageous because it allows for more accurate experimentation of simulated Lunar regolith and volatiles.

As agglutinates range from a few percent to more than fifty percent in some of the Lunar regolith [2], it is essential to know how they affect the properties of the regolith as well as the many processes in which regolith is involved.

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Comparison of NASA Lunar and Martian Landing Sites: Shear Strength Properties of Lunar Highlands (LHS-1) and Mars Jezero Crater (JEZ-1) Simulants

J. M. Long-Fox[1,2], Z. A. Landsman[1,3], D. T. Britt[1,4], J. Morales Gonzalez[1,5], and C. D. Schultz[6], [1]University of Central Florida, Department of Physics, 4000 Central Florida Blvd, Orlando, FL 32816, [2]jared.long-fox@ucf.edu, [3]zoe.landsman@ucf.edu, [4]dbritt@ucf.edu, [5]janelissemorales@knights.ucf.edu, [6]Brown University, Department of Earth, Environmental, and Planetary Sciences, 324 Brook St., Providence, RI 02912, cody_schultz@brown.edu

Introduction: The Lunar south pole and Jezero crater on Mars are of interest to resource utilization effors, and thus these sites are targest for robotic and human exploration (e.g., NASA's VIPER, Artemis program, and Mars 2020). Physical properties of the regolith are unique for each mission and landing site and include mineralogy, gravitation, local geomorphology, and the presence and composition of an atmosphere. These factors are known to affect the planetary system as a whole and provide parameters that must be addressed in exploration and in-situ resource utilization (ISRU) mission planning and hardware design. Here, we present shear strength properties of Lunar and Martian regolith simulants.

Material Properties: Knowledge of regolith shear strength properties, especially the Mohr-Coulomb parameters cohesion (c) and angle of internal friction (ϕ), is essential for in-situ resource utilization (ISRU) applications and exploration hardware design. In the absence of a high volume of returned planetary regolith samples for large-scale scientific experimentation, high-fidelity regolith "simulants" are created to approximate the physical and mineralogical properties of the regolith being simulated. Here, the bulk (uncompressed) density (ρ_b) and Mohr-Coulomb shear strength parameters, cohesion and angle of internal friction, are estimated for a Lunar highlands simulant (LHS-1) and a Mars Jezero crater simulant (JEZ-1), both created by the CLASS Exolith Lab at the University of Central Florida. LHS-1 and JEZ-1 are high-mineralogical fedility simulants representing the target sites of the upcoming NASA Artemis missions and the landing site of the NASA Perseverance Mars Rover, respectively.

Methods: An experimental procedure conforming to the ASTM D3080-98 testing standard was created to estimate cohesion and angle of internal friction of the simulants. The experimental procedure includes measurement of the bulk density of the sample by loading and lightly compacting a measured mass of simulant into the known volume of the direct shear box. Normal stress is distributed throughout the simulant by means of a variable mass resting evenly on the top of the sample during testing. Shear force is measured by a force gauge that is moved parallel to the direction of shearing by a microcontroller-driven linear servo to shear the top portion of the direct shear box while the bottom portion is held in place. Each simulant was loaded to 5 levels of normal stress then the shear measurement was repeated 25 times. The shear strength data are analyzed via linear regression in order to estimate the values of cohesion (y-intercept of linear fit) and angle of internal friction (arctangent of the slope of the linear fit) with their 1-sigma uncertainties.

Results: Estimates of bulk density, cohesion, and angle of internal friction obtained from direct shear testing of LHS-1 and JEZ-1 are given in Table 1, and plots of the direct shear data and results of the corresponding linear regressions are found in Figures 1 and 2, respectively.

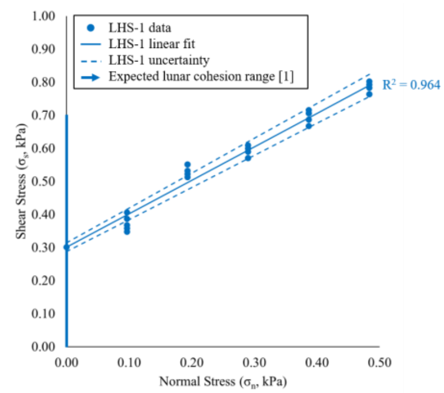

Figure 1. *LHS-1 direct shear data with expected range of cohesion for Lunar regolith (0.0-0.7 kPa) [1].*

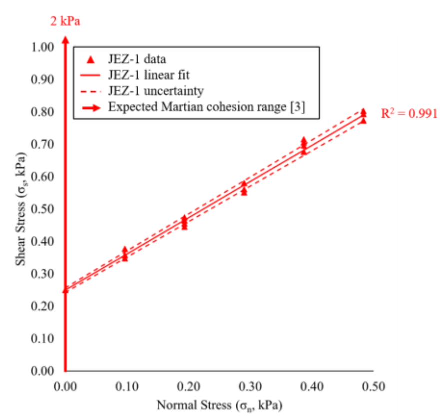

Figure 2. *JEZ-1 direct shear data with expected range of cohesion for Martian regolith (0.0-2.0 kPa) [3].*

Table 1. *Experimental results from direct shear testing of LHS-1 and JEZ-1.*

	LHS-1	**JEZ-1**
c (kPa)	0.301 ± 0.013	0.249 ± 0.007
ϕ (°)	45.34 ± 2.39	48.19 ± 1.31
ρ_b (kg/m^3)	1391.26 ± 7.81	1361.91 ± 3.12

Discussion: These preliminary results show that LHS-1 has a higher estimated value of cohesion (0.301 kPa) compared to JEZ-1 (0.249 kPa), but LHS-1 has a lower estimated value for angle of internal friction (45.34°) than JEZ-1 (48.19°**)** and have similar estimates of bulk density. Estimated values of cohesion, angle of internal friction, and bulk density of LHS-1 are comparable to reported results chanracterizing these properties of returned Lunar regolith and its simulants [1,2]. Estimates of cohesion, angle of internal friction, and bulk density are widely varied for Martian regolith [3] and Martian regolith simulants [4,5,6] with the preliminary results given here are within bounds of these previously published results.

The varying conditions and testing methods to determine physical properties of planetary regolith and its simulants introduce variability into regolith property estimations. The study of planetary regolith using terrestrial regolith simulants, is confounded by differences between the actual planetary regolith and its simulants, i.e., differences in environment, mineralogy, particle size and shape distributions, as well as physical and chemical conditions to which the material has previously been exposed. The Exolith Lab controls for particle size distribution, mineralogy, and, to an extent, particle shape (by using percussive rock crushing); however, our measurements take place in Earth gravity and atmosphere, and the Exolith simulant feedstock rocks and mineals have experienced terrestrial weathering.

References:

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MECHANICAL BEHAVIOR OF REGOLITH

M. Nakagawa[1], Z. Kahdamean[2], R. Garvey[2], and Y. Isabel Casasbuenas[1]
[1]Department of Mining Engineering, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401; mnakagaw@mines.edu, [2]Blueshift, LLC, 575 Burbank St. Unit G, Broomfield, CO 80020 USA; zoheirkhademian@gmail.com, rgarvey@outward.tech

Introduction: Space Mining on the Moon as currently perceived will likely involve a shallow excavation of lunar regolith. Reliable excavation requires good understanding of how the forces exerted by the excavation machine are transmitted to undisturbed layers of regolith. The excavated regolith then needs to be transported to a processing and/or storage point. This requires knowledge about the stability of a heap of excavated lunar regolith against external vibrations. This paper will review our attempt to understand the impact of irregularly shaped lunar agglutinates that are part of regolith constitients on the mechanical behavior of regolith. The agglutinate component has proven difficult to replicate, yet it typically constitutes 25–30%, and up to 60%, by volume, of the lunar soil. Modeling of such a collection of small irregularly shaped particles is indeed a challenging task as the behavior modeled will greatly depend on the assumptions adapted for the modeling effort. We briefly describe the method of material genesis for agglutinate particles. We also share our results of the influence of gravity on the angle of repose.

Modeling Philosophy: We published a paper describing our modeling effort to understand the mechanical behavior of lunar regolith[1]. As there does not exist any data on the mechanical behavior of a single regolith and agglutinate, our work will be based on the simulation to get a statistica trend of the mechanical behavior.

First, as shown in Fig.1, 2D cross-sectional images of regolith are gathered from the previous publication [2]. The readers are encouraged to read the referred paper [1] for technical detail about the material genesis for various types of lunar soil. Here we would like to highlight only how agglutinate particles are modeled as they are peculiar to the Moon's environment. The agglutinate particles should be modeled so that they can be crushed if the load on them exceed the maximum allowable strength or tensile strength. Second, the modeling should capture their jagged shape as closely as they actually. This is important as the electrostatic charges are concentrated at these sharp corners when tribocharge effects take place during excavation. The behavior of electrostatically charged lunar soil is part of our space mining research at Colorado School of Mines.

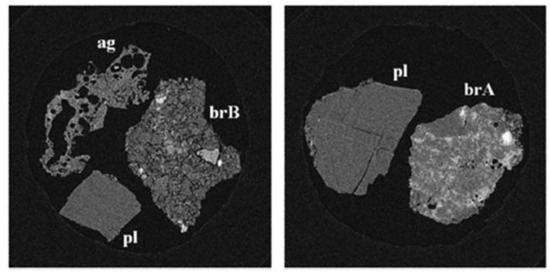

Figure 1. Cross-sectional images of different types of lunar soil for ag(agglutinate), brA(crystalline matrix breccia, brB(fragmental matrix breccia), pl(plagioclase). Katagiri et al. [2]

Modeling Agglutinate Grains: Katagiri et al. [2] showed that if we fit an arbitrary ellipsoid to agglutinate grains of sample 60501, the ratio of the total grain volume to the ellipsoid volume would have a mean value of 0.67. Based on Katagiri's work, the void ratio of agglutinates is 0.13; thus, the ratio of the solid grain volume to the total grain volume has a mean value of 0.87. As a result, the solid volume of an agglutinate grain would be 58% of the fitted ellipsoid

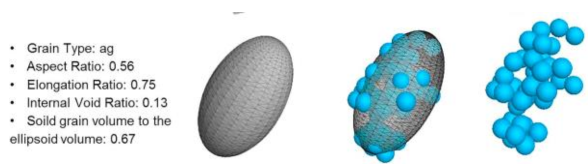

Figure 2. Agglutinate grains

volume, which means such an ellisposode is with a 42% void. (See Fig. 2) Then, we simulate an ellipsoidal mold with the specific aspect and elongation ratios and then randomly remove the spheres remaining outside the mold. This material genesis process yields different agglutinate grains in their structure, but the same volume of vesicles and voids can be expected. It should be noted that these agglutinate particles are nothing but a collection of strategically placed particles, so we must now bond the particles together to make each agglutinate particle a rigid but crushable entity with assigned material properties.

Jager[3] showed that the tensile strength of a single grain can be indirectly estimated by compressing the grain between flat platens until it fails. Many experimental and numerical research studies have been conducted on the overall mechanical behavior of crushable terrestrial soils. However, there are no experimental data available on the strength of individual lunar grains. Figure 3 depicts the way we perform a compression test on a single agglutinate particle. When a grain containing micro fractures is subjected to a similar compression test, it fails in tension. In essense, our simulation model of the uniaxial compression test using bonded agglutinate particles tries to capture this phenomena. There are many outstanding issues with this method. For example, as the agglutinate grain is compressed and crushed, it changes the material property, i.e., evolving material property. If an agglutinate particle is supported by a finite number of contact points and compressed, even the definition of "stress" becomes unclear. We will report this aspect at a different occasion.

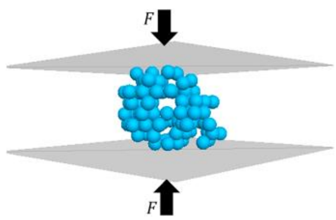

Figure 3. Compression of a single agglutinate particle.

Angle of Repose of Lunar Regolith with Agglutinate Particles: We assume that the initial mining activity on the surface of the Moon will focus on a shallow excavation and transportion of a short distance. Thus, based on the engineering properties of lunar soils by Carrier et al. [4] and Heiken et al.[5], we use the in-situ bulk density of 1.5 g/cm3 with a porosity of 52% at a depth of 15 cm.

The initial sample of a mixture of lunar regolith contained in a box is compressed to achieve the desired porosity of 54% as described earlier, and one of the sidewalls is removed to allow grains to flow under a specific gravity. In Fig 5a and 5b, the angle of repose formed under the Earth and Moon gravity, respectively. There is a striking difference in the upper angle of repose. The angle of repose of the lower part is influenced by the fluid behavior of regolith but that of the upper part is influenced more by quasi-solid behavior. This result demands a study on the stability of the heap. Possible explanations will be given at the time of presentation. Fig. 6 shows how the angle of repose depends on gravity. The overall trend is that as the gravitaty increases, the angle of repose decreases; however, the gravity has less influence beyond the earth gravity.

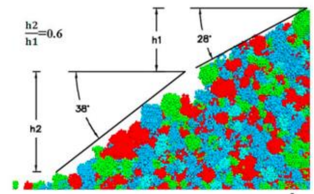

Figure 5a. Static angle of repose formed under the Earth gravity

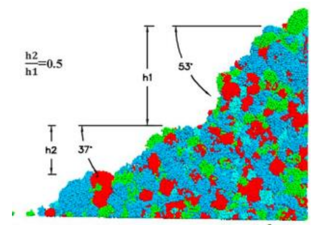

Figure 5b. Static angle of repose formed under the Moon gravity

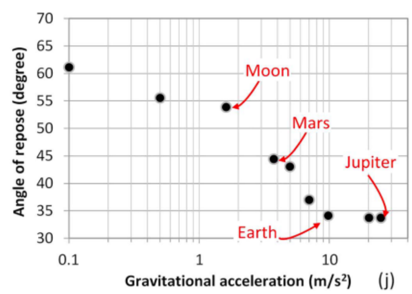

Figure 6. Simulated Angle of Repose under Different Gravitational Accelerations.

Conclusion:

We briefly described how typical regolith particles are modeled. As the angle of repose will play an important role in conveying excavated lunar regolith, we investigated how it is formed and how the gravity influences its formation. The angle of repose of a lunar regolith is much greater than that of Earth's soil. We are investigating the stability of a heap of lunar regolith against external disturbances.

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[1] Khademian, Z., Kim, E. and Nakagawa, M. (2019) *JGR Planets, 124*, 1157–1176. [2] Katagiri, J., et al. (2015) *Journal of Aerospace Engineering., 28(4)*. [3] Jager, J.C. (1967) International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 4(2), 219-227. [4] Carrier, W. et al. (1973)Americal Society of Civil Engineers, Soil Mechanics and Foundations Division. Journal, 99(75), 813-832. [5]Heiken,G. H. et al. (1991) Lunar Source Book, Cambridge University Press.

DUSTY LUNAR SURFACE SIMULATION PROJECT. Thomas Viviano, NASA JSC, Mail Code: EP6, 2101 NASA Parkway, Houston, TX 77058. thomas.v.viviano@nasa.gov

Introduction: The Dusty Lunar Surface Simulation project will develop a lunar surface environment test bed for ISRU systems and subsystems. An environment where interacting with lunar regolith and dust are extremely important factors in the technology development and demonstration. Current thermal and vacuum capabilities of the JSC B351,15ft chamber will be augmented with dust and an icy/regolith capabilities to provide this environment. These capabilities would be geared toward ISRU oxygen extraction from regolith, but could easily be utilized for development of other lunar surface systems and dust mitigation techniques. Need for this test environment is derived from Lunar Surface Innovation Initiative (LSII) guidance to demonstrate ISRU oxygen extraction from regolith starting as early as FY22. Recent ISRU SCLT teams reviewed existing test capabilities across the agency and documented a gap in ISRU test capability in the system/subsystem size range.

Lessons learned from human interaction with the lunar surface during the Apollo missions was that lunar dust is difficult to work in and deal with. Testing in lunar surface environments must be of greater focus for future lunar missions. This project seeks to develop the lunar surface environmental test capabilities from Technology Readiness Level 3 (TRL3) to TRL5 or greater to enable use of these capabilities for lunar, and even Mars, exploration missions.

The Dusty Lunar Surface Simulation project will focus efforts on three main pillars of work - icy regolith test operations, dusty environment, and long duration tests at lunar conditions

The first pillar of work for this project will be to develop an icy-regolith bed to evaluate oxygen extraction from regolith technologies. The icy-regolith bed will be designed to demonstrate drilling techniques, quantify extraction losses, feasibility of down hole ice/water vaporization, sample transfer and resource collection.

Planned test capability will include equipment, areas and processes to prepare lunar simulant to load the bed to a known water content prior to testing. The bed will be sized as large as possible within the limits of the load rating of the chamber support platform. Initial requirement for drill section of the bed is a minimum of 1 meter deep and approximately 24”x 52” area. A minimum of one bed will be fabricated, others may be fabricated if resources and time allows. Once the bed is prepared, it will be moved in the thermal vacuum chamber and connected to a thermal conditioning system (LN2 based) to provide temperature conditioning of the regolith. Figure 1 shows the drill box concept currently in design for drilling into icy regolith.

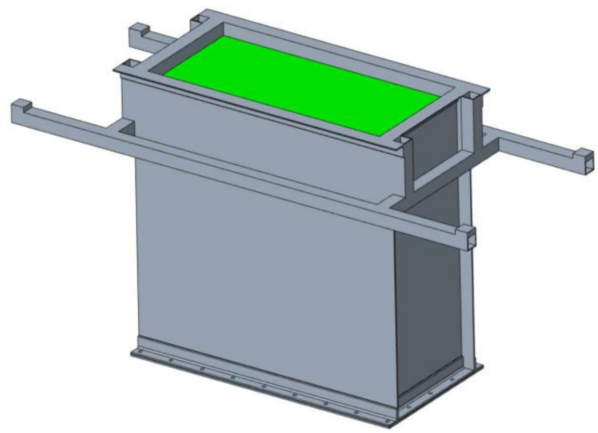


Figure 1: Drill Box Concept for Drilling Into Icy Regolith

The second pillar of work involves creating dusty lunar environment test conditions and will seek to develop a dust exposure capability to evaluate the effects on mechanisms, interfaces and thermal characteristics.

This includes upgrading the mechanical system of the 15’ TVAC at ESTA with dust mitigation components for dusty TVAC operations, loading simulant bed for dusty lunar surface operations testing, and developing in-chamber dust deposition system on a test article while at vacuum to evaluate test article dust mitigation capabilities.

Planned dust exposure capability will include agitated dust and deposition. A minimum of one in-vacuum dusting technique will be installed. Best effort will be made to conceptually plan for multiple dust application methods and how they could be integrated into the chamber. Recommendations from GCD dust mitigation and dust environment classification team will be incorporated as they become available.

The third and final effort will be to develop long duration test capability at lunar conditions

Enhance current capability to support long-term operation of test hardware at lunar surface environment conditions. This capability is needed to understand effects of the dusty environment on mechanisms after long periods of operation.

The chamber systems and support equipment will be evaluated for reliability, failure modes and consumables. Changes will be implemented to improve reliability, system health monitoring and redundancy where feasible. This also involves outfitting the 15’ chamber with backup power and fail-safes, being able to run operations with minimal personnel, and constant remote monitoring of test system, test hardware, and test data This will allow the option for hardware owners to support tests from off-site locations.

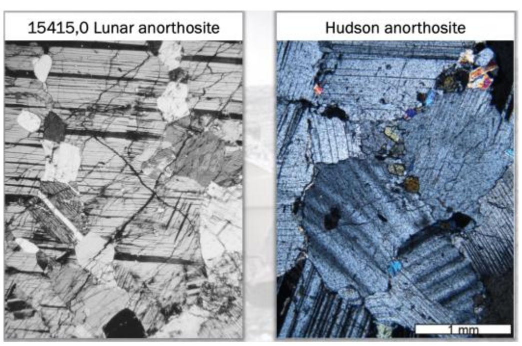
Figure 2 shows the 4’ x 8’ regolith bin inside the 15’ chamber with a trolly/hoist system used to move it into place.

Figure 2: 15' Chamber Entrance with Regolith Bin on the Chamber Floor

UTLIZING ANORTHOSITE AS A LUNAR SIMULANT AND TO MAKE CO2 FREE CEMENT AND WASTE FREE ALUMINA – IN SPACE AND ON EARTH. Author[1] Jim K. Cambon, President Hudson Resources Inc. (420-1639 W. 2ND AVE, Vancouver, BC, jcambon@hudsonresourcesinc.com.

Introduction: Hudson is mining a unique anorthosite (calcium feldspar) in Greenland at the White Mountain mine. The rock 94 wt. % plagioclase with approximately 50% silicon, 30% aluminum and 15% calcium, and very low iron. It is angular and abrasive.

The mineral is very similar to the lunar polar region known as the Feldspathic Highlands Terrane. Rock samples brought back by the Apollo 16 mission show striking similarities to Hudson's anorthosite. See thin section image below.



The anorthosite has numerous industrial applications including the production of reduced CO_2 E-Glass fiberglass, paint and coating fillers, CO_2 free cement, waste free alumina, and as a lunar simulant.

Hudson has been supplying numerous space agencies with material fo use as a lunar simulant, including NASA for their Artemis program.

Aside from being an excellent lunar simulant for testing lunar mission equipment, it has very practical and green applications. The ability to make a CO2 free cement by combining phosphoric acid with the anorthosite may have applications for building future structures on the Moon and Mars. One company is testing the anorthosite for 3D printing of homes which may have applications on the Moon or Mars.

Hudson has successful made smelter grade alumina from the anorthosite at a lab scale. This is a green alternative to using bauxite which results in the production of four tonnes of caustic red mud tailings for every tonne of aluminum produced. The Hudson process does not produce any waste and does not require high atmospheric pressures or temperatures. This could have potential applications on the Moon in the future.

The presentation will go into detail on the chemistry of the anorthosite and applications along with updates on lunar simulant testing, if available.

References: GREENLAND 'WHITE MOUNTAIN' ANORTHOSITE: A NEW LUNAR POLAR REGOLITH SIMULANT COMPONENT. J. E. Gruener , S. R. Deitrick , V. M. Tu , J. V. Clark , D. W. Ming , and J. Cambon , NASA Johnson Space Center, Houston, Texas (john.e.gruener@nasa.gov), Jacobs NASA Johnson Space Center, Houston, Texas, Geocontrols Systems - Jacobs JETS Contract, NASA Johnson Space Center, Houston, Texas, Hudson Resources, Inc., Vancouver, BC, Canada (jamescambon@gmail.com).

NASA LSII Lunar Simulant Project

John Gruener – Johnson Space Center

PTMSS/SRR Joint Meeting
June 2021

LSII Lunar Simulant Project

- **May 2020 - NASA Space Technology Mission Directorate (STMD) Game Changing Division (GCD) creates the Lunar Surface Innovation Initiative (LSII) Lunar Simulant Project**

- **NASA Simulant Advisory Team**

  John Gruener – JSC, planetary scientist, lead

  Jennifer Edmunson - MSFC, geologist, Constellation Program simulants

  Doug Rickman - MSFC, geologist, Constellation Program simulants

  Laurent Sibille - KSC, technology development scientist, Constellation Program simulants

  Julie Kleinhenz - GRC, engineer, testing involving simulants

  Elizabeth Carey - JPL, geologist, icy regoliths

  Julie Mitchell - JSC, planetary geologist, icy regoliths

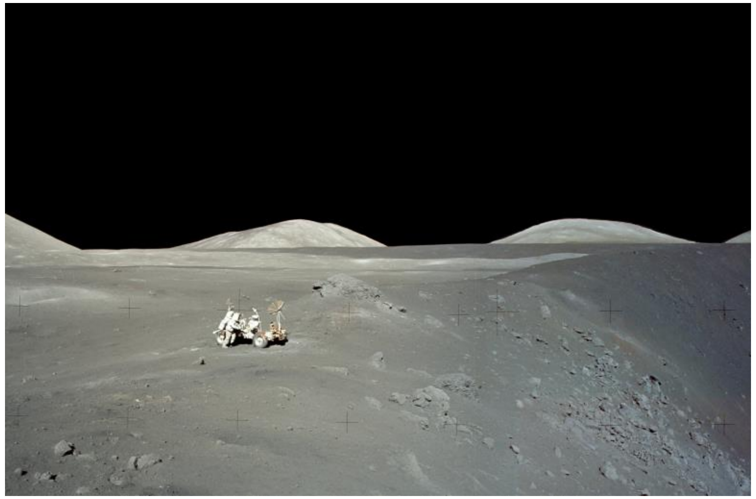
  Sarah Dietrick- JSC, geologist, early career

  Brett Denevi, Karen Stockstill-Cahill – APL Lunar Surface Innovation Consortium (LSIC)

- **Discussions/interactions:** other STMD GCD/LSII Projects (i.e., Dust Mitigation, ISRU); other NASA projects (i.e., HEOMD xEVA); APL LSIC simulant assessment; Commercial simulant providers (Exolith Labs, Off Planet Research, Hudson Resources, Outward Technologies, Deltion)

LSII Lunar Simulant Project Overview

- Project Overview
  - Though lunar simulant is not a “technology” per se, every technology being developed by NASA STMD/GCD for use on the lunar surface needs to be tested with high quality lunar simulants; simulants is more of a "capability/facility"
  - The primary objective of this project is a coordinated approach/voice across NASA for simulant development and to support NASA projects’ simulant needs with a variety of low-, moderate-, and high-fidelity lunar simulants (tied to TRL)
- Technical Capabilities
  - Correct simulant mineralogy, glass content, particle shape, and particle size distribution will be used to create simulants using appropriate equipment for lunar regions of interest (i.e., polar regions)
  - Technical 'tall poles' - production of glass component, particularly lunar-like agglutinate particles is difficult, time-consuming, and expensive, there is currently no large-scale production capability; same comment for simulants containing ice, and nano-phase iron
- Concept of Operations
  - Small team of NASA personnel (civil servants and contractors)
  - Purchase simulants from existing vendors when possible; government development and production when warranted
  - Coordinate with JHU/APL Lunar Surface Innovation Consortium



Apollo 17 – Shorty Crater

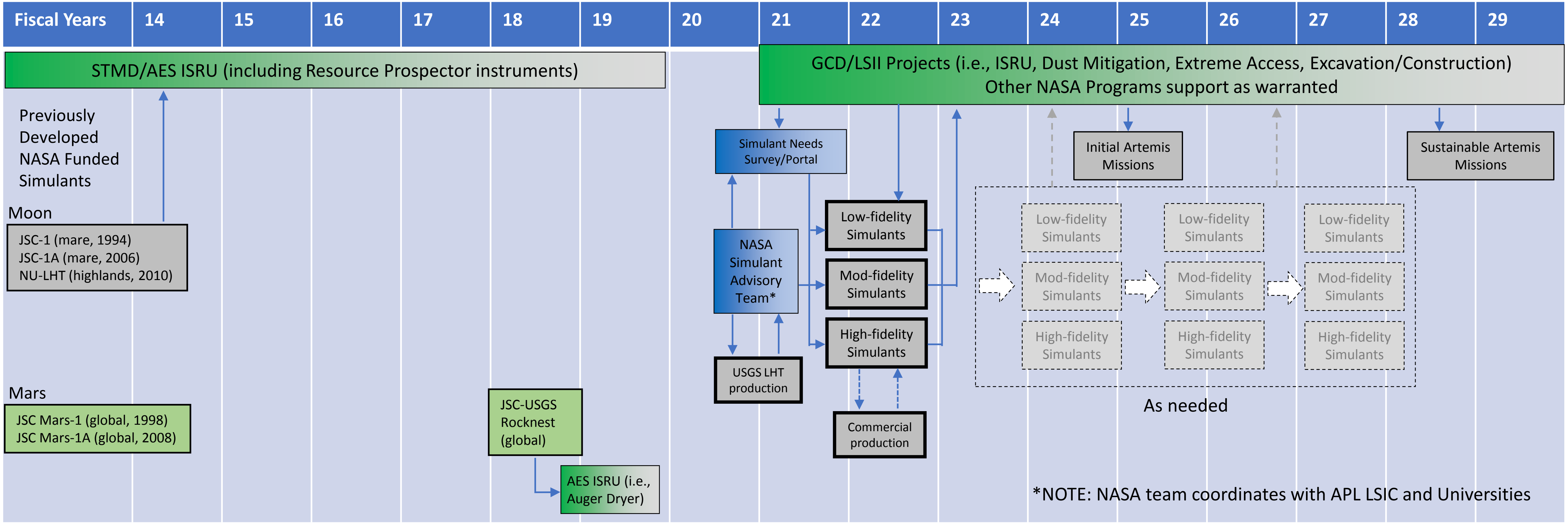
NASA RASSOR excavator testing at KSC in BP-1 lunar simulant

JHU APL Lunar Surface Innovation Consortium (LSIC)

http://lsic.jhuapl.edu/

- **Commercial Lunar Simulant Assessment**
  - Initial review of lunar simulants from Exolith Lab, Off Planet Research, Outward Technologies
  - http://lsic.jhuapl.edu/Resources/files/simulant_eval_2020.pdf
  - "Simulants from the CLASS Exolith Lab or from Off Planet Research could meet the needs of most users"
  - "These providers have worked to develop simulants that provide fidelity to lunar soils in terms of composition, particle size and particle morphology, and have the flexibility to adapt to user needs for a site-dependent composition"
  - "Where the Exolith and Off Planet simulants are lacking, there is no easy remedy"
  - "Including agglutinates in a simulant is likely to benefit only certain uses or testing for advanced TRL"
- **Lunar Simulant Needs Survey**
  - https://docs.google.com/forms/d/e/1FAIpQLSeHoq6_XvUPfY4jV5ZzBGzcYOA06ojWlC-uohynKtu3RWzlVg/viewform
- **Lunar Simulant Working Group (Confluence platform)**
  - Coming Soon!

Schedule of Recent and Planned Simulant Activity



Lunar Chemistry and Mineralogy – The Basis for Lunar Simulants

(from The Lunar Sourcebook)

Major rock-forming chemical elements

Oxygen (∼60% of atoms)
Silicon (∼16-17%)
Aluminum (∼10%, highlands, ∼4.5%, mare)
Calcium (∼5%)
Magnesium (∼5%)
Iron (∼2.5%, highlands, ∼6%, mare)
Titanium + Sodium (∼1%)

OR

Oxygen (∼45 wt%)
Silicon (∼21 wt%)
Aluminum (∼13 wt%, highlands, ∼5 wt%, mare)
Calcium (∼10 wt%, highlands, ∼8 wt%, mare)
Iron (∼6 wt%, highlands, ∼15%, mare)
Magnesium (∼5.5 wt%)
Titanium (< 1 wt%, highlands, ∼1-5 wt%, mare)
Sodium (< 1 wt%)

PLUS

Many, many more minor and trace elements to act as 'irritants' to ISRU systems (i.e, sulfur)

Chemical Elements → Minerals → Rocks

Silicate minerals make up over 90% of the Moon - the Big 3

Pyroxene, $(Ca, Fe, Mg)_2Si_2O_6$
Plagioclase Feldspar, $(Ca, Na)(Al, Si)_4O_8$
Olivine, $(Mg, Fe)_2SiO_4$

Oxide minerals are 'next' most abundant (particularly concentrated in mare)

Ilmenite, $(Fe, Mg)TiO_3$
Spinel
- Chromite, $FeCr_2O_4$
- Ulvöspinel, Fe_2TiO_4
- Hercynite, $FeAl_2O_4$
- Spinel, $MgAl_2O_4$

Armalcolite $(Fe, Mg)Ti_2O_5$ (only in Ti-rich mare)

Other minor minerals of note

Native iron, (Fe)
Troilite, FeS (holds most of the sulfur in lunar rocks)

PLUS

Many, many more trace minerals [i.e., apatite, $Ca_5(PO_4)_3(OH, F, Cl)$]

Lunar Mars Simulants

Basalt: The most common rock in the inner solar system (the dark areas on the Moon)
(from NASA RELAB Facility at Brown University)

Primary Elements
O, Si, Ca, Al, Mg, Fe, (Ti)

Primary Minerals
Pyroxene
Plagioclase Feldspar
Olivine

Dominant Rock Type
Basalt

Bulk chemistry (oxides wt %)	Low-Ti basalt (15071)-52	Medium-Ti basalt (12030)-14	High-Ti basalt (71501)-35
SiO_2	46.07	46.25	31.87
TiO_2	1.89	3.32	9.52
$Al2O_3$	13.87	11.70	11.83
$Cr2O_3$	0.44	0.43	0.43
MgO	10.88	9.42	9.49
CaO	10.52	9.78	10.36
MnO	0.19	0.20	0.22
FeO	13.87	16.27	16.05
Na_2O	0.40	0.46	0.38
K_2O	0.16	0.29	0.09
P_2O_5	0.15	0.25	0.06
SO_2	0.11	0.12	0.19

Source: RELAB

How a geochemist describes basalt

Modal abundance of minerals (wt %)	Low-Ti basalt (15071)-52	Medium-Ti basalt (12030)-14	High-Ti basalt (71501)-35
Ilmenite	1.63	2.93	9.86
Plagioclase	19.10	15.76	18.76
Pyroxene	16.56	23.50	14.60
Olivine	2.86	3.50	3.40
Agglutinitic glass	52.16	48.06	45.40
Volcanic glass	3.90	1.43	6.70
Others	3.76	4.80	1.30

Source: RELAB

How a mineralogist or petrologist describes basalt

This causes confusion!

Lunar Mars Simulants

Basalt: The most common rock in the inner solar system (the dark areas on the Moon)
(from NASA RELAB Facility at Brown University)

Primary Elements
O, Si, Ca, Al, Mg, Fe, (Ti)

Primary Minerals
Pyroxene
Plagioclase Feldspar
Olivine

Dominant Rock Type
Basalt

This is where the simulant community needs to focus

Bulk chemistry (oxides wt %)	Low-Ti basalt (15071)-52	Medium-Ti basalt (12030)-14	High-Ti basalt (71501)-35
SiO_2	46.07	46.25	31.87
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Lunar Mars Simulants

Basalt: The most common rock in the inner solar system (the dark areas on the Moon)
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<u>Primary Elements</u>
O, Si, Ca, Al, Mg, Fe, (Ti)

<u>Primary Minerals</u>
Pyroxene
Plagioclase Feldspar
Olivine

<u>Dominant Rock Type</u>
Basalt

Bulk chemistry (oxides wt %)	Low-Ti basalt (15071)-52	Medium-Ti basalt (12030)-14	High-Ti basalt (71501)-35
SiO_2	46.07	46.25	31.87
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$Cr2O_3$	0.44	0.43	0.43
MgO	10.88	9.42	9.49
CaO	10.52	9.78	10.36
MnO	0.19	0.20	0.22
FeO	13.87	[illegible]	[illegible]
Na_2O	0.40	[illegible]	[illegible]
K_2O	0.16	0.29	0.09
P_2O_5	0.15	0.25	0.06
SO_2	0.11	0.12	0.19

Source: RELAB

How a geochemist describes basalt

This is the tough part

Modal abundance of minerals (wt %)	Low-Ti basalt (15071)-52	Medium-Ti basalt (12030)-14	High-Ti basalt (71501)-35
Ilmenite	1.63	2.93	9.86
Plagioclase	19.10	15.76	18.76
Pyroxene	16.56	23.50	14.60
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Agglutinitic glass	52.16	48.06	45.40
Volcanic glass	3.90	1.43	6.70
Others	3.76	4.80	1.30

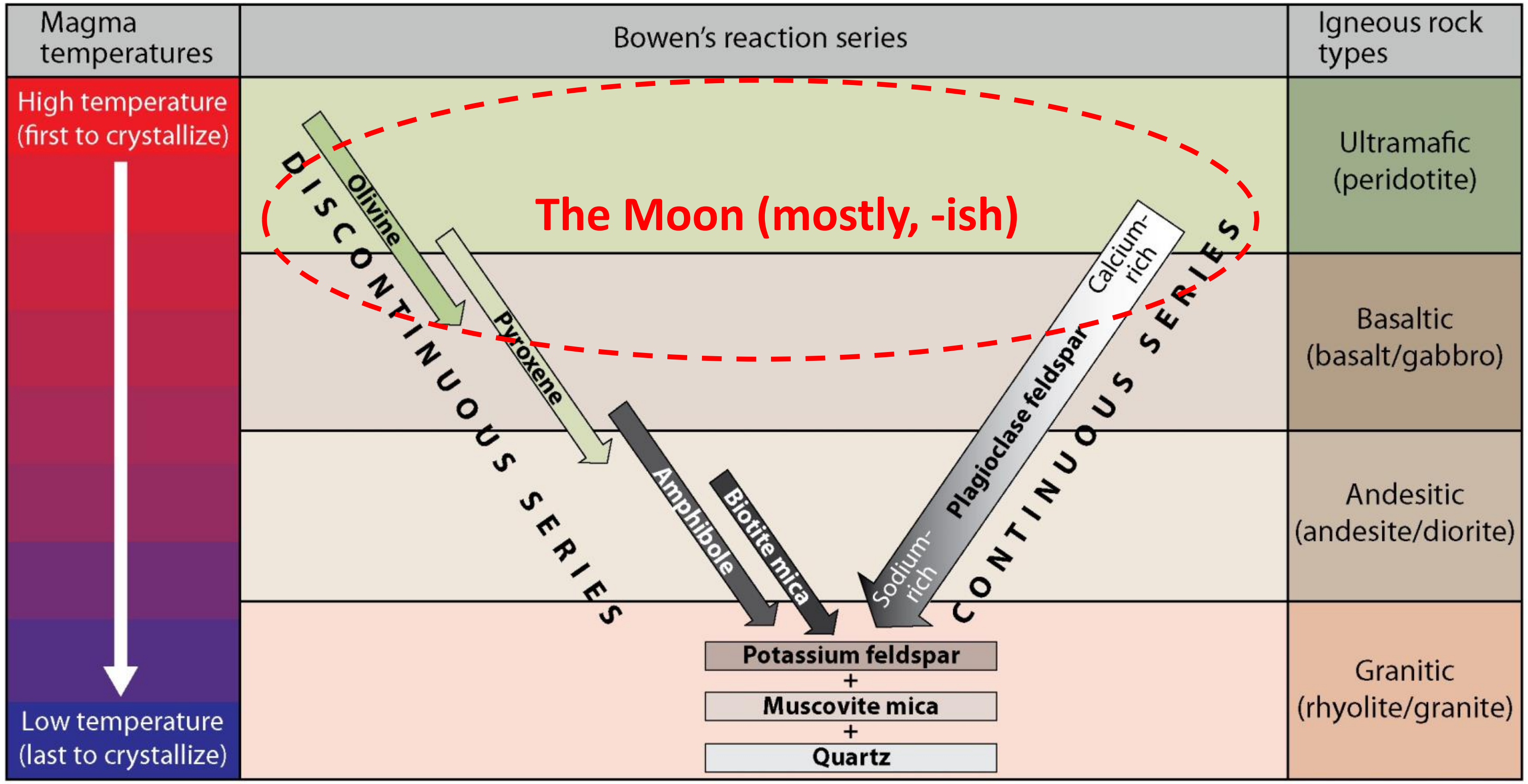
Source: RELAB

How a mineralogist or petrologist describes basalt

This causes confusion!

Lunar Highlands Simulants

Bowen's Reaction series
(from www.nps.gov, photo gallery, National Park Service)



<u>Primary Elements</u>
O, Si, Ca, Al, Mg, Fe

<u>Primary Minerals</u>
Anorthite (Ca-rich plag)
Pyroxene
Olivine

<u>Dominant Rock Types</u>
Anorthosite (plag)
Norite (plag + pyx)
Troctolite (plag + ol)

NOTE: ISRU oxygen from regolith processes used at the lunar poles will have to be able to break apart the Si-O tetrahedra

Classic basis for lunar polar simulants

From The Lunar Sourcebook

Apollo 16 highlands soil (closest to polar soil)

<u>By volume</u>

~17-64%	highlands lithics (i.e., anorthosite)
~21-45%	fused soil (agglutinates + breccias)
~12-33%	plagioclase
~1-3%	glass (i.e., impact)
~1-2%	mare lithics (i.e., basalt)
~1-2%	mafic (i.e., pyroxene, olivine)

<u>Dominant rock and rock fragments</u>

Anorthosite (i.e., plagioclase>>>>pyroxene>>olivine>others)

<u>Dominant mineral and mineral fragments</u>

Plagioclase feldspar

<u>Lesser minerals</u>

Pyroxene, Olivine, others

Agglutinate = rock fragments + mineral fragments + impact glass

Breccia = complex rock composed of fragments of older rocks, created by heat and shock associated with impacts

Highland lithics + plagioclase = 50-76 vol %

Agglutinates + glass + breccia = 22-48 vol %

Mare lithics + mafic minerals < 5 vol %

292 *Lunar Sourcebook*

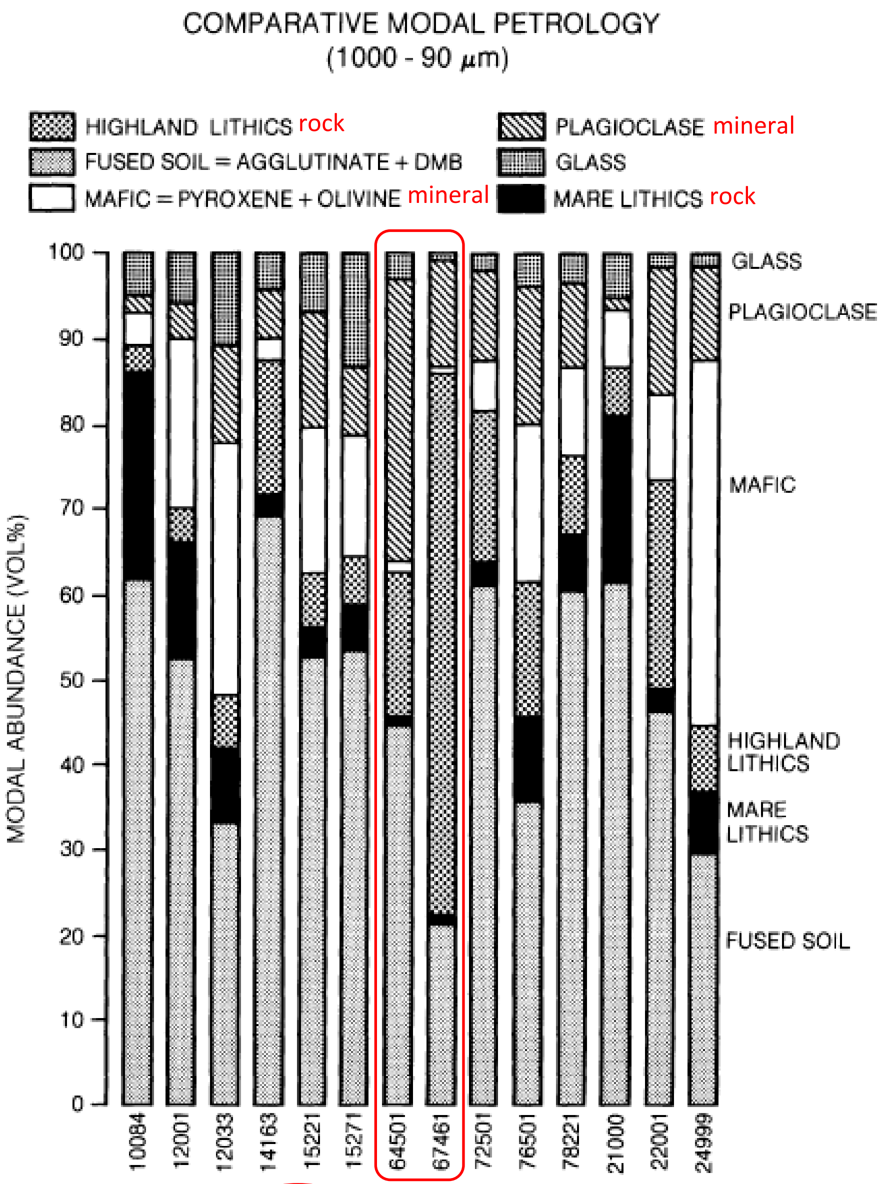


Fig. 7.1. Bar graphs showing modal (volume) abundances of principal particle types in 14 lunar soil samples (*Simon et al.*, 1981). This diagram distinguishes between rock fragments (mare lithics, highland lithics), single mineral and glass fragments (pyroxene and olivine, plagioclase, glass), and fused soil (agglutinates and dmb—Dark Matrix Breccia). Soil samples are from Apollo 11 (10084), Apollo 12 (12xxx), Apollo 14 (14163), Apollo 15 (15xxx), Apollo 16 (6xxxx), Apollo 17 (7xxxx), Luna 16 (21000 and 22001), and Luna 24 (24999).

Limitations with Terrestrial Feedstock

- **We live on a water world**
  - Many hydrated minerals typically found with the targeted lunar-like minerals (plagioclase, pyroxene, olivine)

    Amphiboles - e.g., hornblende $(Ca, Na)_{2\text{-}3}(Mg, Fe, Al)_5Si_6(Si, Al)_2O_{22}(OH)_2$

    Micas – e.g., muscovite $KAl_2(AlSi_3O_{10})(OH)_2$

    Apatite $Ca_5(PO_4)_3(F, Cl, OH)$
  - Minerals associated with chemical weathering are also present

    Clays – e.g., kaolinite $Al_2Si_2O_5(OH)_4$

    Quartz SiO_2

- **We live on a world teaming with life**
  - Many carbon-bearing minerals typically found with the targeted lunar-like minerals
    - Calcite $CaCO_3$
    - Dolomite $CaMg(CO_3)$
  - Volcanic ash and mineral sands may have plant material (e.g., roots)
  - Lunar regolith has very little carbon content, typically ≤ 100 μg/g implanted by the solar-wind

- **The 'rock-loving' lithophile elements Na and K are depleted on Moon compared to Earth**
  - This affects the melting and melt viscosity of lunar minerals vs simulants, particularly plagioclase

Limitations with Terrestrial Feedstock

Example: A Plagioclase Challenge

- Lunar highland regolith (including the poles) is predominantly plagioclase, which is the basis for the many highland simulants (e.g., NU-LHT series, LHS-1, OPRH series, GreenSpar)
    - Plagioclase consists of sodium (Na) and calcium (Ca) components, but in varying ratios
    - More Na will decrease viscosity (i.e., make a melt more fluid)
    - More Ca will increase viscosity (i.e., make the melt ‘thicker’ and less fluid)

- Lunar plagioclase has higher Ca content than the vast majority of terrestrial plagioclase, which form the basis of lunar simulants
    - The An (Anorthite) number is the ratio of Ca / (Ca + Na)
    - Anorthite is the Ca-rich endmember plagioclase solid solution series (see previous chart)
    - Melt viscosity increases with increasing An number
    - Lunar plagioclase An number ~ 95
    - Best simulant An number in high 80’s

- Increasing the An number will also increase the melting point temperature of the simulant

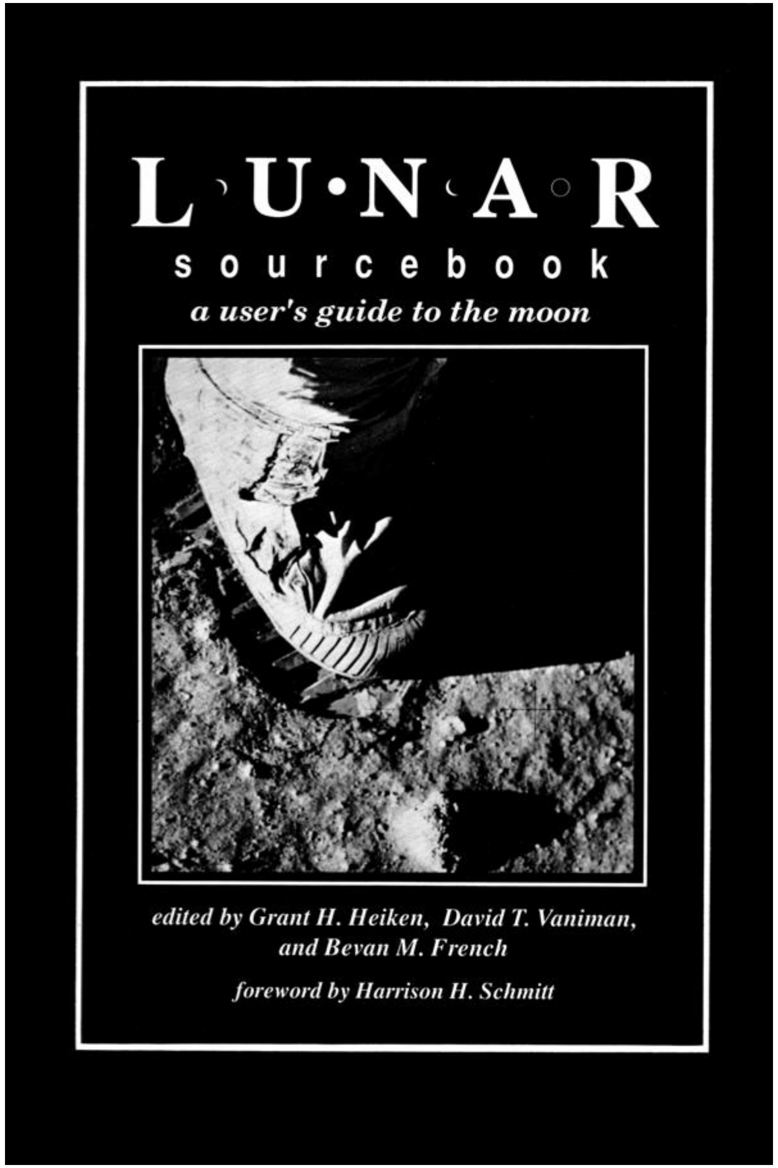
Key Performance Parameters

Increasing complexity, lead-time, and cost

Parameter	State of the Art	Threshold Value	Project Goal
KPP 1: Basic simulants (i.e., low fidelity; partial mineralogy and particle size distribution(PSD) match)	commercial availability	N/A	N/A
KPP 2: Standard simulants (i.e., moderate fidelity; correct mineralogy for major minerals, decent match to PSD, and particle shape)	commercial availability	N/A	N/A
KPP 3: Enhanced simulants (i.e., high fidelity; mostly correct mineralogy, PSD, and particle shape + agglutinates)	partial commercial availability	N/A	N/A
KPP 4: Specialty simulants (i.e., above + ice-bearing, nano-phase iron, etc.)	possible commercial availability[1]	N/A	N/A

Notes:
(1) Creating and using ice-bearing lunar simulants is currently under development at NASA Johnson Space Center (Julie Mitchell), and Jet Propulsion Laboratory has created some ice simulants (Liz Carey) for outer solar system investigations in the past. Off Planet Research has developed an icy-simulant process, but the operational aspects are under development.

Lunar Simulant Resources



The Lunar Sourcebook is free to download

https://www.lpi.usra.edu/publications/books/lunar_sourcebook/

Lunar Simulant Resources

Cross Program Design Specifications for Natural Environments (DSNE)

- SLS-SPEC-159 Revision H, Effective Date August 12, 2020
- https://ntrs.nasa.gov/api/citations/20205007447/downloads/SLS-SPEC-159%20Cross-Program%20Design%20Specification%20for%20Natural%20Environments%20(DSNE)%20REVISION%20H.pdf

National Aeronautics and Space Administration

SLS-SPEC-159
REVISION H
EFFECTIVE DATE: AUGUST 12 , 2020

CROSS-PROGRAM DESIGN SPECIFICATION FOR NATURAL ENVIRONMENTS (DSNE)

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The electronic version is the official approved document.
Verify this is the correct version before use.

Particle Size Distribution (DSNE Section 3.4.2.2.1)

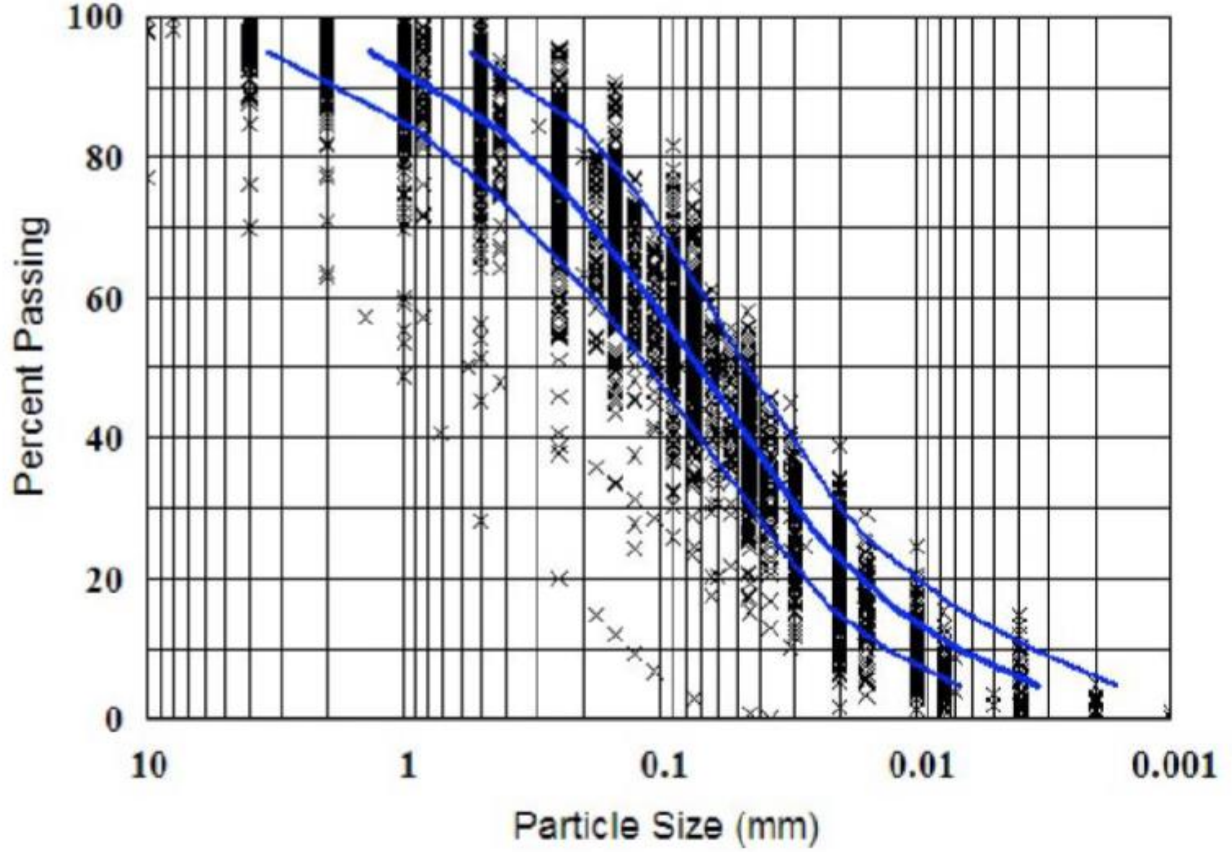

Figure 3.4.2.2.1-1 Geotechnical particle size distribution: middle curve showing the average distribution; left-hand and right-hand curves showing ± 1 standard deviation (from Carrier 2003).

Particle Shape (DSNE Section 3.4.2.2.2)

Table 3.4.2.2.2-1 Summary of grain-specific properties (<1mm size-fraction)

Property	Value	Units	Notes	Section	Sources
Sorting	1.99 - 3.73: range	ϕ	Very poorly sorted	3.4.2.2.2.1	Heiken et al. 1991
Elongation	1.32 - 1.3835: range; 1.35: avg	-	Somewhat elongated	3.4.2.2.2.2	
Aspect ratio	0.3 - 0.9: range; 0.55: avg	-	Slightly to medium elongation	3.4.2.2.2.3	
Roundness	0.19 - 0.29: range; 0.21: avg	-	Subangular to angular	3.4.2.2.2.4	
Volume Coefficient	0.32 - 0.35: range; 0.3: avg	-	-	3.4.2.2.2.5	
Specific Surface Area	0.4 - 0.78: range; 0.5: avg	$m^2\ g^{-1}$		3.4.2.2.2.6	

Particle Shape (DSNE Section 3.4.2.2.2)

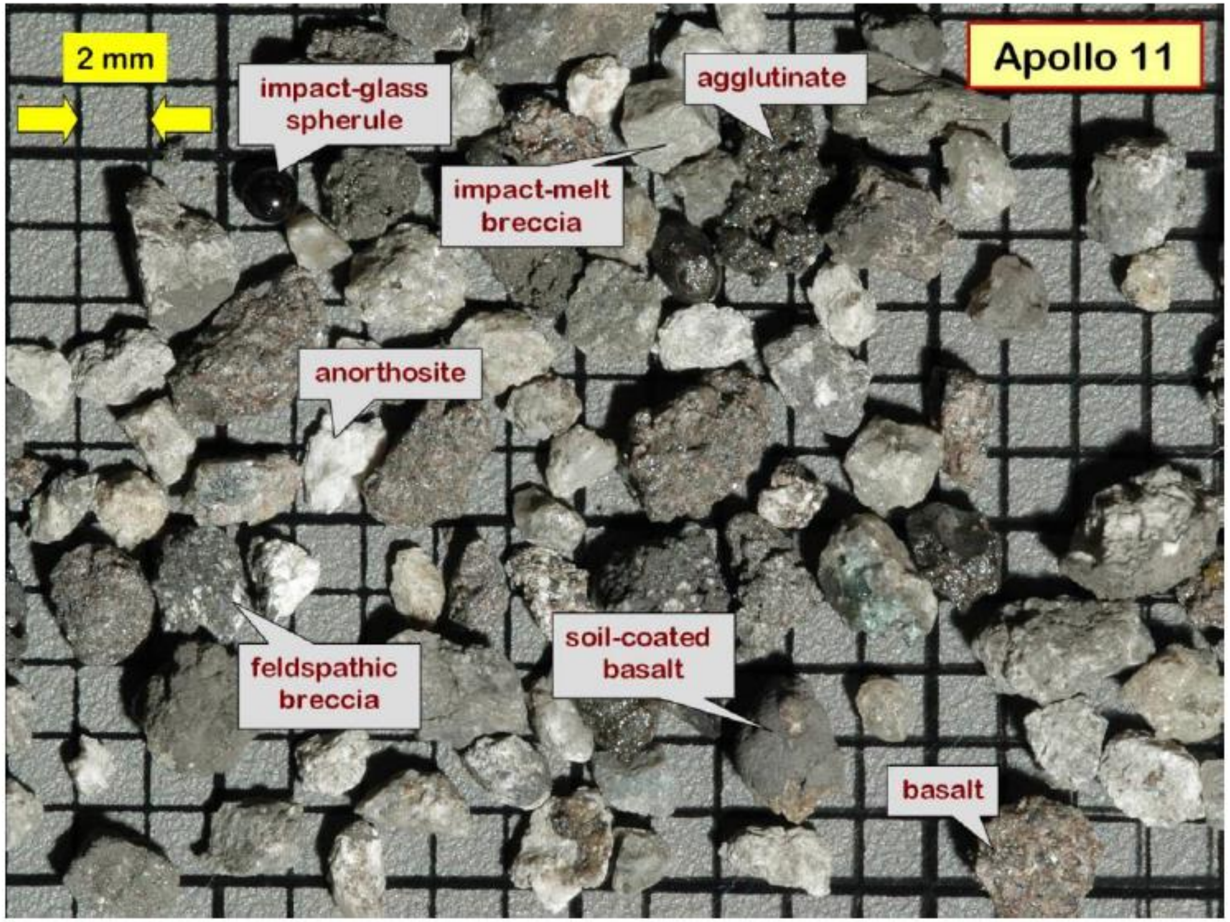

Figure 3.4.2.2.2-2 Apollo 11 regolith fragments from the 2-4 mm grain-size fraction. Note the diversity in shapes and angularity, including two impact-glass spherules. (Photo Credit: Randy Korotev, http://meteorites.wustl.edu/lunar/regolith_breccia.htm).

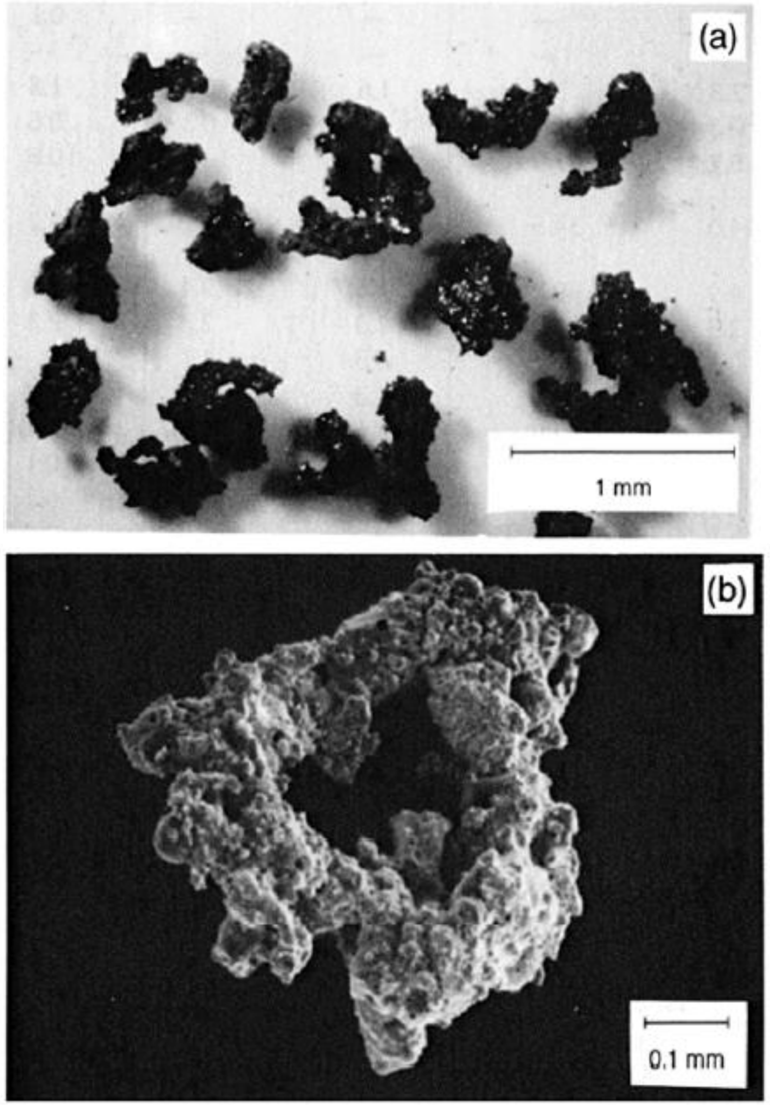

Figure 3.4.2.2.2-1 Typical lunar soil agglutinates.

Lunar Simulant Resources

Commercial Simulant Suppliers that NASA has talked with

Deltion Innovations Ltd
Ontario Canada
https://deltion.ca/

Exolith Lab, University of Central Florida
NASA SSERVI CLASS (Center for Lunar & Asteroid Surface Science) Node
https://sciences.ucf.edu/class/exolithlab/

Hudson Resources Inc
Vancouver Canada
https://hudsonresourcesinc.com/

Off Planet Research
Lacey, Washington
https://www.offplanetresearch.com/

Outward Technologies
Broomfield, Colorado
https://outward.tech/

Other Useful Resources

Kevin Cannon's Simulant Database
https://simulantdb.com/

Lunar Regolith Simulant User's Guide (to be updated in 2021, contingent on Covid-19 lab restrictions)
NASA/TM-2010-216446
https://www.nasa.gov/sites/default/files/atoms/files/nasa_tm_2010_216446_simuserg.pdf

Lunar Regolith Simulant Materials: Recommendations for Standardization, production, and Usage
NASA/TP-2006-214605
https://ntrs.nasa.gov/api/citations/20060051776/downloads/20060051776.pdf

NASA MSFC Simulant Archive
https://www.nasa.gov/oem/simulants

Lunar and Planetary Institute (LPI) lunar simulant references
https://www.lpi.usra.edu/lunar/samples/#simulants

Regolith Simulant Report Cards: A User-Friendly Simulant Certification System

Sarah R. Deitrick[1,2]
Kevin M. Cannon[1]

[1]Colorado School of Mines Center for Space Resources
[2]Jacobs/NASA Johnson Space Center Astromaterials Research and Exploration Science Division

COLORADO SCHOOL OF MINES
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NASA Jacobs

Introduction

- As the nation prepares to return to the Moon, the need for testing tools, instruments, and equipment in accurate simulated lunar regolith is increasing

- Previous systems like the Figures of Merit (FoMs) and fit-to-use matrices were not very user-friendly or updated with recent simulants

Certification System

- We are building an objective, user-friendly certification and reporting system for regolith simulants
  - Ensures suitable simulants are being used appropriately

- Takes in analytical data for a simulant as inputs and automatically generates an easy to digest simulant report card
  - Emphasizes the most and least appropriate use cases for that specific simulant
  - Answers the question: “What task should I use this simulant for?”

Certification System

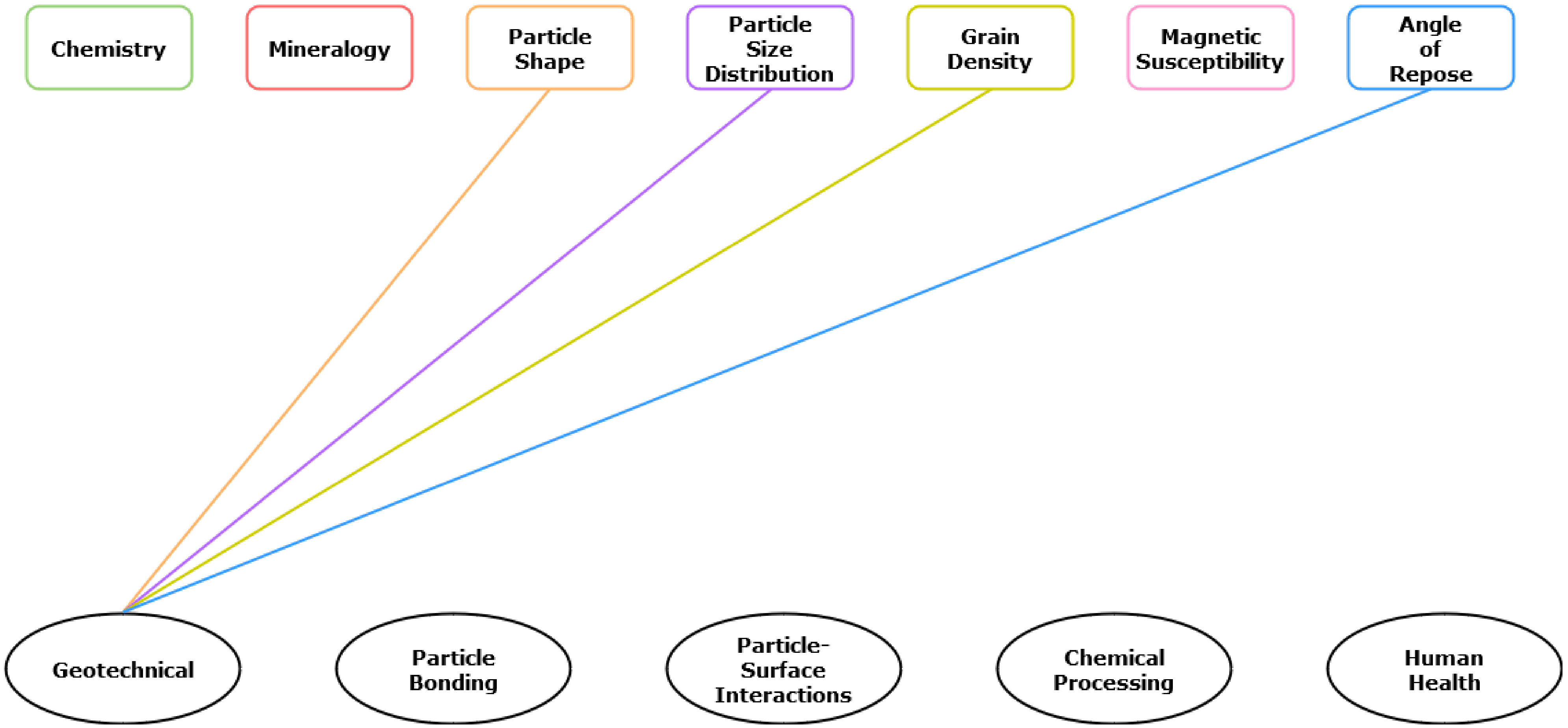
- Identified five *general groups* of use cases that require testing with simulants:
  1. Geotechnical
     - Excavation, drilling, mobility, etc.
  2. Particle Bonding
     - 3D printing, sintering, polymer binding, regolith-based concrete, etc.
  3. Particle-Surface Interactions
     - Dust mitigation, plume-surface interactions, etc.
  4. Chemical Processing
     - Oxygen/volatile/metal production
  5. Human Health
     - Dust toxicity, respiratory, radiation shielding, etc.

Certification System

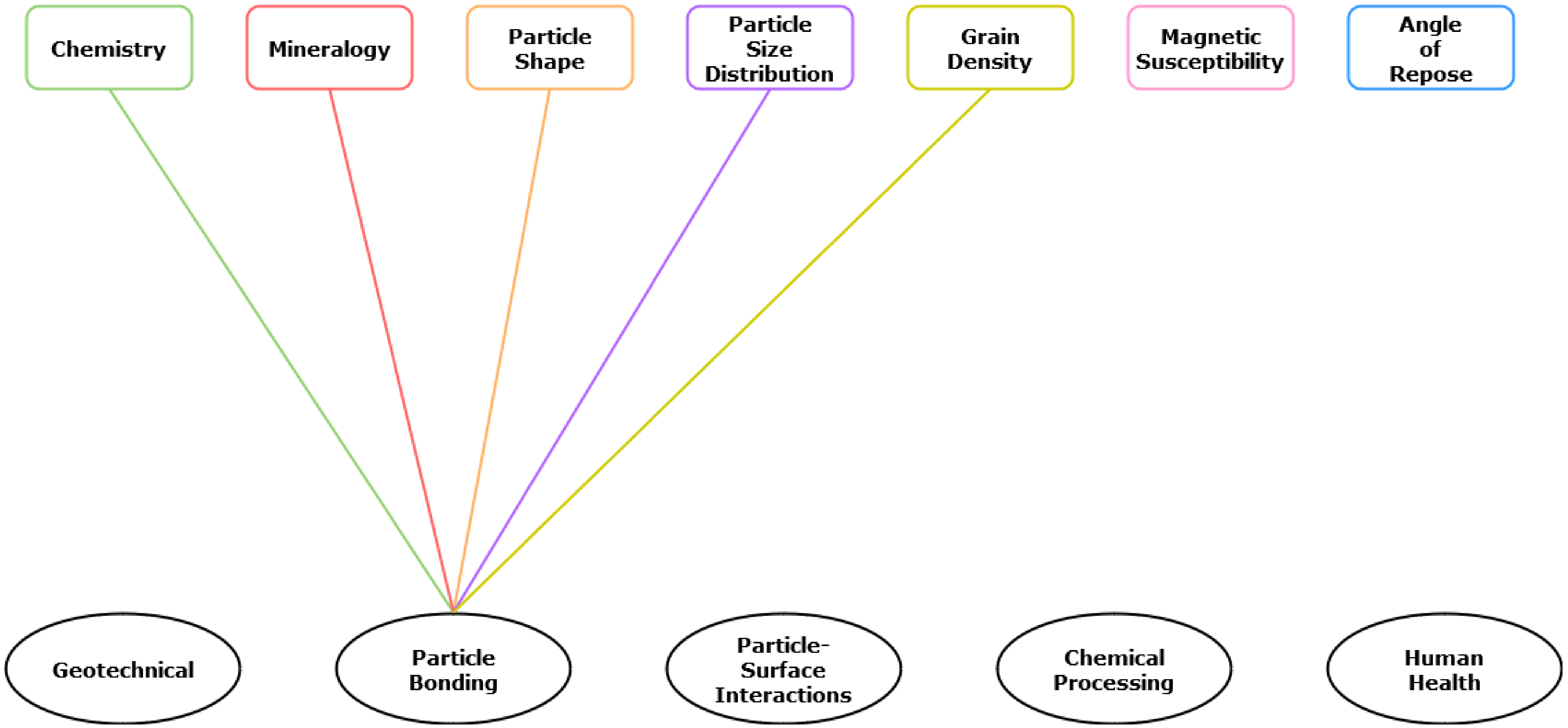
- Our system calculates FoM values for seven properties of the simulant compared to the reference material (single lunar sample or entire Apollo suite)
    1. Bulk chemistry
    2. Modal mineralogy
    3. Particle size distribution
    4. Particle shape
    5. Grain density
    6. Magnetic susceptibility
    7. Angle of repose

- Outputs an overall score and suitability level of the simulant for each of the five use cases

Certification System



Certification System



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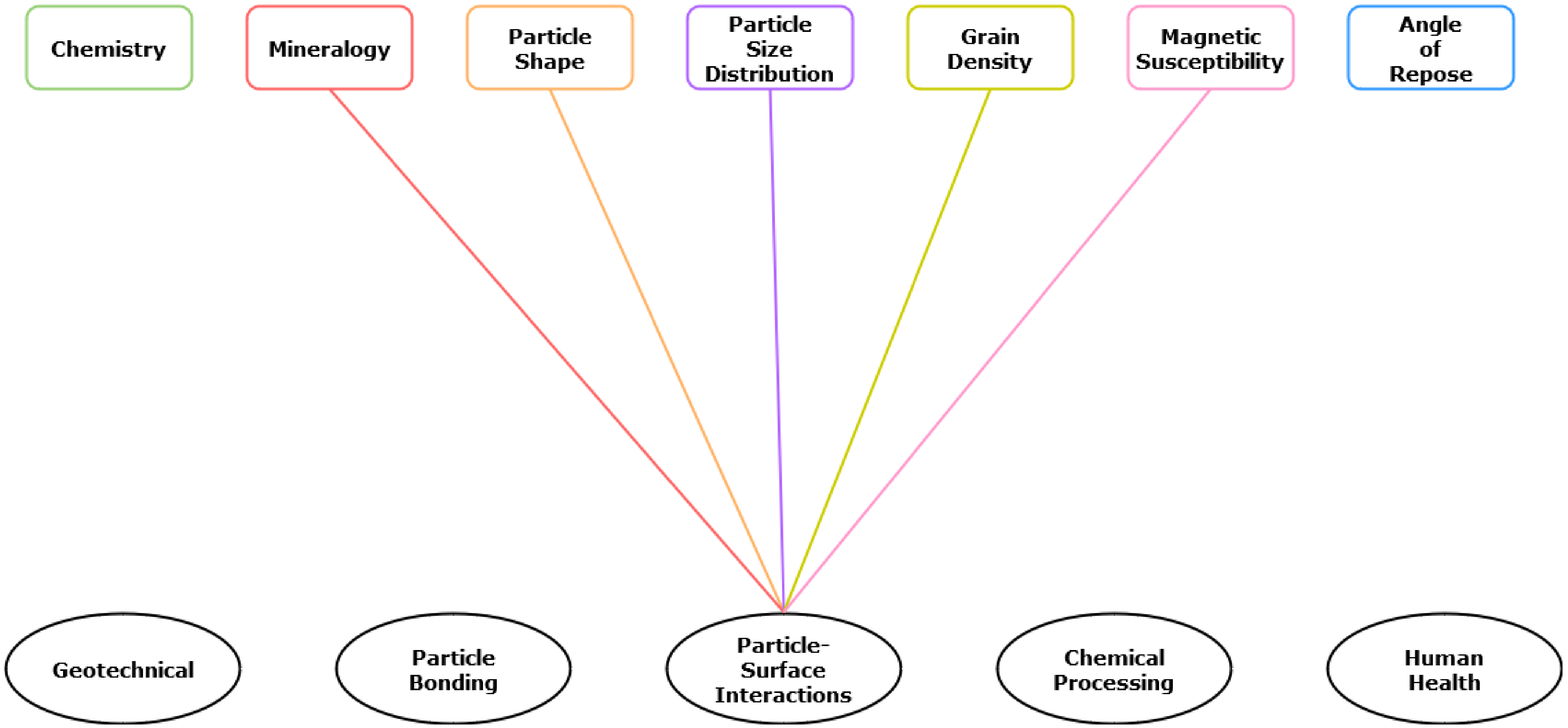
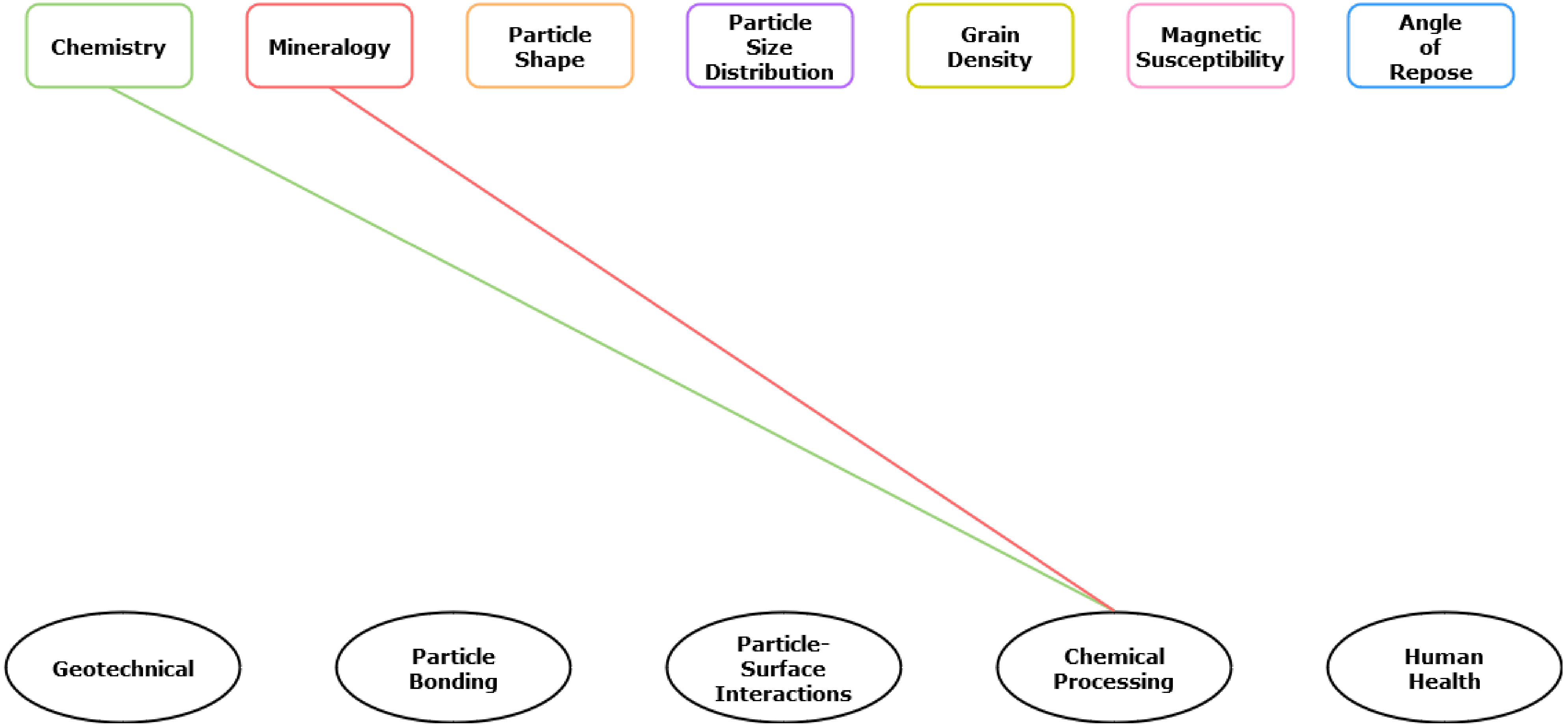


Certification System



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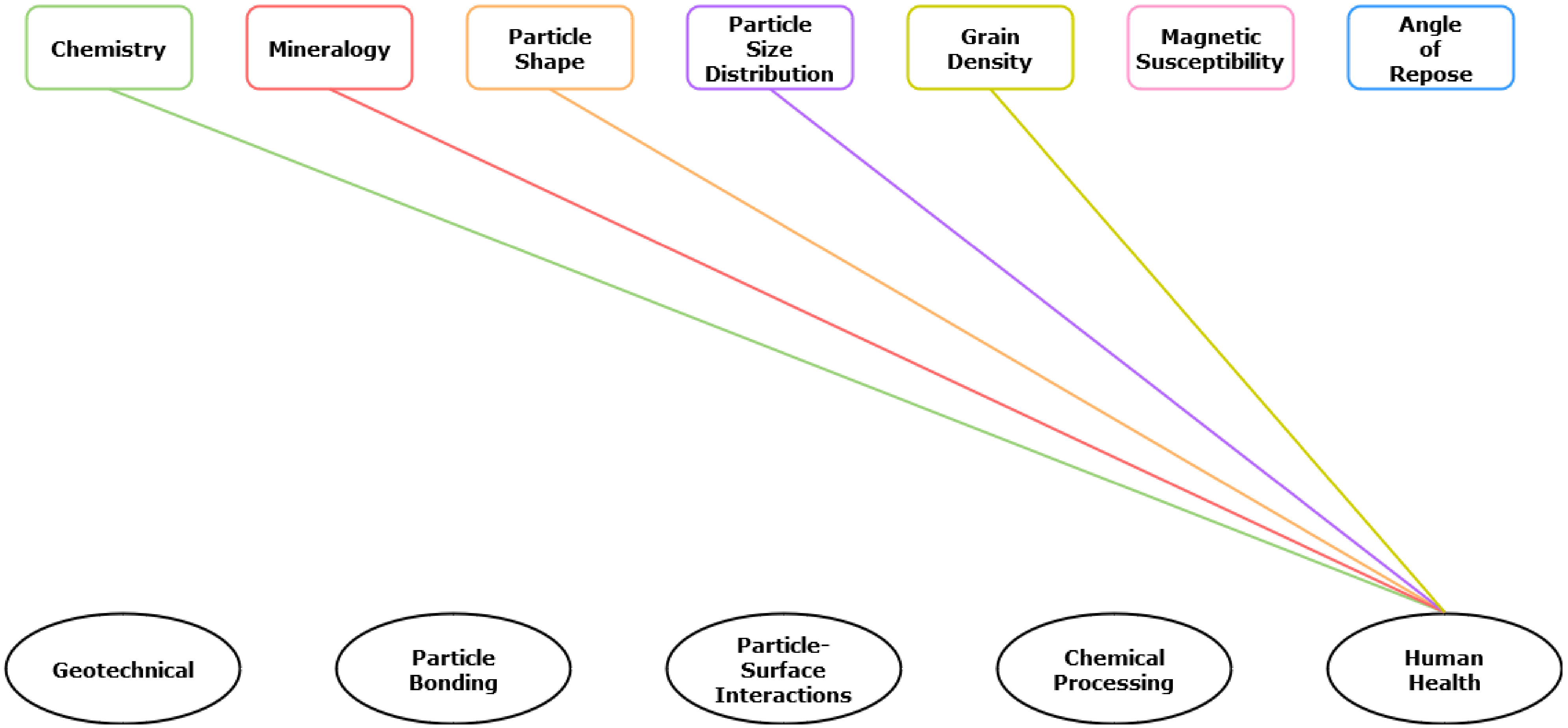
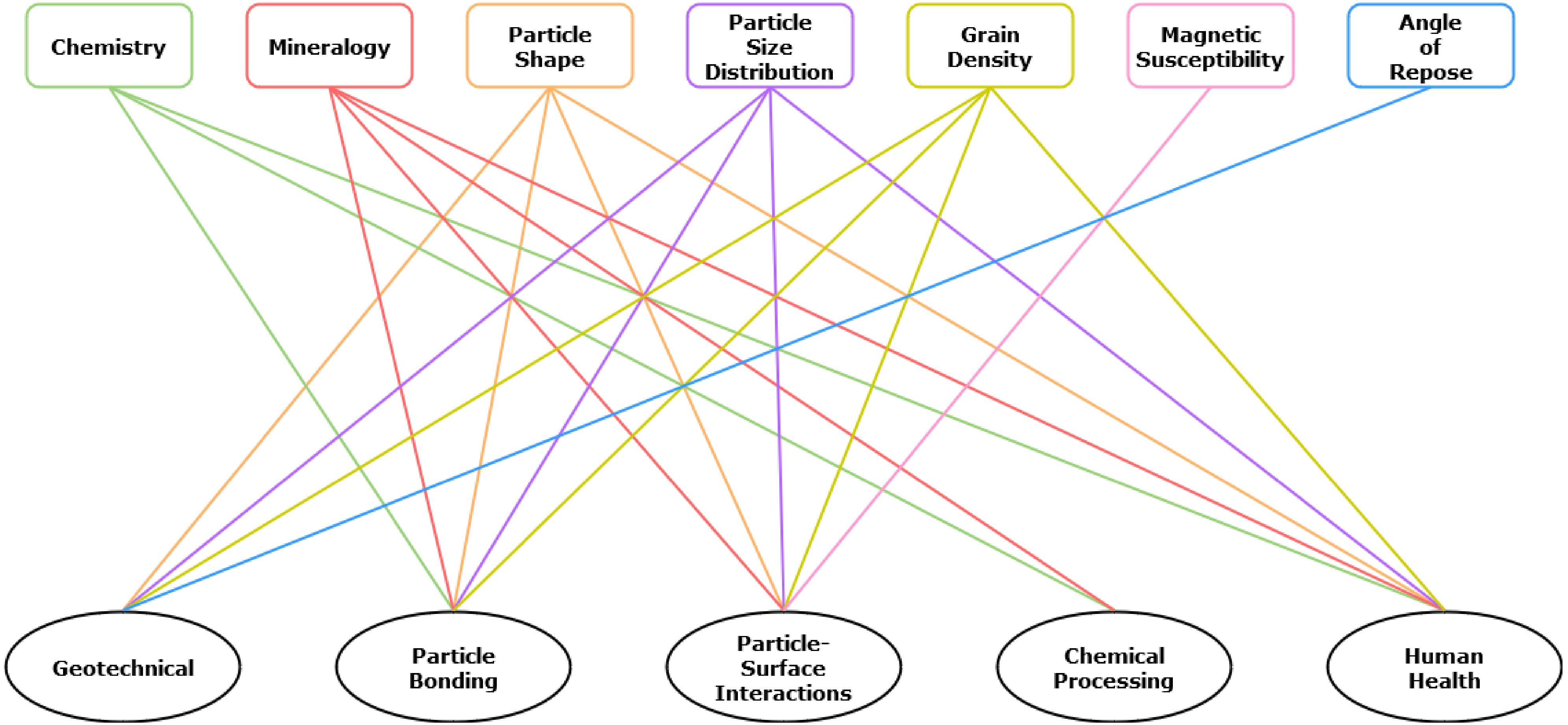


Certification System



Weighting System

- Overall scores are calculated based on a weighting system

- The relevant properties for each use case are assigned a weight according to the significance of the property to the use case
  - E.g., For Geotechnical use case, particle shape is most significant and therefore is assigned the highest weight

- The FoM values for each property are multiplied by the respective property weight and summed to give overall score for each use case
  - If not enough data to calculate FoM, properties are re-normalized

Weighting System

Property Weight per Use Case					
	Geotechnical	**Particle Bonding**	**Particle-Surface Interactions**	**Chemical Processing**	**Human Health**
Chemistry		15%		50%	25%
Mineralogy		20%	25%	50%	20%
Particle Shape	30%	15%	25%		25%
Particle Size Distribution	28%	30%	30%		25%
Grain Density	15%	20%	10%		5%
Magnetic Susceptibility			10%		
Angle of Repose	27%				
	100%	**100%**	**100%**	**100%**	**100%**

- *Weights were assigned based on best judgement, we are open to input

Worked Example

Property FoM per Use Case					
	Geotechnical	Particle Bonding	Particle-Surface Interactions	Chemical Processing	Human Health
Chemistry		89		89	89
Mineralogy		57	57	57	57
Particle Shape	59	59	59		59
Particle Size Distribution	78	78	78		78
Grain Density	89	89	89		89
Magnetic Susceptibility			77		
Angle of Repose	21				

Worked Example

Use Case Scores					
	Geotechnical	**Particle Bonding**	**Particle-Surface Interactions**	**Chemical Processing**	**Human Health**
Chemistry		13.4		44.5	22.3
Mineralogy		11.3	14.2	28.3	11.3
Particle Shape	17.6	8.8	14.7		14.7
Particle Size Distribution	21.8	23.3	23.3		19.5
Grain Density	13.3	17.8	8.9		4.5
Magnetic Susceptibility			7.7		
Angle of Repose	5.8				
Total Score	**58.49**	**74.59**	**68.77**	**72.83**	**72.13**

Suitability

	Geotechnical	Particle Bonding	Particle-Surface Interactions	Chemical Processing	Human Health
Most Suitable (score > 75)					
Suitable (score = 33 – 75)					
Less Suitable (score < 33)					
Not Enough Information					

Suitability

- Front page summarizes simulant suitability level for each use case
- Followed by appendices with full analytical data for the seven properties

REGOLITH SIMULANT REPORT CARD

Simulant name: CRH-1
Simulant producer: Colorado School of Mines
Report last updated: 05/10/21

	Use Case	Suitability for Use Case
	Geotechnical Excavation, drilling, mobility, etc.	**Less Suitable** This simulant may give poor results that lack most characteristics of lunar regolith
	Particle Bonding Sintering, 3D printing, regolith-based concrete, etc.	**Suitable** This simulant should give moderate results that lack some characteristics of lunar regolith
	Particle-Surface Interactions Dust mitigation, plume interactions, etc.	**Suitable** This simulant should give moderate results that lack some characteristics of lunar regolith
	Chemical Processing Production of oxygen, metals, etc.	**Most Suitable** This simulant should give highly accurate results that compare well to lunar regolith
	Human Health Dust toxicity, respiratory, radiation shielding, etc.	**Suitable** This simulant should give moderate results that lack some characteristics of lunar regolith

Results of individual instrumental analyses. Details shown in Appendices.

	Chemistry	Mineralogy	Particle Shape	Particle Size	Grain Density	Magnetic Susceptibility	Angle of Repose
FoM (0-100)	89	57	59	78	89	77	21

Signature

Date

Simulants at Mines | https://space.mines.edu/simulants/

Future Work

- Working to automatically generate PDF report cards based on numerical input data

- Produce set of report cards for commonly used lunar simulants, starting with new CSM-LHT-1 and CSM-LMT-1 (to be available for $3/kg)

- Report cards will be generated as new simulants are developed

Creation, Methodology, and Applications of Simulated Lunar Agglutinates

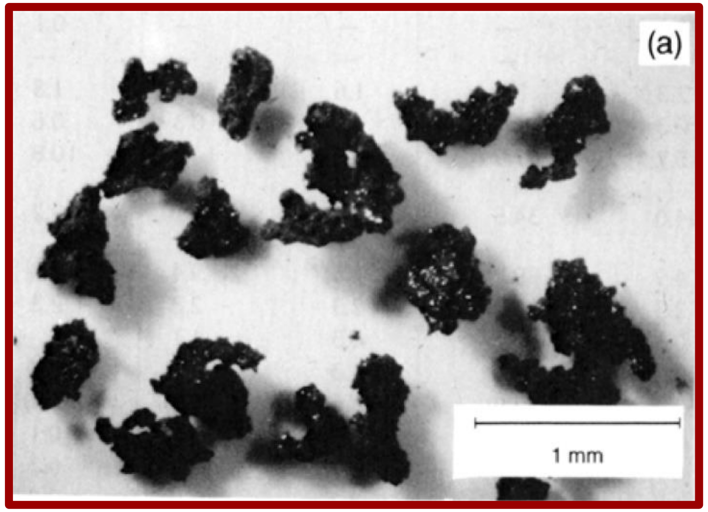
C. Sipe*, P. Easter, Z. A. Landsman, L. Weber, D. T. Britt, J. M. Long-Fox, K. L. Donaldson-Hanna, B. Patterson, G. L. Schieber, and A. Metke.

University of Central Florida, Orlando, FL, USA.

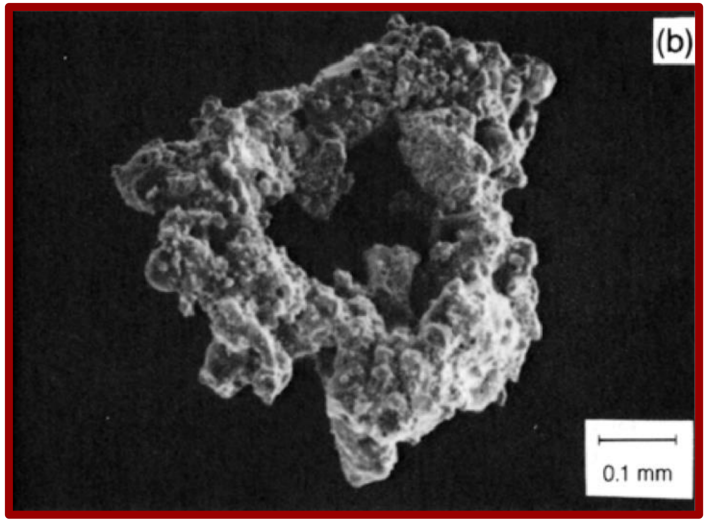
*ChristianSipe@knights.ucf.edu

Agglutinate Background

- Lunar agglutinates are the products of high energy micrometeorite impacts on the Lunar surface.
  - This causes melting and vaporization of the regolith, followed by rapid cooling.
  - This creates a glassy matrix that welds Lunar regolith grains.
- Agglutinates make up roughly 5% - 65% of the Lunar regolith, depending on maturity[2].
- Agglutinates contribute to many of the regolith's known mechanical characteristics such as
  - Flowability
  - Abrasiveness
  - Interaction with volatiles
  - Electrostatic charge
  - And many others

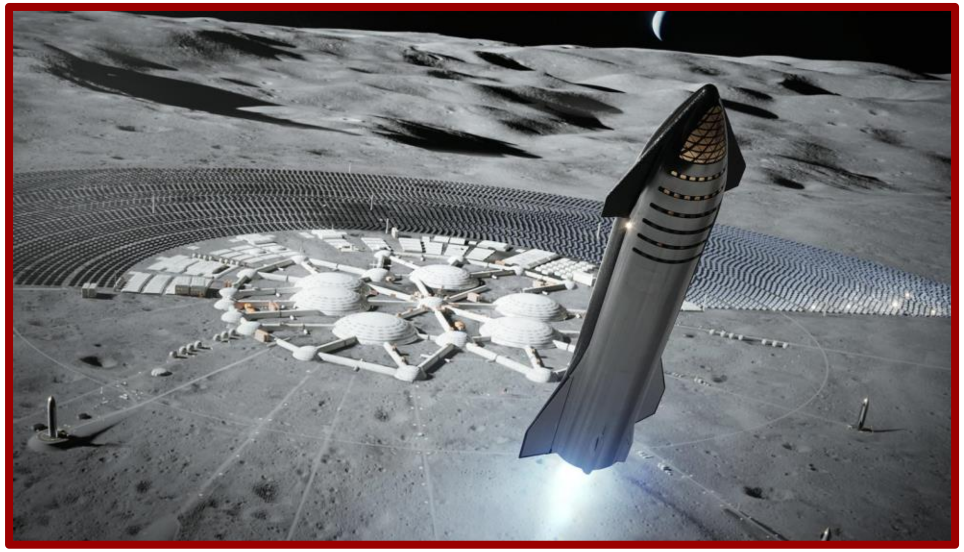


Lunar regolith agglutinates from Apollo 11 soil sample 10084.



Relevance to ISRU

- A large range of Lunar ISRU technologies are currently in development such as:
  - Oxygen & water extraction processes
  - Beneficiation
  - Habitat construction and launch infrastructure
- Using simulated agglutinates can increase the accuracy of experiments
  - Magnetic properties allow for various experiments
    - Beneficiation and magnetic dust separation can be very useful.
  - More accurate flowability can be assessed
    - Lunar regolith with agglutinates have less flowability due to the contact of the angular glassy particles [3].
    - This increases the contact between individual regolith particles, which decreases flowability.
- More accurate experimentation with volatiles



Relevance to Lunar Applications

- Lunar spacecraft and mission hardware need to be realistically tested to.
- The Lunar regolith can be extremely detrimental to spacecraft and mission hardware
    - Since it is so abrasive, it may more rapidly damage hardware.
- Adding simulated agglutinates helps to replicate the abrasiveness of the Lunar regolith
    - This can make testing more accurate and can allow for the construction and planning of more robust and regolith resistant mission hardware.
- It is essential to know how the agglutinates affect the properties of the regolith.

Simulated Agglutinates

Creation and Methodology

- The CLASS Exolith Lab Approach
  - Constrained maximization of fidelity while keeping costs as low as possible.
  - Replicating, in a cost-effective manner, Lunar mineralogy, particle size, and texture.
  - Provide a safe, useful and affordable product to support the Lunar community's science and engineering
- Exolith agglutinate simulants are a work in progress. We are developing our procedures to maximize the fidelity of the product and minimize the costs.
- The Exolith Lab uses a custom-built solar concentrator to produce the simulated Lunar agglutinates.
- There are two prototype simulated agglutinates that we are currently offering
  - Lunar Highlands agglutinate base – 99% Anorthosite & 1% fine metallic iron (25µm) by weight
  - Lunar Mare agglutinate base – 99% LMS-1 & 1% fine metallic iron (25µm) by weight
- Purchases and Consultation
  - We are still in the prototype stage but will work with customers to fashion simulants that meet their needs and requirements.
  - More information on purchases and consultation at https://exolithsimulants.com/

Creation and Methodology

- Formation
  - We begin with base regolith simulant.
  - Concentrated solar illumination rapidly melts the base simulant which welds un-melted grains to the overall melt.
  - We are currently studying the morphological differences between slow cooling and rapid quenching.
  - The cooled aggregate is percussively crushed and sieved to Lunar regolith particle size distribution.
- What we do not simulate (our approach is constrained maximization):
  - Nanophase iron [1] (very difficult to do in terrestrial conditions).
  - Vapor deposition (very difficult to do safely and with large volumes of agglutinates).
  - Fairy-castle structures (we are in 1g after all).
- Exolith is refining the process to increase the fidelity and lower the costs.

Creation and Methodology

Lunar Highlands and Mare Simulated Agglutinates

- The figure on the right shows two recently formed simulated agglutinate source materials.
- These aggregates are later percussively crushed and sieved to the appropriate particle size distribution.

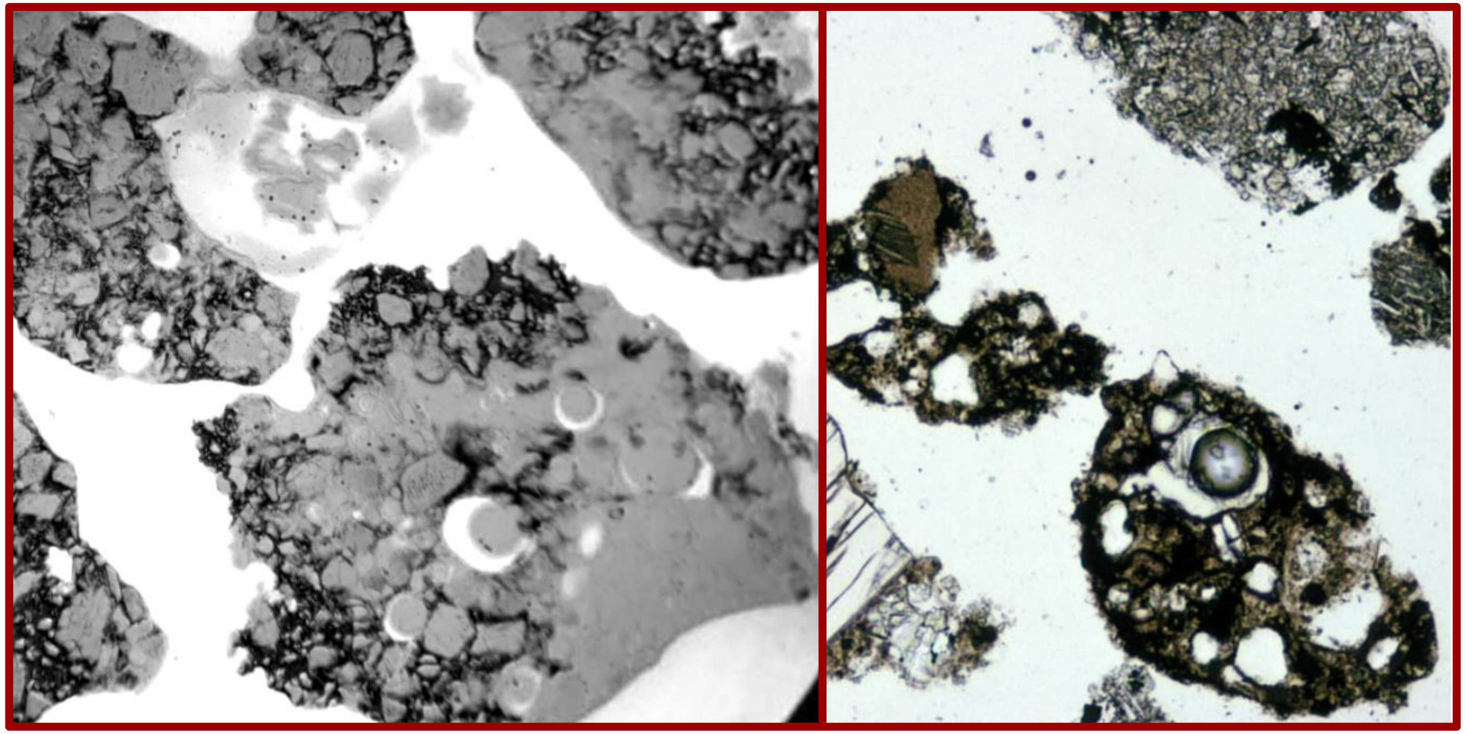
Lunar Mare simulated agglutinate source material

Lunar Highlands simulated agglutinate source material

Creation and Methodology

Simulated Lunar agglutinate vs Lunar agglutinate

- Petrographic thin sections were compared with an agglutinate from an Apollo Lunar Highlands sample (*68501).
  - There are comparable internal structures present.
- The left image is a transmitted, **plane-polarized** thin section of a simulated Lunar highlands agglutinate (Field width ~ 1.5mm).
- The right image is an actual Lunar highlands agglutinate (Field width ~ 1.6mm)



Simulated Lunar highlands agglutinates

Real Lunar agglutinates

Acknowledgements

- I’d like to thank my team and supervisors at the Exolith Lab and CLASS for constantly supporting this project and for providing much appreciated mentorship and assistance as well.
- This work was possible through the NASA Cooperative Agreement 80NSSC19M0214.

Contact

- For any questions or consultations, please reach me at christiansipe@knights.ucf.edu and/or exolithlab@ucf.edu.

References

- [1] Pieters, C. M. and Noble, S. K. Space weathering on airless bodies, J. Geophys. Res. Planets, 121, 1865–1884, doi: 10.1002/2016JE005128.
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- [3] Colwell, J. E., Batiste, S., Horányi, M., Robertson, S., & Sture, S, 2007. Lunar surface: Dust dynamics and regolith mechanics. Reviews of Geophysics. doi: 10.1029/2005rg000184.
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Thank you!

Questions and comments?

Comparison of NASA Lunar and Martian Landing Sites: Shear Strength Properties of Lunar Highlands (LHS-1) and Mars Jezero Crater (JEZ-1) Simulants

Jared M. Long-Fox[1*], Zoe A. Landsman[1], Daniel T. Britt[1], Janelisse Morales Gonzalez[1], and Cody D. Schultz[2]

*jared.long-fox@ucf.edu

[1]University of Central Florida - Department of Physics

[2]Brown University – Department of Earth, Environmental, and Planetary Sciences

Overview

- Motivation and Relevance
- Exolith Lab Regolith Simulants
  - Philosophy
  - LHS-1
  - JEZ-1
- Methods
  - Direct Shear Test
  - Data Analysis
- Results
- Discussion and Conclusions
- Q&A

Motivation and Relevance

- Motivation
  - Different locations, even on the same planetary body, have different surface properties
    - Unique requirements for each mission
  - Limited returned regolith sample availability → need to accurately simulate regolith with Earth-based materials → Exolith Lab regolith simulants

Exolith Lab Regolith Simulants

- Motivation
  - Shear strength is one of the most frequently used characterizations of any planetary regolith strength
- Philosophy
  - Accurate mineralogy = high-fidelity planetary regolith simulant = accurate simulation of regolith properties
  - Constrained maximization of fidelity relative to cost, safety, and availability

- LHS-1
  - **L**unar **h**ighlands **s**imulant
  - Based on returned samples and remote sensing
- JEZ-1
  - Mars **Jez**ero delta simulant
  - Includes aqueous alteration products
- Detailed data on simulants available at: https://exolithsimulants.com/

LHS-1

- Simulates typical Apollo Lunar regolith samples in both composition and grain geometry
  - Particle Size Distribution
    - Mean particle size = 60 μm
    - Median particle size = 50 μm

Component	Wt. %
Anorthosite	74.4
Glass-rich basalt	24.7
Ilmenite	0.4
Olivine	0.3
Pyroxene	0.2

LHS-1 regolith simulant created by Exolith Lab.

JEZ-1

- Simulates the Mars Jezero delta in composition (including products of aqueous alteration) and grain geometry
  - Particle Size Distribution
    - Mean particle size = 70 µm
    - Median particle size = 60 µm

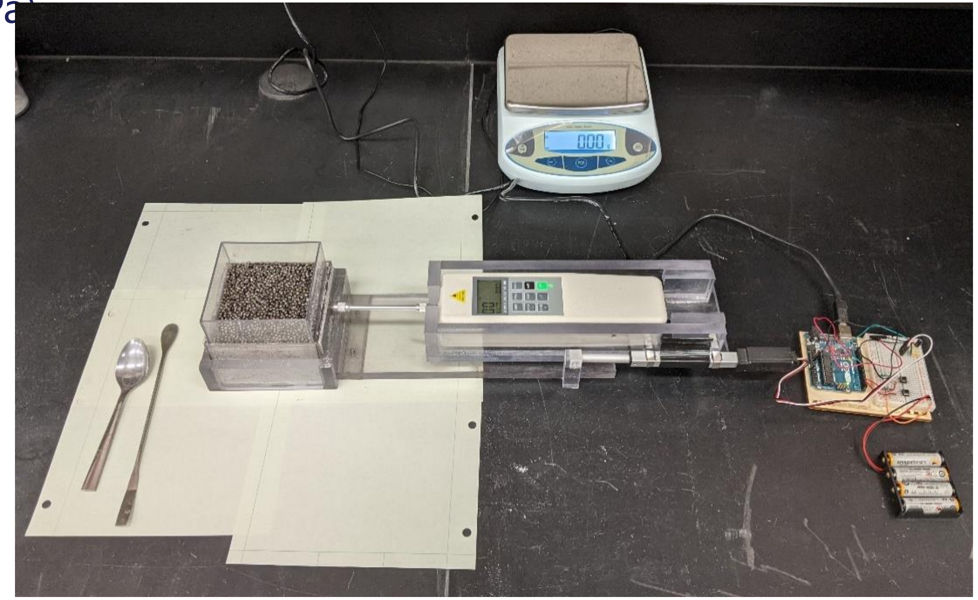
JEZ-1 regolith simulant created by Exolith Lab.

Component	Wt. %
Olivine	32.0
Anorthosite	16.0
Glass-rich basalt	13.5
Pyroxene	12.0
Mg-carbonate	11.0
Smectite	6.0
Mg-sulfate	2.4
Ferrihydrite	2.1
Hydrated silica	1.8
Magnetite	1.1
Anhydrite	1.0
Fe-carbonate	0.8
Hematite	0.3

Methods

- Direct Shear Test
  - ASTM D3080-98 - Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions
  - Applied normal stress vs. measured shear stress at failure
    - Shear strength characterization is key to understanding regolith behavior
  - Custom direct shear testing equipment
  - 25 total samples for each simulant - 5 samples of uncompressed shear strength with 5 different normal loads (0.1 kPa, 0.2 kPa , 0.3 kPa, 0.4 kPa, and 0.5 kPa)

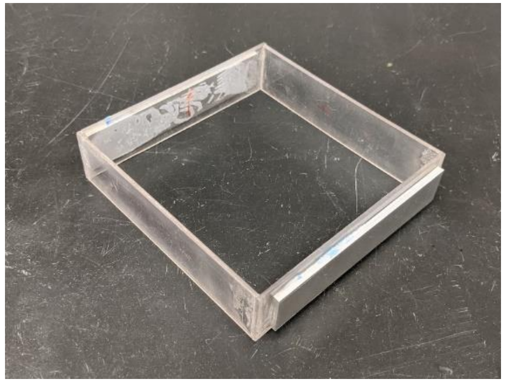
- Analysis
  - Mohr-Coulomb Failure Criteria
    - $\sigma_s = c + \sigma_n tan(\varphi)$
      - σ_s = shear stress
      - σ_n = shear stress
      - c = cohesion
      - Φ = angle of internal friction
  - Estimate:
    - Cohesion (c)
    - Angle of Internal Friction (φ)
    - Bulk density (ρ_b)



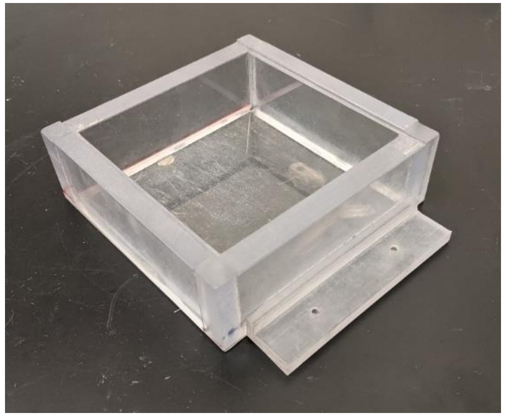
Custom direct shear testing equipment. Includes shear box, force gauge, linear servo, with controls provided by Arduino-based circuitry.

Methods – Direct Shear Test

Normal force box, filled with pre-determined mass of metal pellets and sits on top of simulant sample to prescribe desired normal load (0.1 kPa to 0.5 kPa)

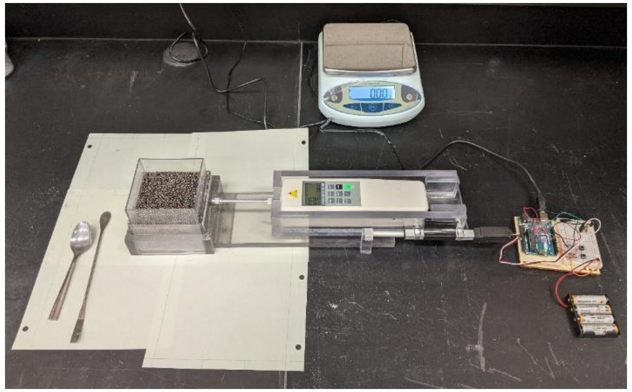


Top of direct shear box, pushed by force gauge, guided by "rails" on bottom portion of the shear box.



Bottom of direct shear box, held stationary. Has "rails" to guide top portion of shear box parallel to the plane of shearing

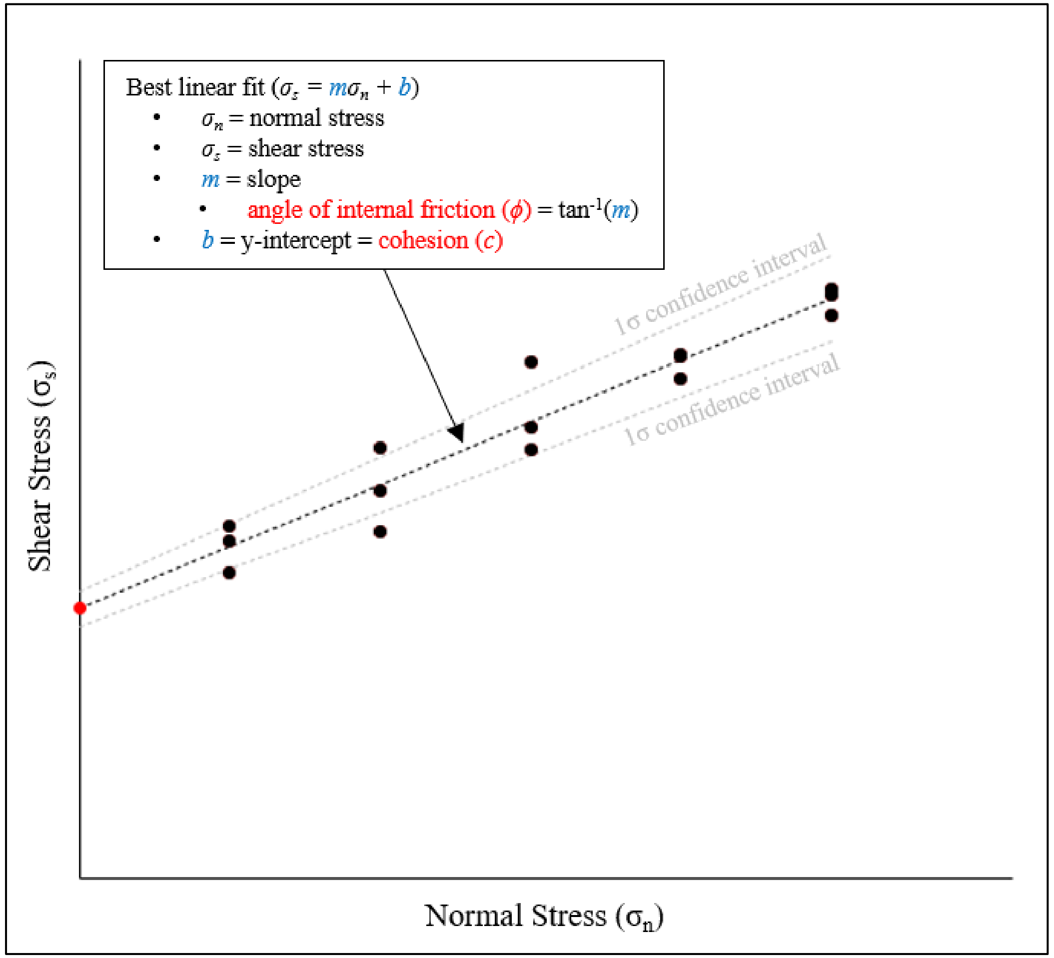
HP-500 push-pull force gauge in a housing, extended and retracted at 8 mm/s by an Actuonix L16-R linear servo controlled by an Arduino UNO R3



Fully assembled testing setup

Methods – Data Analysis

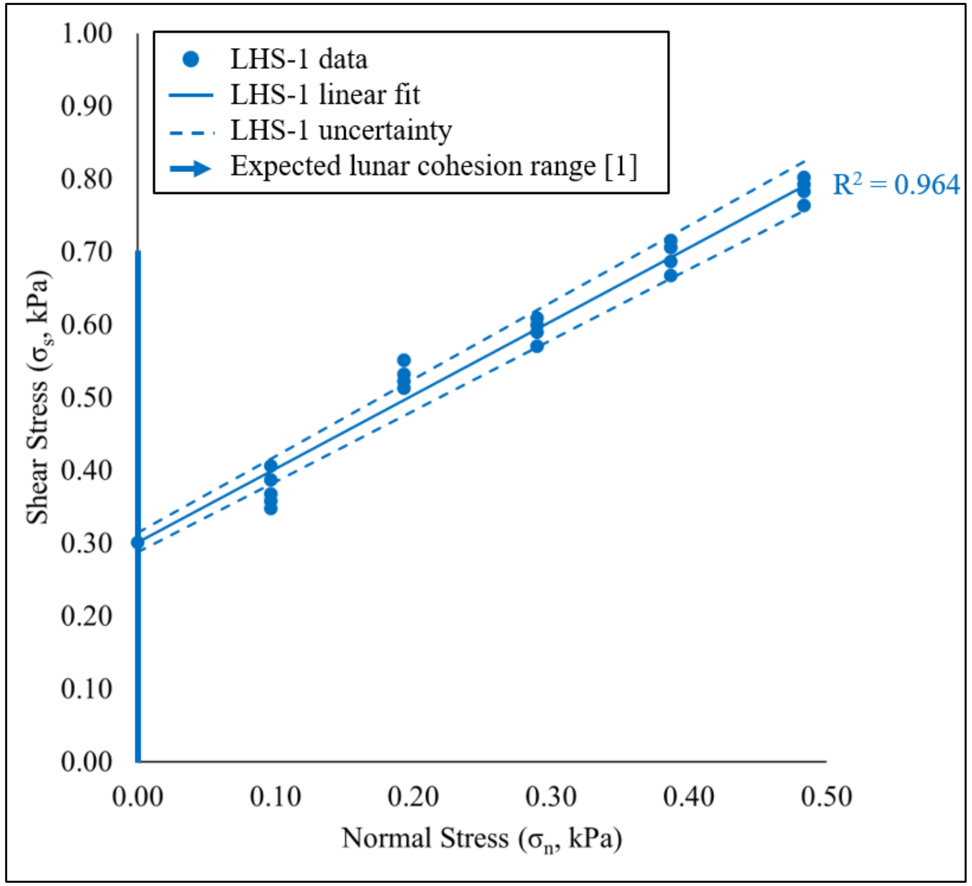
- Mohr-Coulomb Failure Criterion
  - Expected linear relationship between shear stress and normal stress
    - $\sigma_s = c + \sigma_n tan(\varphi)$ → *c* and *φ* are the only unknowns
  - Linear regression, including 1-sigma uncertainties on *c* and *φ*



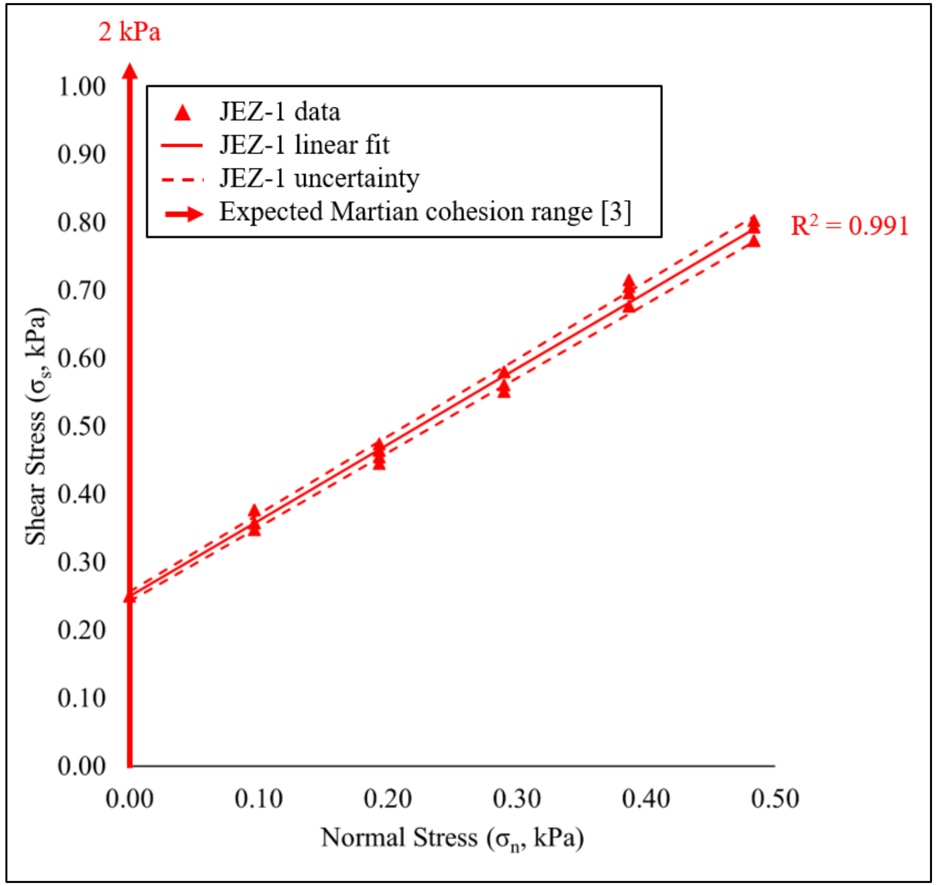
Generalized plot of example direct shear testing results

- Bulk Density (ρ_b)
  - Measure uncompressed mass of simulant in the known volume of the direct shear box
  - $\rho_b = mass / volume$

Results



LHS-1 direct shear data with expected range of cohesion for Lunar regolith (0.0-0.7 kPa) [1] and 1-sigma confidence intervals

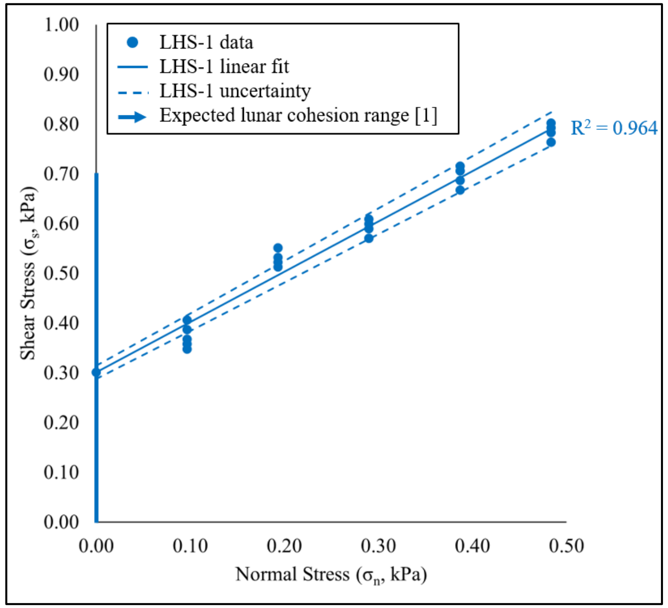


JEZ-1 direct shear data with expected range of cohesion for Martian regolith (0.0-2.0 kPa) [3] and 1-sigma confidence intervals

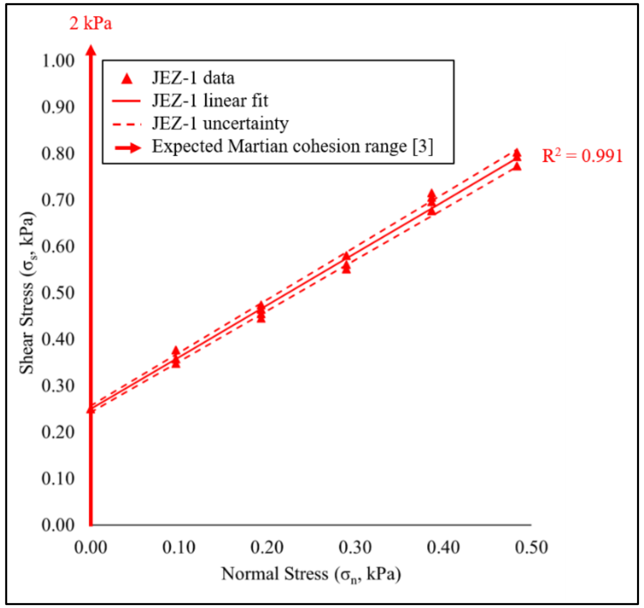
Results

Mohr-Coulomb parameter estimates and bulk, uncompressed density estimates for LHS-1 and JEZ-1

	LHS-1	JEZ-1
c (kPa)	0.301 ± 0.013	0.249 ± 0.007
ϕ (°)	45.34 ± 2.39	48.19 ± 1.31
ρ_b (kg/m^3)	1391.26 ± 7.81	1361.91 ± 3.12



LHS-1 direct shear data with expected range of cohesion for Lunar regolith (0.0-0.7 kPa) [1] and 1-sigma



JEZ-1 direct shear data with expected range of cohesion for Martian regolith (0.0-2.0 kPa) [3] and 1-sigma

Discussion and Conclusions

- Discussion
  - LHS-1 has higher cohesion than JEZ-1
  - JEZ-1 has a higher angle of internal friction than LHS-1
  - Bulk densities are (qualitatively) similar, but LHS-1 is relatively more dense
- Conclusions
  - Differences in mineralogy spawn variation in physical properties of planetary regolith and its simulants, as shown by a Lunar Highlands Simulant (LHS-1) and a Mars Jezero delta simulant (JEZ-1), made by Exolith Lab
    - Varying physical properties → varying hardware, software, and logistical requirements
- Future Work
  - Statistical quantification of differences in progress
  - Wider range of applied normal loads in progress
- We have shear strength data for our available simulants and are happy to share this and create custom simulants and carry out testing on these custom orders
  - Please reach out to us at https://exolithsimulants.com/
- For detailed information and any questions or comments, please feel free to reach out: jared.long-fox@ucf.edu

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Special thanks to the amazing simulant, science, engineering, and administrative teams at Exolith Lab. Without your hard work and dedication to excellence, this work would not have been possible.

We also gratefully acknowledge our collaborators in CLASS, including Clive Neal, and external experts such as Doug Rickman for your advice and thoughtful conversation.

This work is supported by NASA Cooperative Agreement 80NSSC19M0214

Closing Comments

- Discussion
  - LHS-1 has higher cohesion than JEZ-1
  - JEZ-1 has a higher angle of internal friction than LHS-1
  - Bulk densities are (qualitatively) similar, but LHS-1 is relatively more dense
- Conclusions
  - Differences in mineralogy spawn variation in physical properties of planetary regolith and it's simulants, as shown by a Lunar Highlands Simulant (LHS-1) and a Mars Jezero delta simulant (JEZ-1), made by Exolith Lab
    - Varying physical properties → varying hardware, software, and logistical requirements
- Future Work
  - Statistical quantification of differences in progress
  - Wider range of applied normal loads in progress
- We have shear strength data for our available simulants and are happy to share this and create custom simulants and carry out testing on these custom orders
  - Please reach out to us at https://exolithsimulants.com/
- For detailed information and any questions or comments, please feel free to reach out: jared.long-fox@ucf.edu

Abstract References: [1] Carrier III D.W. et al. (1972) *Geochimica et Cosmochimicha Acta*, 3, 3223-3234. [2] Mitchell J.K. et al. (1972) *Geochimica et Cosmochimicha Acta*, 3, 3235-3253. [3] Sullivan R. et al. (2011) *J. Geophys. Res.*, 116, E02006. [4] Perko H.A. et al. (2006) *Journal of Aerospace Engineering*, 19:3, 169-176. [5] Peters G.H. et al. (2008) *Icarus*, 197, 470-479. [6] Zeng X. et al. (2015) *Earth, Planets and Space*, 67:7. [7] Williams J.P. et al. (2017) *Icarus*, 283, 300-325. [8] Owen et al. (1977) *J. Geophys. Res.*, 82:28, 4635-4639.

Questions?

Email: jared.long-fox@ucf.edu

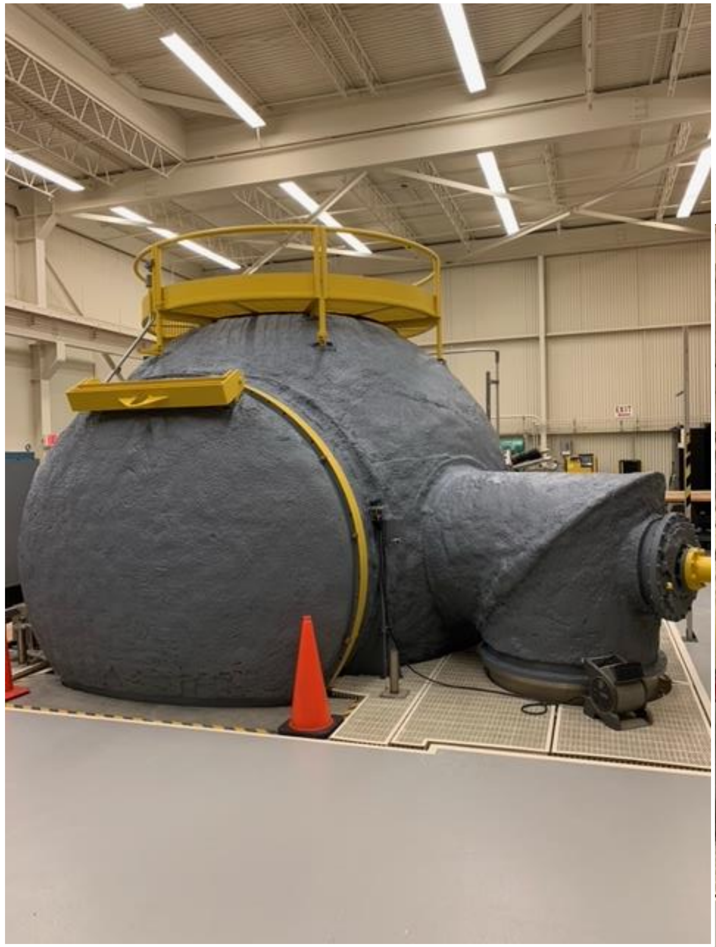
Dusty Lunar Surface Simulation Test Capabilities

Thomas Viviano, Project Manager
Propulsion and Fluids Group at the Energy Systems Test Area (ESTA)
NASA Johnson Space Center

B351: Thermal Vacuum Test Facility

15ft Chamber

- Description:
  - 15ft Φ Spherical Chamber with ~78in Φ clear entry
- Environment Capability:
  - **Vacuum:** 1x10^{-6} torr (ultimate),
    - Pumping, rotary piston pumps, roots blowers & two 36in diameter diffusion pumps
  - **Atmosphere:** Air or GN_2 Repressurization
  - **Thermal Range:** -196^{o}C to +120^{o}C Thermal shroud temperatures
  - High channel count data feedthroughs
  - High power feedthroughs available
  - Max platform load: 4,000 lb
  - Test article operation on 48” x 96” regolith bed in chamber with surface interactions with regolith to depths down to ~6 ft
- Previous tests: used for fuel cell, electric APU during Shuttle, Cryogenic propellant storage, Apollo lunar rover tire

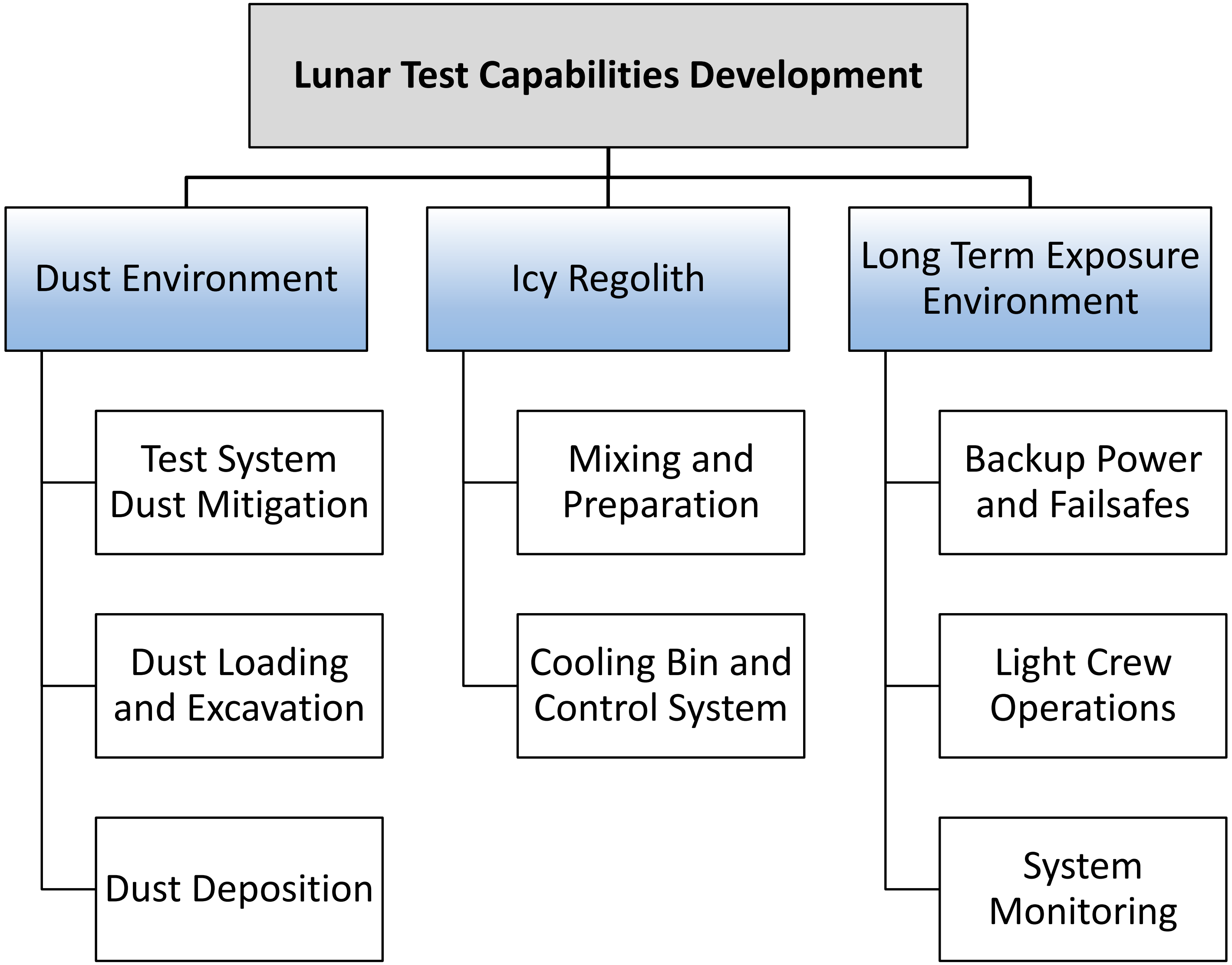


Goals & Objectives

Technology Goals	
Goal #1	Develop a lunar surface environment test bed for ISRU systems and subsystems.
Goal #2	Enable various projects to achieve TRL advancement.
Goal #3	Enable the following domains for Lunar surface ops: power, ISRU, dust mitigation, robotics, excavation, lunar surface tools, hardware, and xEMU suit

Project Objectives	
Objective #1	Create dusty lunar environment test capability that includes test system dust mitigation on ESTA 15’ TVAC at ESTA for dusty TVAC operations. Create a simulant bed for dusty lunar surface operations testing, and create an in-chamber dust deposition system to deposit dust on a test article while at vacuum to evaluate test article dust mitigation capabilities.
Objective #2	Create icy regolith test conditions to test drilling operations conducted on icy regolith. This also includes developing regolith mixing and preparation processes for icy regolith test operations.
Objective #3	Develop long term lunar exposure environment by enabling long term test operation capabilities. This involves outfitting the 15’ chamber with backup power and fail-safes, being able to run operations with minimal personnel, and constant remote monitoring of test system, test hardware, and test data.

DLSS Test Capability Main Pillars



Test System Dust Mitigation

- Dust Environment
  - Test System Dust Mitigation
  - Dust Loading and Excavation
  - Dust Deposition

- The vacuum system for the 15’ TVAC was modified to protect the pump train from damage related to ingesting simulant by installing a new dust mitigation system.
  - A multi-pronged approach was employed to control aerosolized dust.
    - Pumping speed is slowed in critical regions by a throttling valve to allow gases to escape slowly without carrying simulant and causing “dust geysers”.
    - A sharp 90-degree bend with a sump is utilized to drop particulate out of the flow stream.
    - Filtration is utilized to capture any dust that may have escaped the chamber.
  - This system contains a bypass leg to be utilized for normal “clean” pump downs.

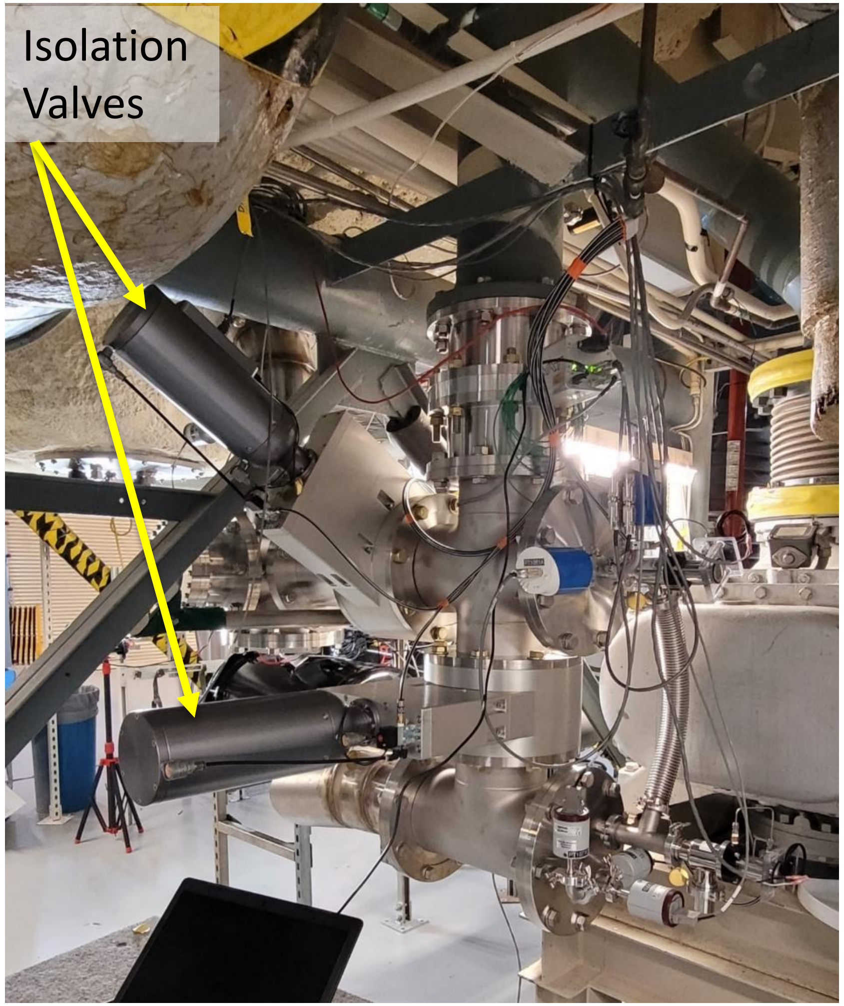
Test System Dust Mitigation

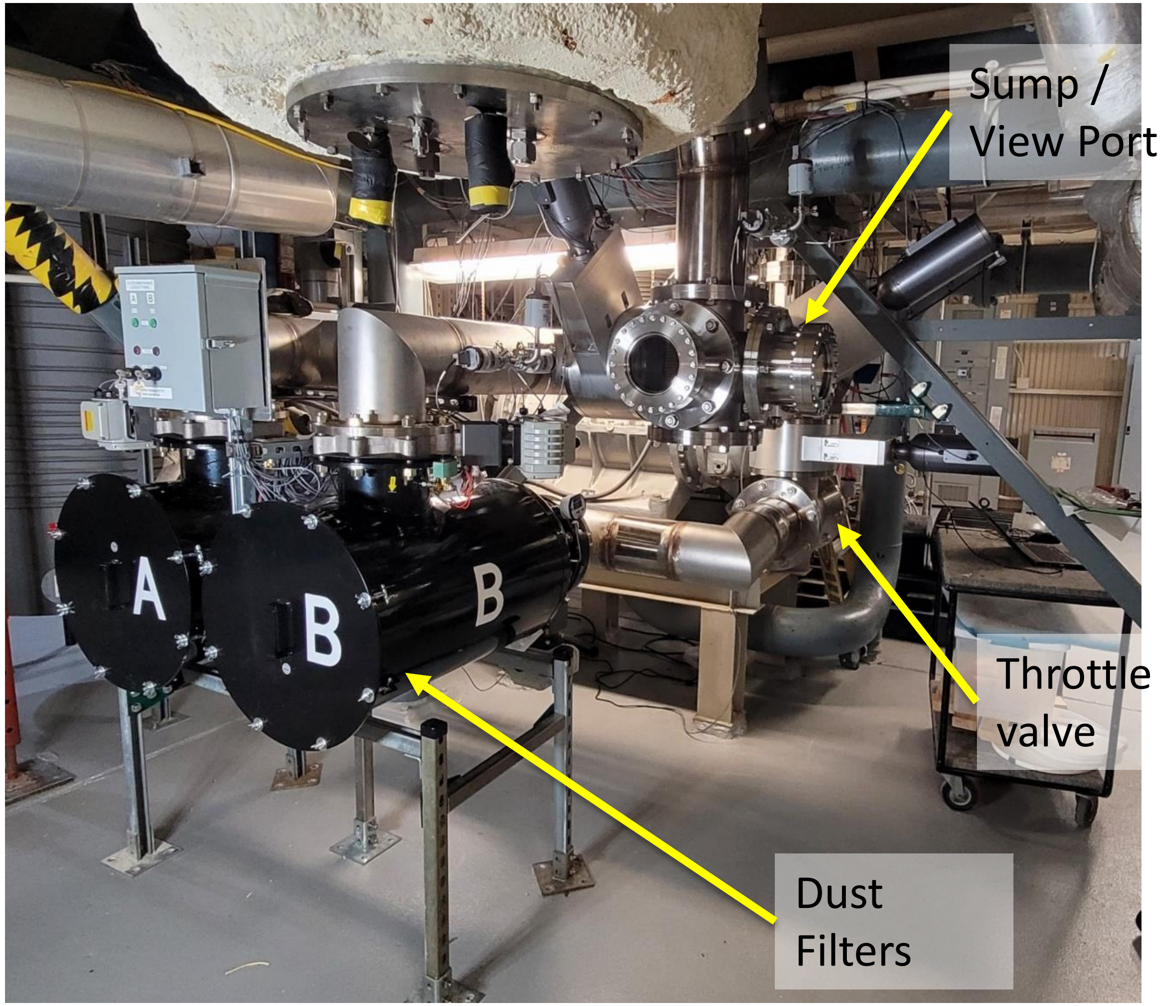
Dust Environment

Test System Dust Mitigation

Dust Loading and Excavation

Dust Deposition





Test Article Dust Loading

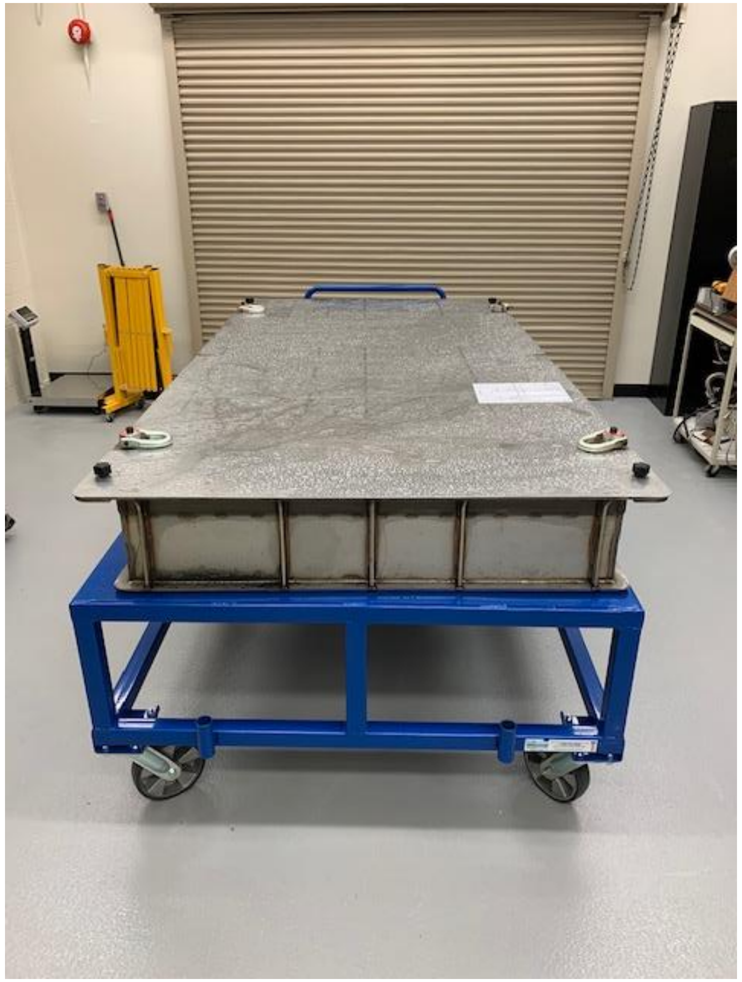
Dust Environment

- Test System Dust Mitigation
- Dust Loading and Excavation
- Dust Deposition

- **Description**
  - For use in 15’ Chamber
  - Basic bin, designed to be filled with simulant in dust containment room and transported into chamber after preparation.
- **Soil Bin Specifications**
  - Dimensions: 48” x 96”
  - Empty weight: 650 lb
  - Max level fill: 8”
  - Max level fill weight: 2,880 lb
  - Max test article weight at max fill: 520 lb*

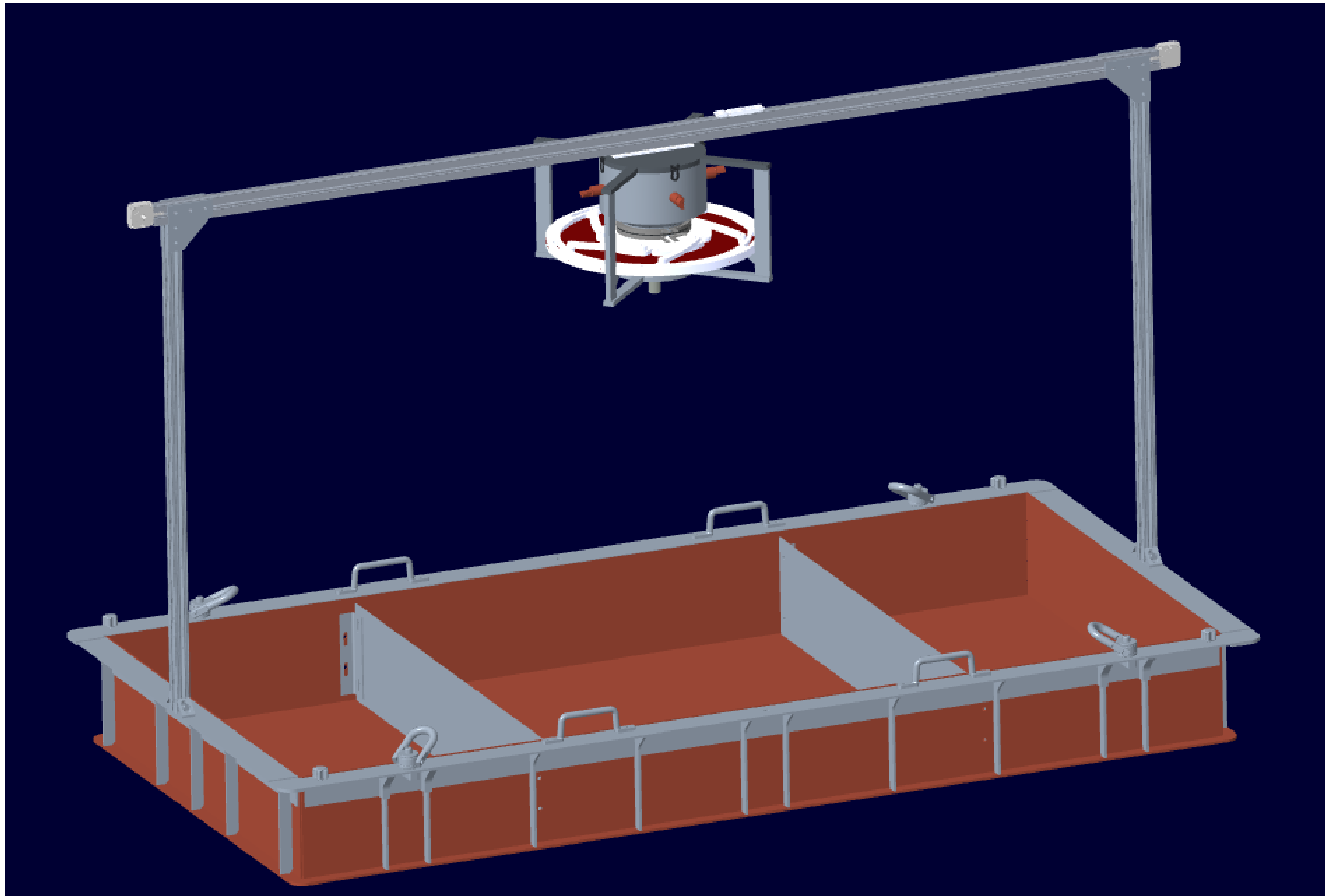
* Based on max platform load of 4,000 lb and assuming two techs (200 – 300 lb each) are needed to install into chamber.

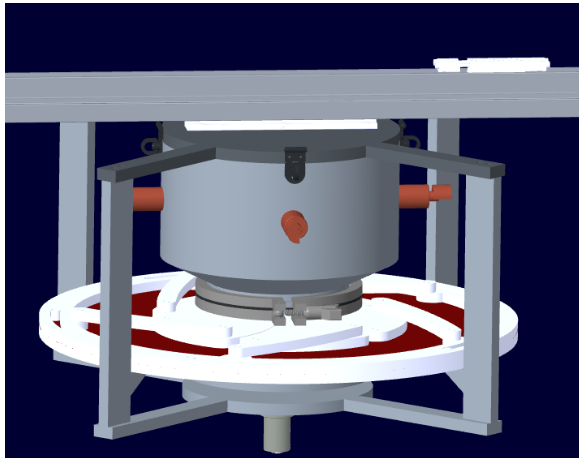
Movable partitions provide customization for a lower fill percentage to minimize unnecessary simulant and maximize test article weight budget

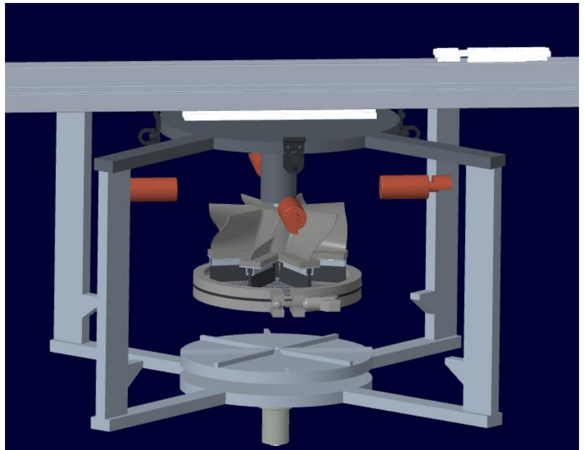


Dust Deposition

- Dust Environment
  - Test System Dust Mitigation
  - Dust Loading and Excavation
  - **Dust Deposition**

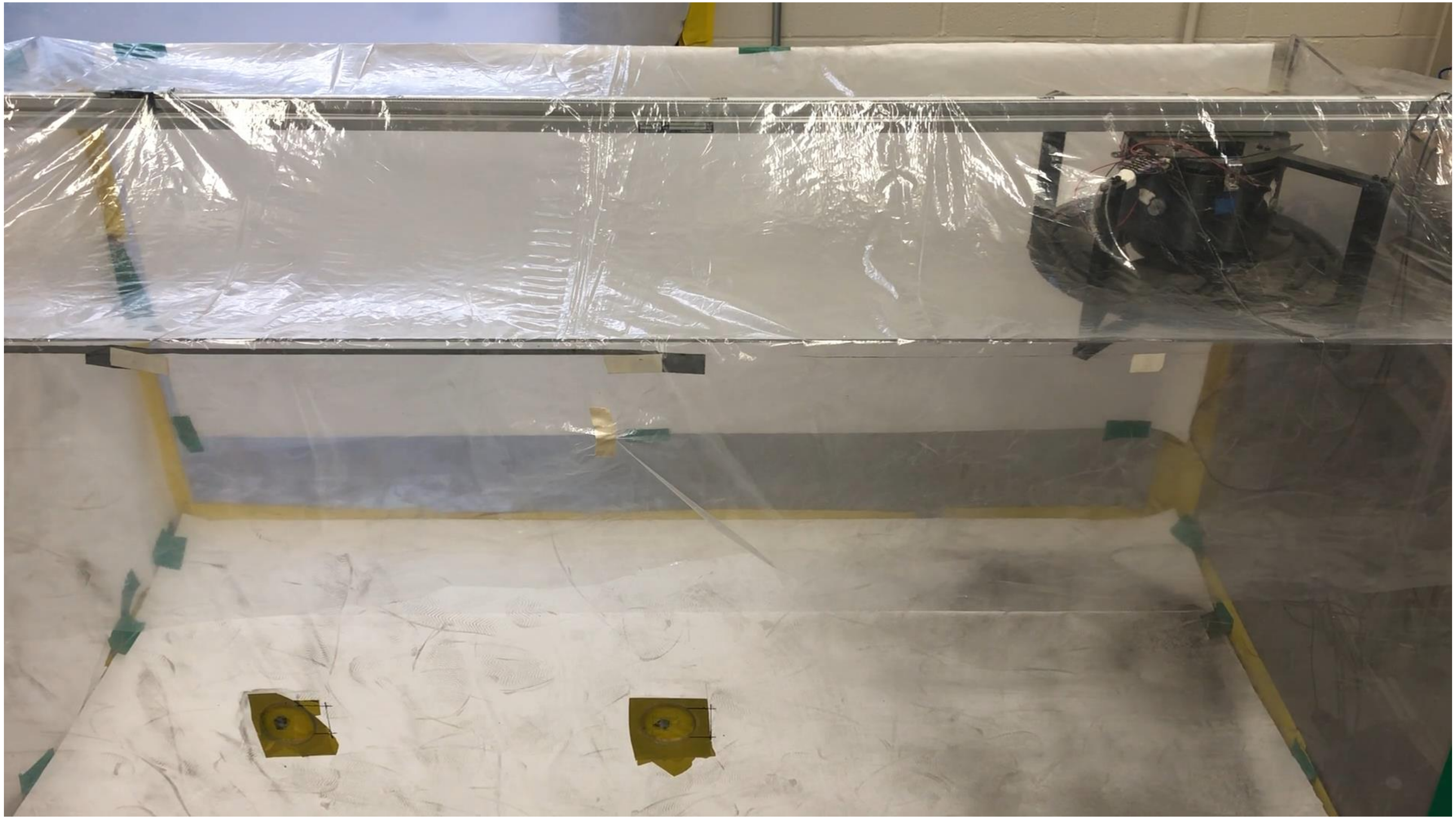

Assembly mounted on existing soil bin


External view


Internal view

Dust Deposition Proof of Concept

- Dust Environment
  - Test System Dust Mitigation
  - Dust Loading and Excavation
  - Dust Deposition



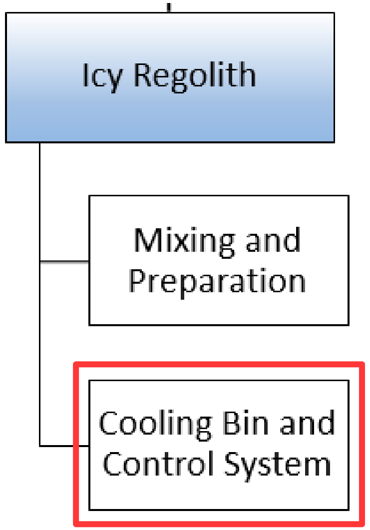
Dust Containment and Preparation Room

Icy Regolith

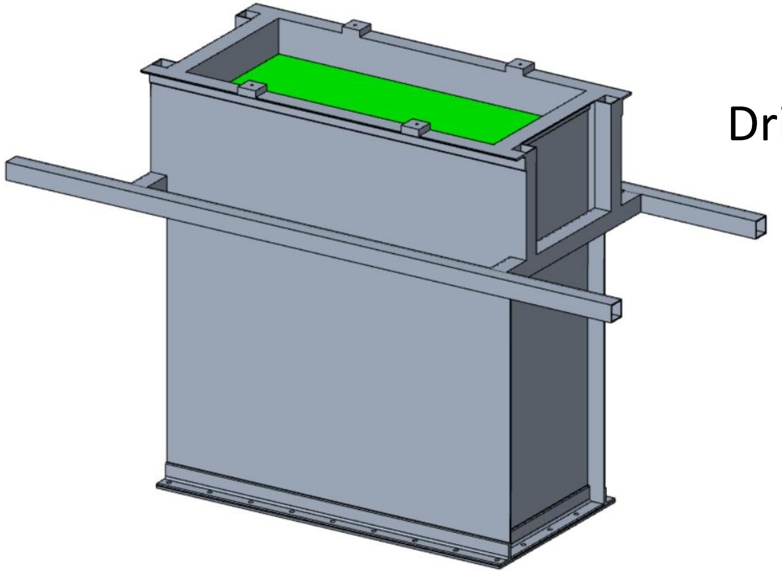
- Mixing and Preparation
- Cooling Bin and Control System

- Enclosed 750 ft^2 room sealed and equipped with HEPA fan filtration unit for dust containment and negative pressure maintenance.
- Particulate monitoring and audible alarm to ensure air quality is maintained.
- Provides room for regolith bin loading and preparation.
- Provides room for test article preparation and pre-conditioning prior to transfer to the 15’ chamber.
- Houses desktop ambient dust box and small vacuum bell jar.

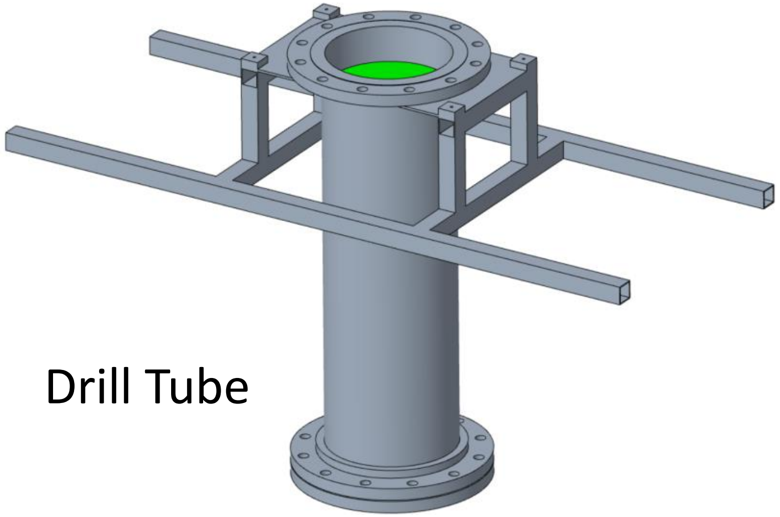
Icy Regolith Drill Bin & Drill Tube



- To be filled with compacted lunar regolith simulant.
- Utilize Nitrogen as cooling fluid.
  - Walls are to be used as heat transfer surfaces.
- Drill Bin has a 18” x 38” surface area at 42” depth (1.07m) with 4” walls above full soil height.
- Drill Tube similar to Drill Box concept, but holds less soil for faster simulant conditioning (13.25” ID).



Drill Box

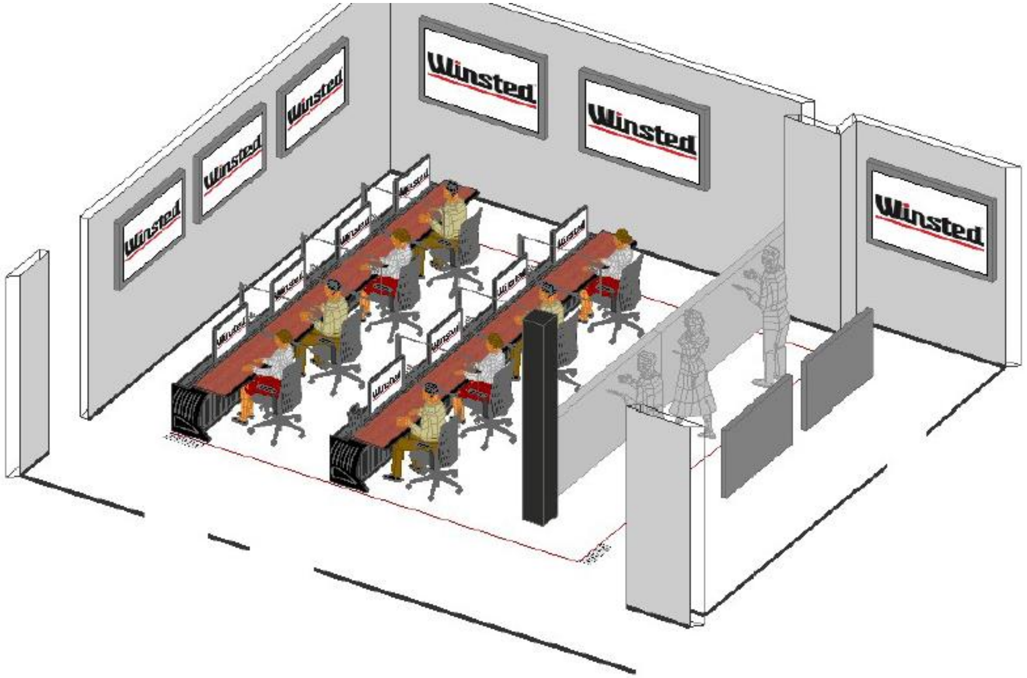


Drill Tube

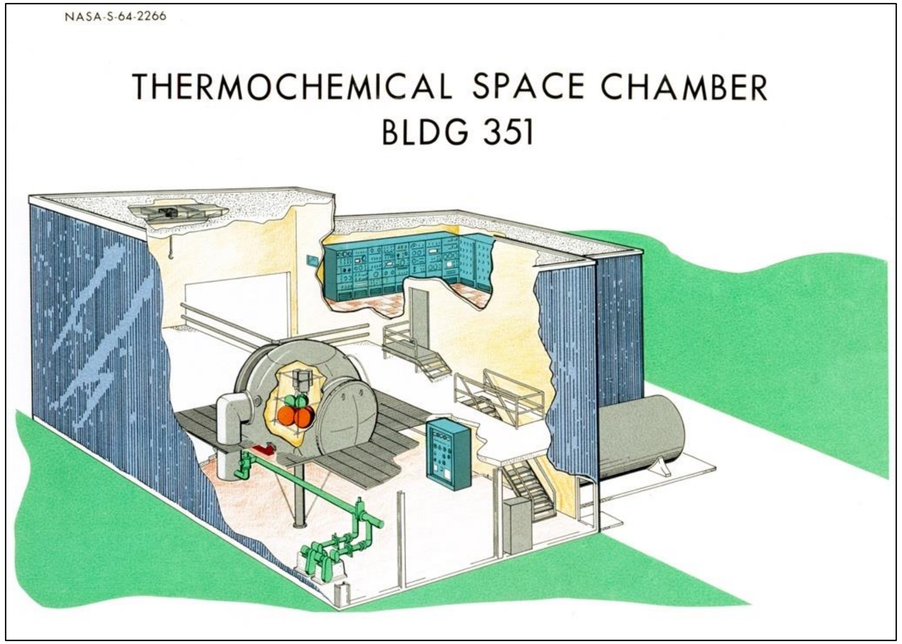
Long Test Operations

- Long Term Exposure Environment
  - Backup Power and Failsafes
  - Light Crew Operations
  - System Monitoring

- Goal is to be able to simulate lunar day and night for 30 days with a stretch goal of 60 days.
- Maintaining pressure and thermal over long durations.
  - Reliability of the test system
  - Equipment health monitoring
  - Out of tolerance notifications
- Minimize the need for full test crew.
- Provide on and off-site test system and test article monitoring.



15ft Chamber



“Vintage” Building 351

Apollo Fuel Cell 1000-hr Test, 1964

Apollo Block II Fuel Cell Test, 1969

Ready for Lunar Dust, 2021

Thank You

Dusty Lunar Surface Simulation B351 & Chamber Upgrades

Propulsion and Fluids Group at the Energy Systems Test Area (ESTA)

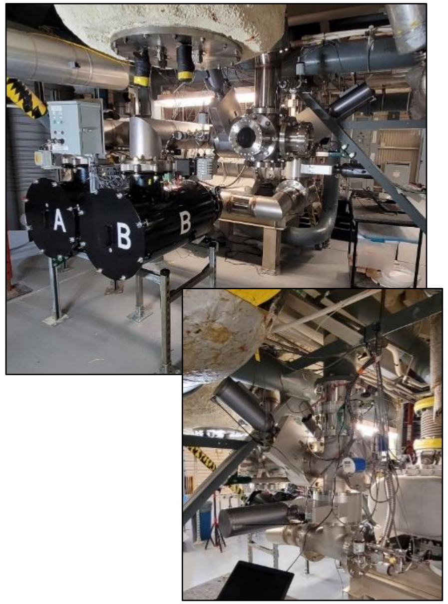
LN2 Dewar

- Demo old 13k gallon dewar
- New pad and piping for 15k gallon tank installed and put in service
- Backup 3k gallon dewar from B356

-before-

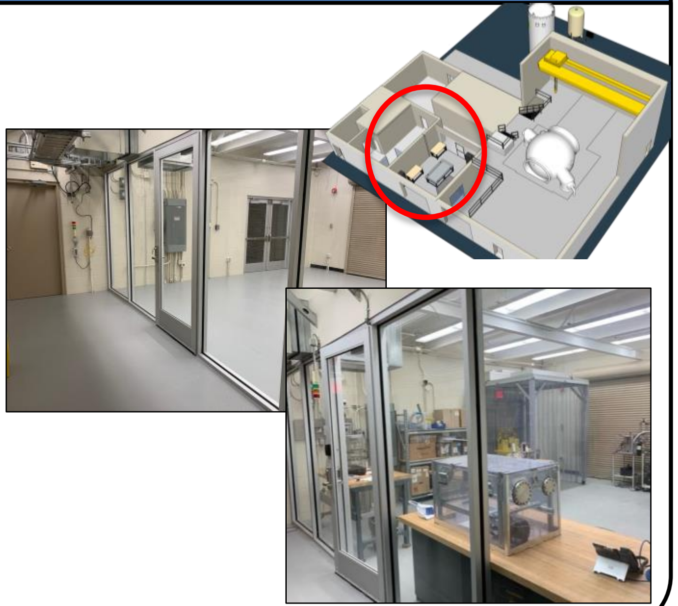
15' TVAC Chamber Dust Mitigation

- HEPA Filtration (0.3 Micron) to capture dust particles
- Sharp 90-degree bend with a sump to drop particulate out of the flow stream
- System contains a bypass leg to be utilized for normal "clean" pump downs



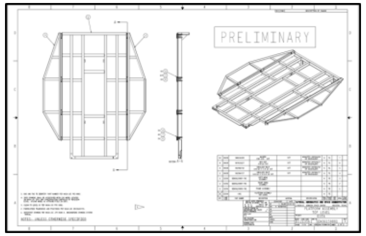
Dust Containment & Preparation Room

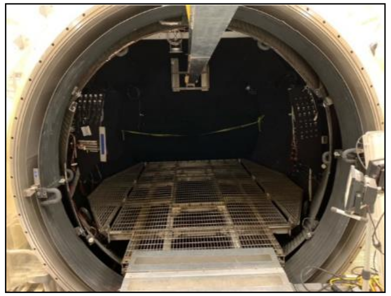
- Sealed 750 ft^2 room
- HEPA fan filtration for dust containment and negative pressure maintenance
- Particulate monitoring with alarm to ensure proper air quality



15' TVAC Chamber Platform

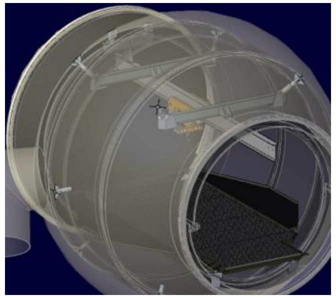
- Increased load rating from 2300lb to over 4000lb





Trolley / Hoist System

- New hoist and I-beam to move soil bin

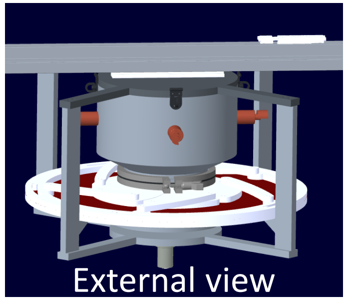


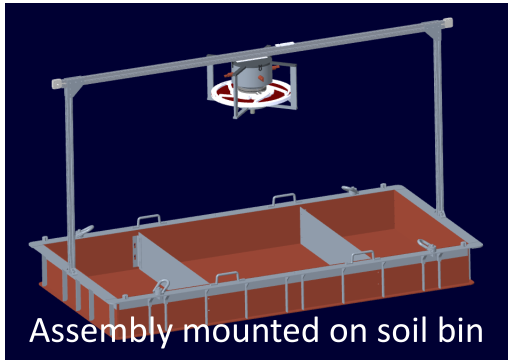
Dusty Lunar Surface Simulation B351 & Chamber Upgrades

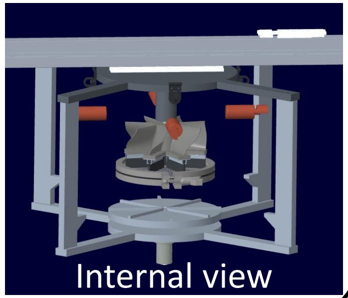
Propulsion and Fluids Group at the Energy Systems Test Area (ESTA)

Dust Deposition System (Placeholder)

- Hold >2kg of lunar simulant
- ~ 100 g/m2 surface accumulated loading
- ~ 5-10 g/s deposition speed


External view


Assembly mounted on soil bin


Internal view

Soil Bin

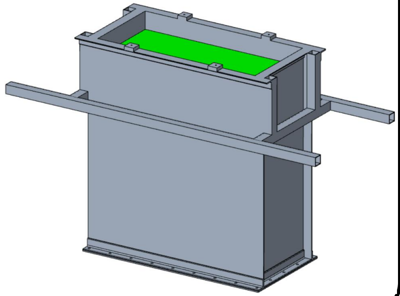
- Movable partitions provide customization for a lower fill percentage
- 48” x 96” x 10”
- Empty weight: 650 lb
- Max level fill: 8”
- Max level fill weight: 2,880 lb

Control Room (Placeholder)

- Goal is to be able to simulate lunar day and night for 30 days with a stretch goal of 60 days.
- Minimize the need for full test crew.
- Maintaining pressure and thermal over long durations.
- Provide on and off-site test system and test article monitoring.

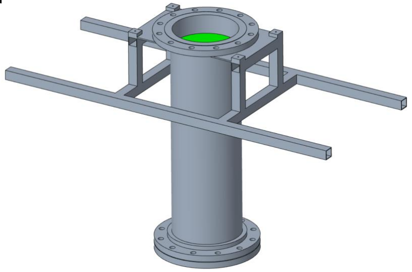
Icy Regolith Bed (Placeholder)

- Maximizes available surface area while maintaining clearances from shroud and installation handling
- Holds ~2105 lb (955 kg) of simulant for a combined weight of ~2650 lb (1202 kg)



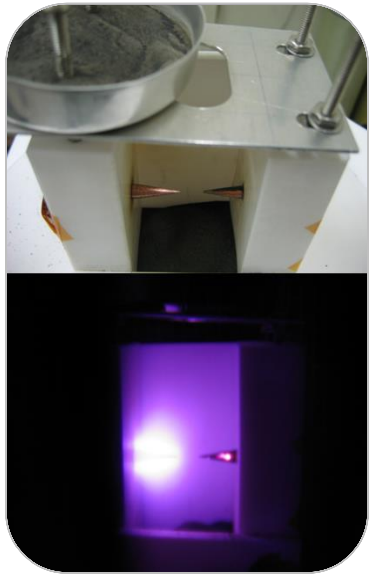
Icy Regolith Tube (Placeholder)

- Holds less soil for faster simulant conditioning
- Holds ~424 lb (192 kg) of simulant for a combined weight of ~1050 lb (476 kg)



Past Experience With Regolith/Dust

Lunar dust effects on electrical components (corona test)



OVEN in Dust Box (ISRU/Resource Prospector)

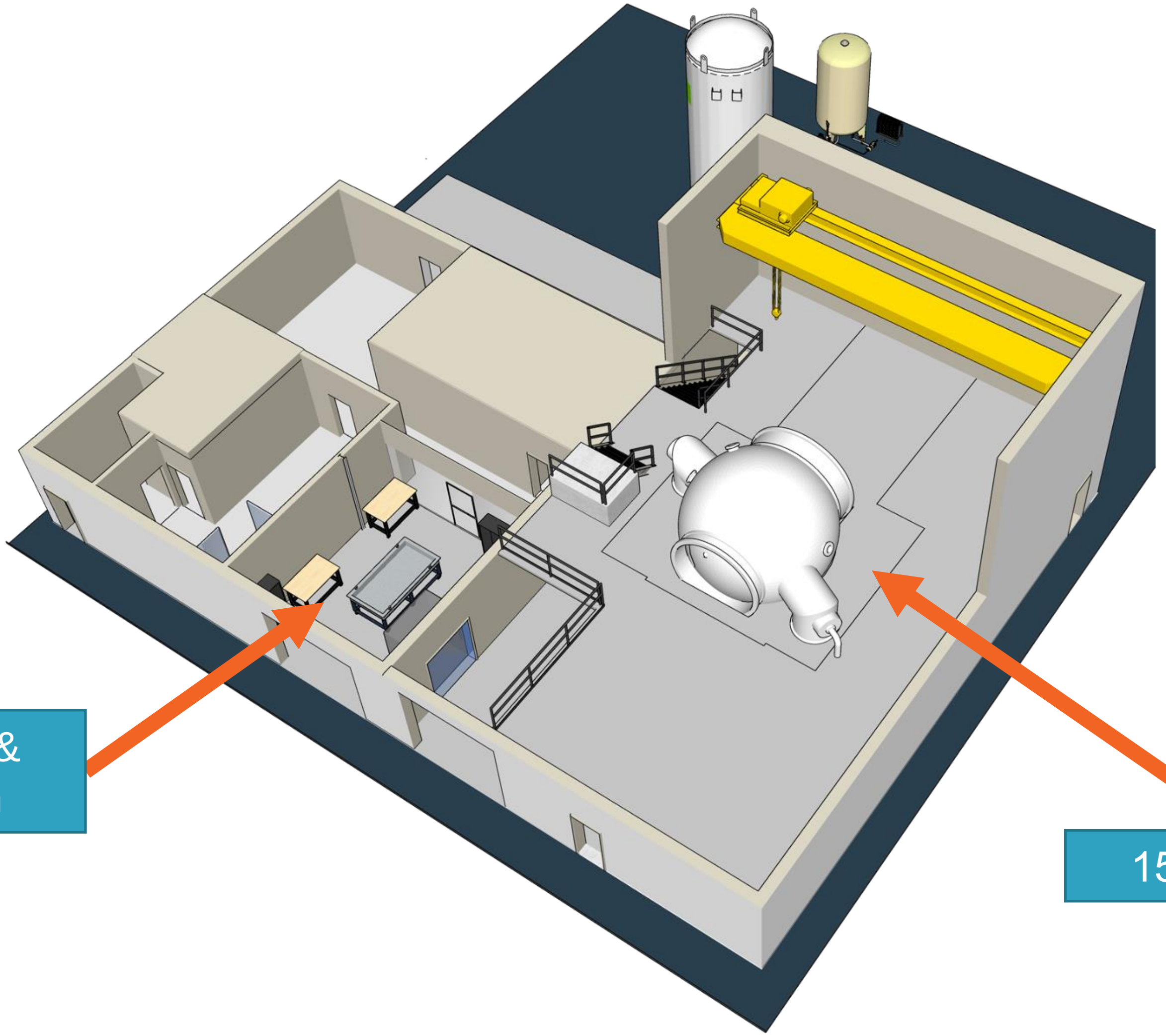
O2 Extraction via H2 Reduction (ISRU)

Planetary Surface Simulation- Dust mitigation

Auger Dryer for Water extraction using Mars and Lunar simulants

VIPER Wheel Assy Dust Exposure Test

Building 351



Dust Containment & Preparation Room

15’ chamber

HUDSON RESOURCES INC

WHITE MOUNTAIN (QAQORTORSUAQ) ANORTHOSITE PROJECT
A Lunar Highland Simulant from Greenland

PTMSS Presentation June 9, 2021

Map of Greenland

White Mountain Anorthosite Mine

- Unique calcium-rich feldspar
  - Silicon (50%), aluminum (30%) and calcium (15%)
  - Low sodium and low iron
  - Four potential commercial uses
- Mine is fully permitted for 50 years
  - Minimum 100-year lifespan
- Simple mineral processing
- Green operation with no water or chemicals used
- Hudson supports cultural and educational initiatives in local communities. Focus on local hiring.

Chemical Oxide	Percent by Weight
Silicon Dioxide (SiO2)	50.69
Aluminum Oxide (Al2O3)	30.47
Calcium Oxide (CaO)	14.64
Sodium Oxide (Na2O)	2.44
Iron Oxide (Fe2O3)	0.44
Magnesium Oxide (MgO)	0.31
Potassium Oxide (K2O)	0.19
Loss on Ignition + H2O	0.67

Multiple Revenue Streams

Hudson has identified four revenue streams for the anorthosite:

1. A replacement for kaolin in the production of E-Glass and insulation fiberglass
2. A replacement for kaolin and nepheline syenite as a filler/extender in the paints and clear coatings market
3. A replacement for bauxite as a primary source of green alumina
4. Ability to make CO_2 free white cement when mixed with phosphoric acid

E-Glass Fiberglass

Paint and Coating Fillers

Green Alumina

CO_2 Free White Cement

Simple Mining and Processing

- Drilling & Blasting
  - Open pit operation with 10m benches
  - No stripping and no overburden
- Hauling
  - Resource is 10km from process plant
- Crushing & Separating:
  - Four crushing phases, screening and dedusting of crushed material
  - High intensity magnetic separation
  - Final product is <60 mesh (250μm)
- Storage & Loadout
  - Covered storage for 30,000 tonnes
  - Load out with a 1,000 tph shiploader

Anorthosite Sizes

Various rock sizes available at the White Mountain Project

Blasted anorthosite <2m

Blasted anorthosite <1m

Jaw Crusher 40-160mm

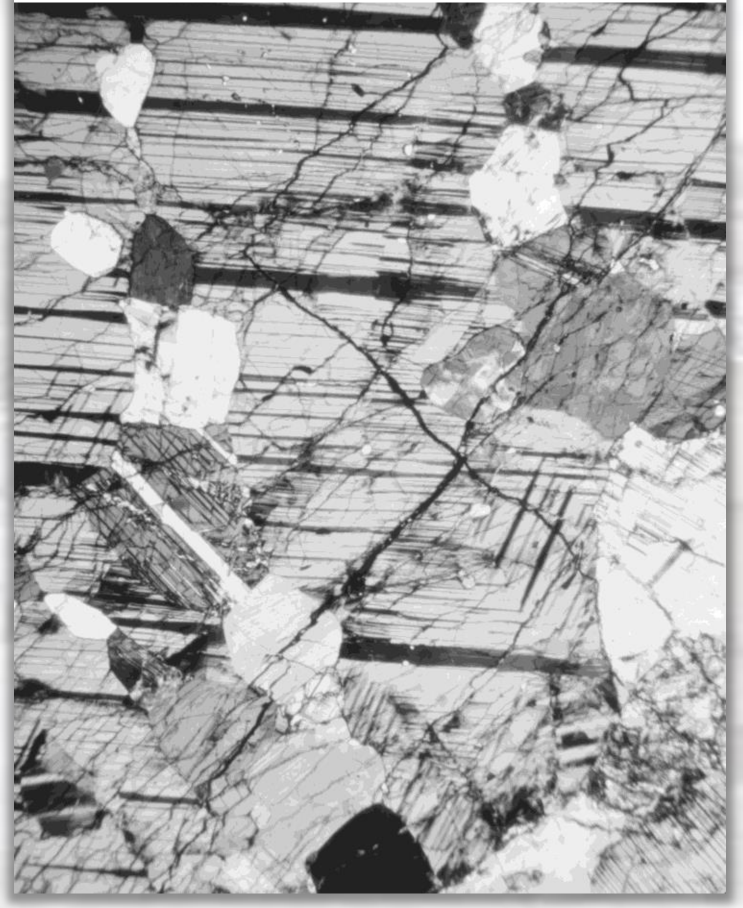
Cone Crusher <35mm

GreenSpar 1000µm

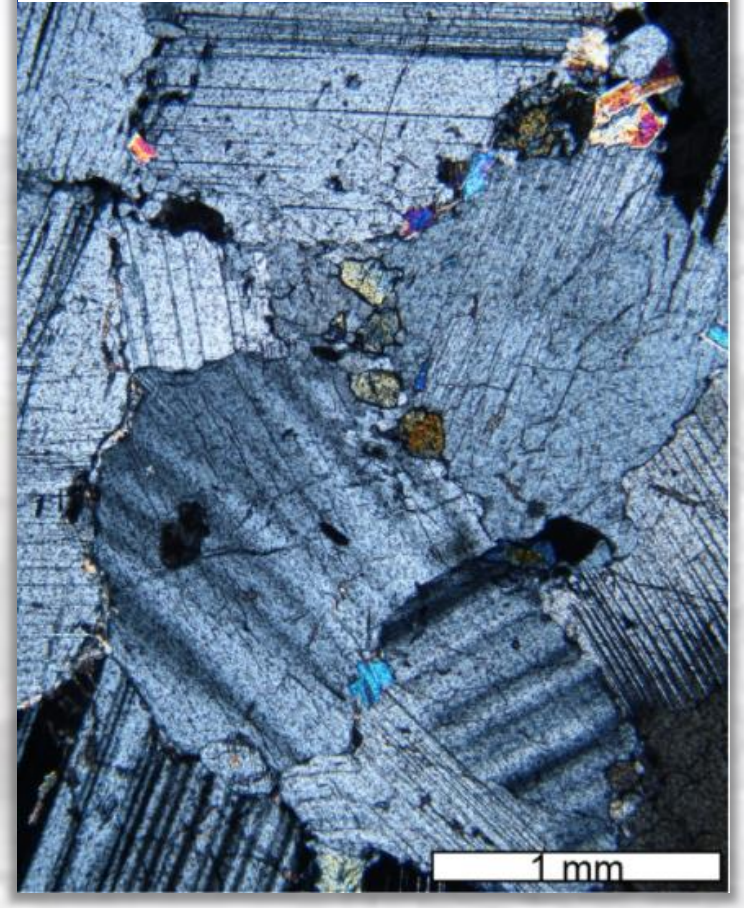
GreenSpar 250µm

An Excellent Lunar Highland Simulant

15415,0 Lunar Anorthosite

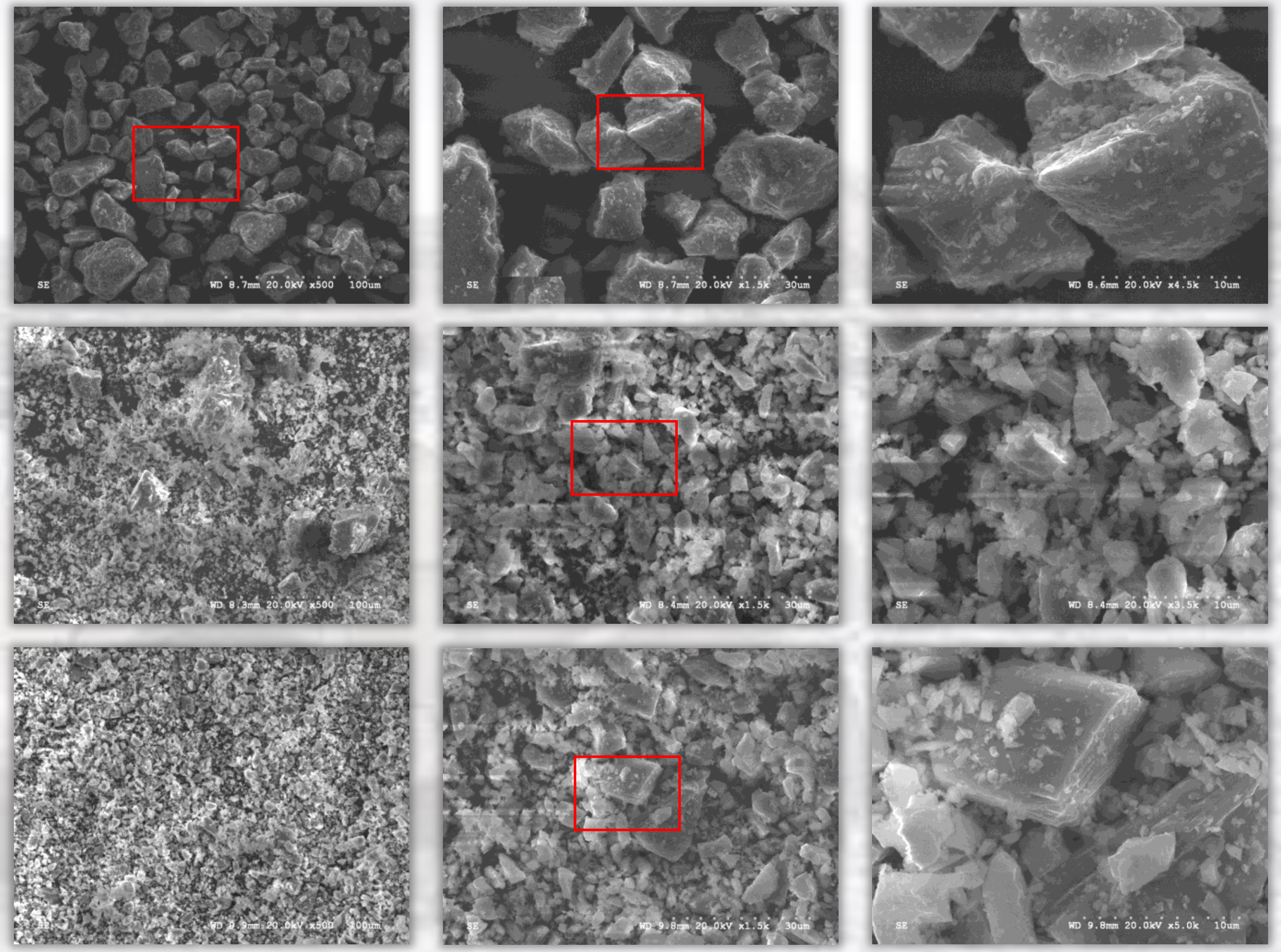


Hudson Anorthosite



SEM Analysis Photos

- GreenSpar 60µm
- GreenSpar 45µm
- GreenSpar 15µm



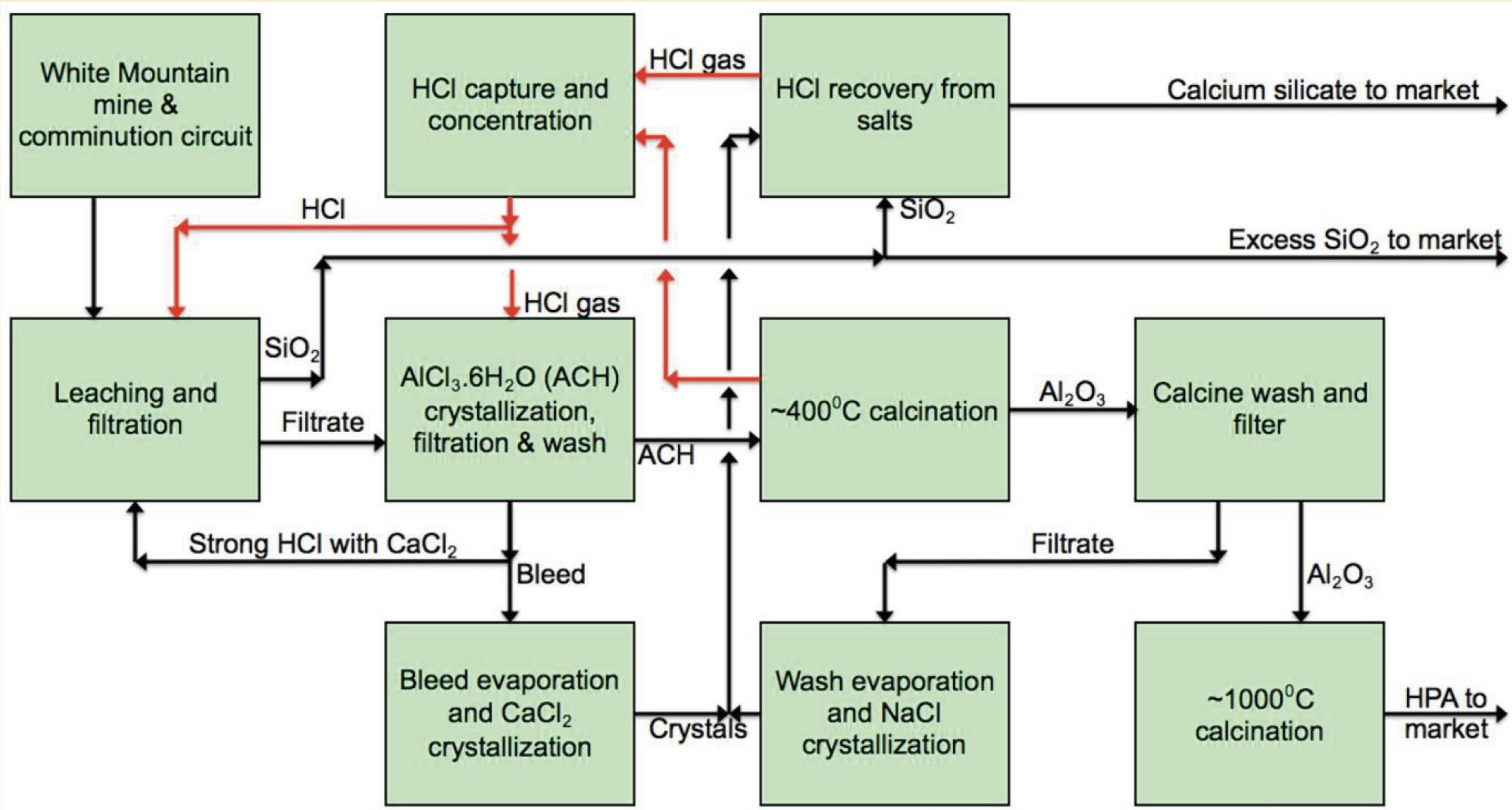
Product in Warehouse

Product in Warehouse

Green Alumina Production

- Anorthosite is easily leachable due to high solubility in hydrochloric acid
- +90% of alumina goes into solution
- Does not require pressure autoclaves that bauxite requires (or caustic soda)
- Using proven, scalable technologies
- Minimum 70% acid regeneration for hydrochloric acid
- Ability to make Smelter Grade Alumina and a High Purity Alumina
- Ability to make Alumina Trihydrate (ATH), the world's most widely used fire retardant
- Zero waste. Only by-products of amorphous silica and calcium silicate (wollastonite)

Green Alumina Flowsheet



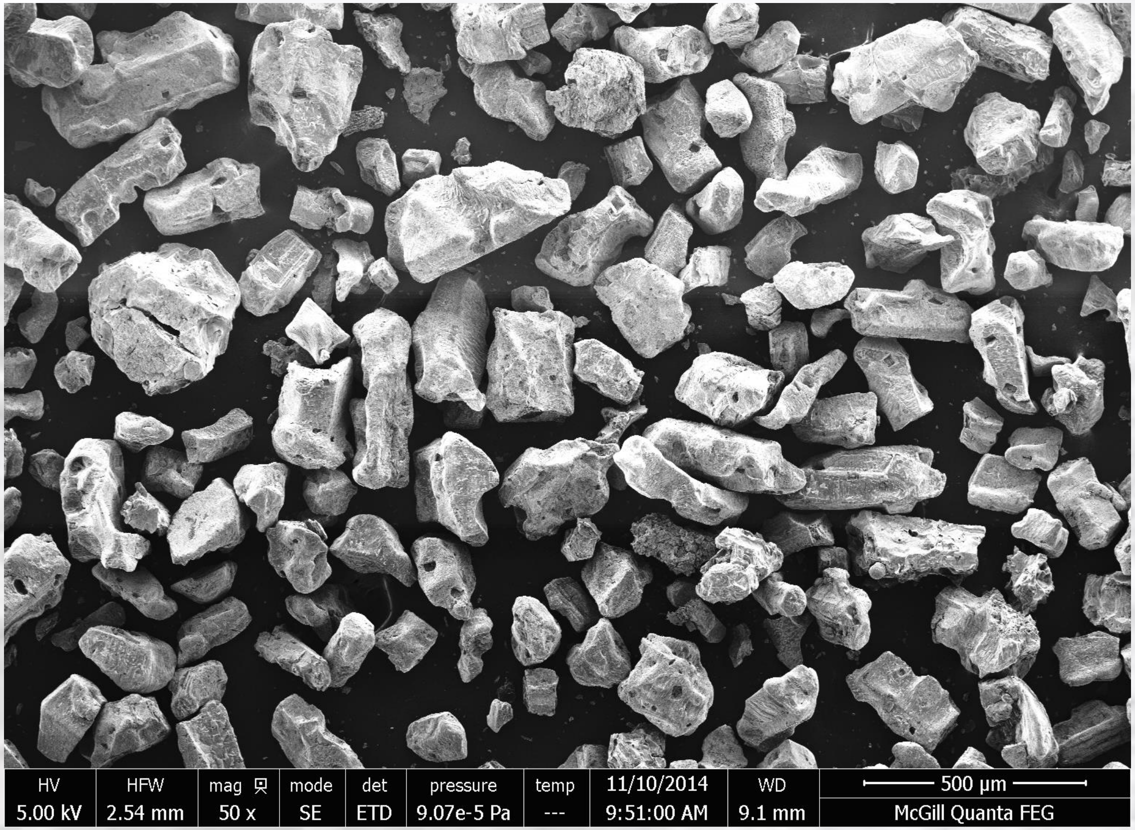
Overall reaction

$$CaAl_2Si_2O_8 + Energy \rightarrow Al_2O_3 + CaSiO_3 + SiO_2$$

Green Alumina SEM

SEM images of alumina from Anorthosite

- Tight specifications
- Need to have 55-80 sq meters of surface area per gram of smelter grade alumina



CO_2 Free Cement Production - AnoCrete

- By adding dilute phosphoric acid to raw crushed calcium rich Anorthosite you can produce a white competent cement
- The chemical reaction forms a cement without adding CO2 to the environment
- Portland cement adds 0.9 tonnes of CO2 to the environment for every tonne produced
- Initial findings show the cement to be at least as strong as Portland cement (30 Mpa) with a very high tolerance to heat (1000°C)
- High durability - insoluble in water and acidic solutions, resistant to sulphate solutions

Concrete block made entirely of anorthosite and phosphoric acid

CO_2 Free Cement Production - AnoCrete

AnoCrete applications:

- Structural cements such as white architectural cement concrete, heat-reflecting cement for warm climates, marine cement
- Cost effective, hard and chemically resistant ceramic components such as countertops and tiles
- High temperature materials such as castable refractories for the metal industry, insulating firebricks and foams, fireproof panels
- Lightweight acid resistant composite materials compatible with E-glass and steel fibres
- Encapsulation of nuclear waste
- 3D printing of buildings

Made with fine powders

Qujanaq - Thank You

Roundtable Wednesday June 9 - 72

Topic suggestion from audience:

GIS is used heavily in terrestrial mineral exploration and mining to integrate data from all aspects of operations throughout the mining life cycle. Similarly, GIS is a valuable tool for planetary science research. Because of the drastically different environments and available data of Earth, Moon, Mars, and asteroids, analysis methods developed for one body may be inapplicable for others. There is a large opportunity for the development of new analytical methods to address the unique challenges posed by space prospecting. At least one group is developing dedicated lunar GIS software for commercial use, while others have developed innovative methods using existing platforms. A round table discussion focusing on GIS applications for space resources would offer an excellent opportunity for people using GIS in their work to compare notes and identify key challenges and opportunities.

Three key elements:

- Recoverable resource
- Technology to recover it
- customer

- focus today is recoverable resource
- what would it take to go from resource to a reserve – what should we be going after
- lunar resources registry - who is the target customer for space resources – the supply chain is building itself, but cryptocurrency sucking out all the investment capital – once through macroeconomic cycle, space resources is well placed to take off then
- market signals there are investors that support what is going on in the space resources sector
- one of first questions asked to understand risk is what resource are we going after
- first principles – define resource – conduct ground truthing – need to do it cost effectively ie orbital missions – similar to terrestrial exploration
- several rounds of data and funding before setting up operations
- what constitutes enough information? Is that defined the same for terrestrial as space?
- Need a showing – ie some commodity that we know is there for sure
- Current orbital data – 5km on a side pixel – not the resolution that is needed to generate the type of maps USGS showed in presentations
- Really need to touch down and sample something before we can define what's next
- Viper first, it will help define the next step
- Ice is difficult, work to do before we can be sure we know how to handle it for a valuable commodity
- NASA putting in a lot of $ for missions related to regolith and resources other than ice
- Intent of NASA is to enable commercialization of space – expected markets currently are oxygen and propellant
- If a market develops for something else, then NASA is willing to support it
- Resource to a reserve – there is a lot that still needs to be understood about the water

- Earliest reserve to set up would be oxygen for propellant based on NASA's propellant for first missions
- 40% of regolith is oxygen – sitting on top of a silver mine and people are speculating about a gold mine with maybe 1% (analogous to going after water on the moon)
- We tend to look at elemental composition and not mineralogical – may be 40% oxygen but it may be bound to something and you need to find a way to split it from the other elements for it to be usable commodity
- There are a lot of technologies that are pretty mature for extracting the oxygen
- Suggestion that that technology is more advanced than water production on the moon
- Yield and quality of the ore is important – why isn't there talk of beneficiation and size sorting? Terrestrial operations do this to make it economically viable
- Any simple approaches to find water ice in PSR's that doesn't require a rover to run all over
- Is there a small spectrometer that can quickly tell us that there is ice below the surface by deploying many
- Magellen aerospace has penetrometer with sensor that will go just below the surface to look for water
- In the past, Paul Spudis suggested a series of impactors that could be a secondary payload and get more data to determine where to put the expensive rovers
- Depends on where, when, how you eject the impactors – from orbit, need propulsion, sensors etc – if last part of a Clips, then less expensive
- Mining industry is conservative when looking at space – partly because there are a lot of small technology gaps – use CLIPS missions to test out small aspects of various technologies
- Everyone's desire is to get on lunar surface – infrastructure gap – standard mobility platform - VIPER – learn about mobility – use that to develop the lunar platform that can be mass produced
- As private company, cost of equipment is less of a concern – launch cost is the bigger concern
- Water and ice mixed in with other stuff – provides protection from bombardment – J. Plate believes that once material is in PSR, it will stay there
- Gardening effect – Dave Page found correlation btw subsurface temperature and higher indications of H in the surface -how is this explained if gardening has gotten rid of the ice
- How much should NASA be investing with commercial companies in public/private partnerships? – if all the data will be shared publicly, then NASA would have to pay the whole cost of the mission – if you share the data, then you remove the advantage of the commercial company that has invested in the mission
- Does this community think there is a market for data?
- If there is a period for commercial confidentiality, then it becomes more viable
- NASA does not have to share data
- There would be market for data if we had a tiered mining system - small companies, larger companies, operators
- Business plan proposal model and ask from the commercial entity, then NASA decides if and how much they are willing to invest

- In early exploration in Canada, govt does fund some data – geochemical survey – released to mining companies
- In Australia – there was private company that worked with govt to define complex features in a metalurgical belt – cooperation, sharing of data
- Data and terrestrial mining – low mag surveys are available on line today – in terms of the moon, has anyone done this – topography or any other data – create baseline
- Once holes go in the ground, that data becomes valuable and tied to a competitive advantage
- This may be distinct from terrestrial mining – in space, you cannot have a right to the location tied to the data – can't protect interest – currently can only own once it has been extracted – so data is the only thing that has value – information on how to use the data is not very common, so a single company cannot hire all the expertise required – want to share the data in order to interpret