THE SCIENCE BEHIND LUNAR RESOURCE EXPLORATION AND UTILIZATION. C. R. Neal[1] [1]Department of Civil & Env. Eng. & Earth Sciences, 156 Fitzpatrick Hall, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu).

Introduction: The Moon is known to be rich in resources and has been for many decades (e.g., [1]). The last ~10 years have seen a new recognition of lunar volatile deposits as being a resource of interest for supporting human space exploration. This has been due to new science data from samples [2], orbital data [3,4], and a controlled impact into a permanently shadowed region (PSR) [5]. This has led to a focus on the lunar polar regions.

International Focus: In 2017, the Lunar Exploration Analysis Group (LEAG) was asked by the International Space Exploration Coordination Group (ISECG) to examine the plethora of planned robotic missions to the Moon and in particular the lunar south pole (**Fig. 1**). This Special Action Team (SAT – [6]) was to provide options for these missions to answer science and exploration questions related to the resource potential of lunar polar volatiles.

This SAT indicated that prospecting for lunar polar

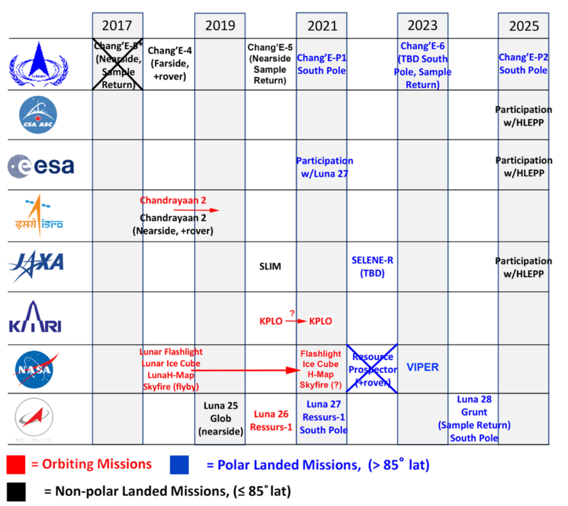

Figure 1: Planned missions to the Moon.

volatiles should be executed as a coordinated two-phase approach: Phase 1 - common and comparable measurements at diverse sites across the region would find the best locations and develop good models for distribution, preliminary characterization of the deposit, and ore grade at several regions of high interest. Phase 2 requires follow up missions to comprehensively characterize the ore grade and distribution and to enable future development at a narrow set of promising sites, including PSRs identified from orbit or from the surface in Phase 1.

Integrated Datasets: Since the 2017LEAG SAT, efforts have been made to integrate the current orbital

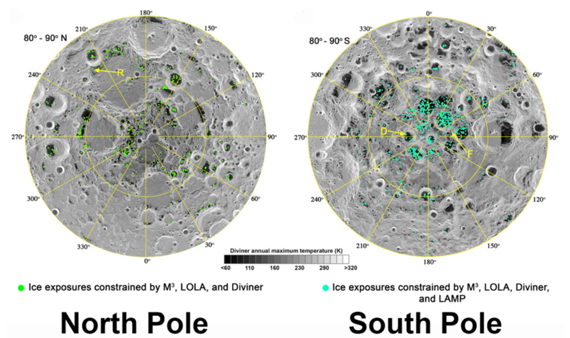

Figure 2: Locations of surface areas with ≤30 wt% water ice exposed at the surface. From Li et al. [7].

data sets, as exemplified by Li et al. [7]. This study used Moon-Mineralogy-Mapper (M3) data from Chandrayaan-1, along with Lunar Orbiter Laser Altimeter (LOLA) reflectance values, Lyman Alpha Mapping Project (LAMP) instrument UV ratio values, and Diviner Lunar Radiometer Experiment temperature data (<110 K K annual average temperature represents areas where water ice is stable). This resulted in a map (**Fig. 2**) of areas (280 m x 280 m) within PSRs where surface water ice is exposed at ~30 wt% concentrations.The data from [7] also mirror the LRO Lunar Exploration Neutron Detector (LEND), which also shows that neutron suppression areas extend around the PSRs [8,9] (**Fig. 3**).

Exploring Lunar Volatile Resources: The data needed to understand the origin(s) and formation of

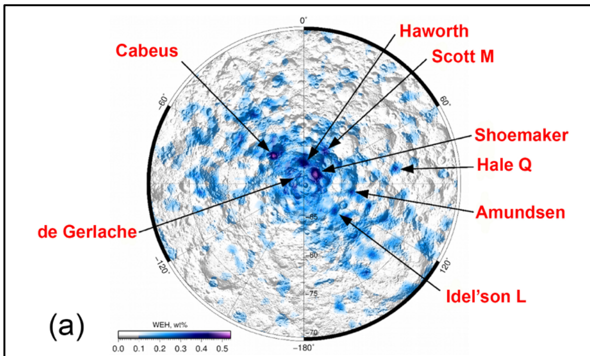

Figure 3: Neutron suppression regions in and around lunar south pole PSRs. From [9].

lunar volatile deposits are very similar to those needed to understand the resource potential of such deposits, as well as the commercial prospects. An assessment of the types of data needed to explore lunar volatile deposits demonstrates that the majority of data needed to characterize these deposits benefit science, exploration, and commercial stake holders (**Fig. 4**). With the NASA Volatiles Investigating Polar Exploration Rover now being planned (VIPER - for a 2022 launch?), it is essential that this mission not be

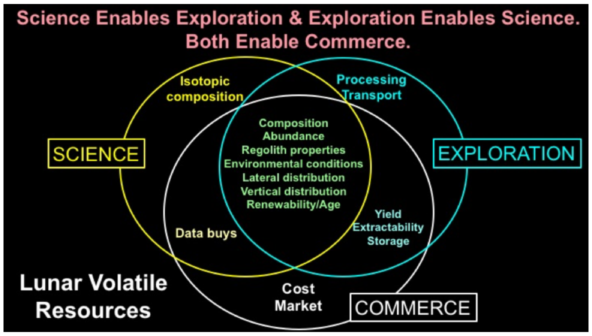

Figure 4: Data types needed to characterize lunar volatile deposits for science, exploration, and commercial purposes.

viewed as just a science mission or the only one to "prospect" for resources – it is a lunar mission that will benefit the different stake holders interested in the Moon, and should form the first in a campaign of volatile deposit exploration.

Resources vs. Reserves. It is known that the Moon contains volatile deposits that represent potential resources that could aid in sustaining human exploration (e.g., [7,10,11]). In geological terms, a **resource** is that amount of a geologic commodity that exists in both discovered and undiscovered deposits – and is by definition a "best estimate". A **reserve** is a subgroup of any resource that has been discovered, has a known size, and can be extracted *economically*. Therefore, on the Moon the volatile deposits need to be investigated to understand the concentrations of the different species present (e.g., [5]), define the extractability of the deposit, quantify the lateral and vertical abundance, etc. This is what VIPER will do, but this can also be done, in certain locations, with humans on the lunar surface as part of the Artemis program.

Artemis Evaluation of Volatile Reserve Potential: With humans being sent to the lunar south pole in 2024, an opportunity is presented to explore polar volatiles in a way heretofore unimagined. If the landing site is located in a region close to a PSR that shows neutron suppression (**Fig. 3**), the astronauts to explore if water ice deposits exist around PSRs. These would be buried in the top 1-2 meters of regolith. By using a portable drill (*cf.* Apollo; Honeybee Robotics), regolith can be exposed and analyzed for volatile species. The types of data that could be acquired are shown in **Figure 4**. This type of investigation would inform science, exploration, and potential commercial involvement in the extraction of such deposits. If it can be shown that the neutron suppression regions around the PSRs contain water ice deposits that are actually reserves, the need for entering a PSR could be obviated, at least initially.

The investigation would require multiple drill sites along a transect with known neutron suppression zones around a PSR. This could be achieved along Spudis Ridge [12], or around Shoemaker or Cabeus (**Fig. 3**). In addition, a neutron spectrometer would be needed to examine the area to understand the fine scale distribution of the deposit. Drilling would occur to understand the low suppression zones as well as the high to then quantify the neutron data. This could then be used to ground truth the orbital data from Lunar Prospector [13] and LRO LEND [8,9]. Potentially, the neutron spectrometer could be deployed on a mini-rover to define the fine scale structure of the neutron suppression zones around PSRs. This would free up the astronauts for other investigations.

The astronauts could be involved with the drilling aspect of the investigation. As the drilling proceeds at a known rate, a spectrometer is needed to quantify the different volatiles that are being brought up to the surface. By understanding the penetration rate of the drill, the depth at which the material comes from as it is analyzed can be approximated. The amount of torque and power required for the drill will also inform us about the geotechnical properties of the regolith.

Summary: Having humans involved in the investigation of potential ice deposits around PSRs will demonstrate if water ice deposits can be used without entering the hostile environment of a PSR. For example, Shoemaker crater has a lot of surface water ice within it (**Fig. 2**), but the floor of the crater is 4.5 km down a ~30˚ slope. Therefore, this investigation is vital for using lunar resources much quicker in the Artemis program for life support consumables and propellant production. Basically, the first Artemis mission can direct future infrastructure that will be used to explore lunar volatile deposits.

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