FINDING VOLATILES ON THE LUNAR SURFACE: AN INNOVATIVE MULTI-SOURCE ARCGIS-BASED APPROACH.

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Introduction: The presence of volatiles on the Moon has important implications for both human exploration and our understanding of volatiles in the Solar System. Should a local source of water or other volatiles be both present and accessible on the lunar surface, it would make future human habitation of the Moon feasible through the use of *in-situ* resource utilization (ISRU), which would, in turn, enable further exploration and use of the lunar environment. However, the distribution and properties of volatiles and of the regolith in which they lie must first be more fully understood. An understanding of volatiles on the lunar surface could also help shed light on both planetary formation and ongoing solar processes.

For those reasons, the National Research Council (US) highlighted the study of lunar volatiles—particularly those at the poles—in one of its scientific Concepts in its 2007 report *The Scientific Context for Exploration of the Moon* [1]. Within that Concept, the NRC provided five specific goals to guide future studies and exploration: (a) determining the distribution and composition of lunar polar volatiles; (b) determining the sources for lunar polar volatiles; (c) understanding the transport, retention, alteration, and loss processes of volatile materials in permanently shaded lunar regions; (d) understanding the physical properties of extremely cold polar regolith and (e) determining what the cold polar regolith (and its volatile component) reveals about the ancient solar environment [1]. Our objective is to identify locations on the lunar surface that will best allow human and robotic explorers to address these goals and further our understanding of lunar volatiles.

Data and Methods: In order to locate likely volatiles on the lunar surface, we used data from several instruments on different spacecraft. From the Lunar Reconnaissance Orbiter we used the Diviner instrument to look for minimum and maximum annual temperatures [2] below the sublimation points of known materials [3]; the Lunar Orbiter Laser Altimeter [4] to map permanently shadowed regions (PSRs) where volatiles could potentially be trapped, to find and reject areas too steep to be navigated based on current engineering constraints [5], to obtain a digital elevation model and shaded relief map to better characterize poorly lit areas; and Wide Angle Camera mosaics [6] as our base map. From Chandrayaan-1 we used the Mini-SAR instrument to investigate circular polarization ratio as a possible indicator of the presence of water/ice of ~2-3 m thickness [7,8]. From Lunar Prospector we used the Neutron Spectrometer to look at hydrogen abundances [9] as a proxy for volatiles in the top 50 cm of regolith [10]. Finally, we used USGS geologic maps [11] as our source for the relative ages of surface geologic units. These datasets provide complementary information about potential volatiles depending on the wavelength used by the sensor, the depth of the signal, the interaction with the ground, and the spatial resolution, among other factors.

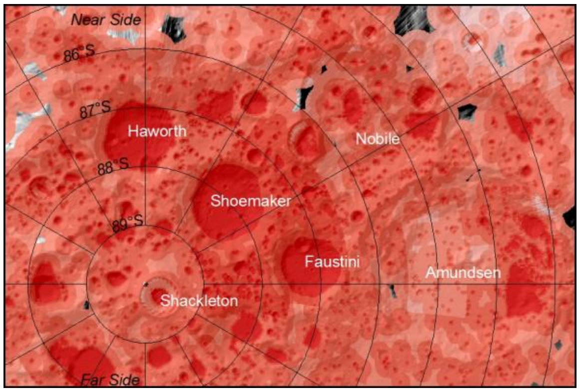

Figure 1. Locations best suited for determining the state and distribution of volatiles near the lunar south pole. Values go from bright red (highest chance of scientific return) to pink (lowest). Uncolored regions are excluded due to distances from PSRs > 10 km.

To determine potential landing sites, we performed a multi-source spatial analysis with the widely-used software suite ArcGIS. First, we imported and georeferenced our data sets into ArcMap. We assigned them a geographical coordinate system (GCS Moon 2000), a datum (Moon 2000), and a polar stereographic projection. We then re-classified hydrogen abundances, maximum annual and minimum annual temperatures, PSR locations, and slope data into "ranks" 1–4, where 1 represents the most scientifically interesting range of values. For example, instead of viewing hydrogen data as abundances from 0–195 ppm, we binned the values into ranks 1 (150-195 ppm), 2 (100-150 ppm), 3 (50-

100 ppm) and 4 (0-50 ppm) corresponding to enhanced, elevated, average, and low equatorial hydrogen abundances discussed in [12]. We then combined the ranked layers with the raster calculator tool, weighted each layer based on which goal was being addressed, and obtained a map of suitable locations for each Science Goal (Figure 1).

We then performed a manual post-classification analysis to remove likely artifacts and consider broader regional factors (*e.g.*, temperatures, CPR data). Finally, we integrated results from all science goals into a final map of lunar sites with the best science potential (*i.e.*, where all goals could be addressed).

Potential Sites: Both north and south polar regions show multiple sites ideal for studying lunar volatile history and processes. These sites all have hydrogen abundances of ~150-195 ppm, maximum and minimum annual temperatures < 54 K, slopes < 25°, and are within PSRs.

The north polar region includes potential sites in (1) Hermite and Lenard craters, (2) the polar highlands near Bosch and Rozhdestvenskiy W craters, (3) the polar highlands between Hermite and Peary craters, and (4) Peary crater (Figure 2a). These sites are generally small areas on crater floors. The north polar region exhibits the highest hydrogen abundances on the Moon and is characterized by the presence of a tremendous number of small (< 1 km diameter) PSRs.

The south polar region includes potential sites in craters such as (1) Amundsen, (2) Haworth and Shoemaker, (3) de Gerlache, and (4) Faustini (Figure 2b). Generally, sites are larger but more sparsely distributed than those in the north polar region. Large PSRs (~30 km diameter) are found on the floors and walls of Haworth, Shoemaker, and Faustini, but only a very few locations in each PSR have maximum and minimum annual temperatures < 54 K. Instead, temperatures range from ~54-100 K, which while cold enough to enable some trapping of volatiles, are not as ideal as colder locations according to our criteria. Notably, Shackleton crater does not contain any potential landing sites according to our criteria; even though it contains a large (~17 km diameter) PSR, the local maximum annual temperatures are ~75-105 K, which means noble gases, carbon dioxide and many other volatiles cannot be trapped there (water is questionable, with a sublimation temperature of 106 K) [3]. Moreover, its walls are steeply sloped, ranging from 25° to over 55°.

Discussion: We propose four regions at each pole that are optimally suited for exploration of lunar polar volatiles. Those regions are selected based on very restrictive classification criteria. Those criteria could be relaxed and would result in more sites. In the near future, new data (*e.g.,* M^3) can be added to the analysis and might result in a more complete investigation. This study also demonstrates that a GIS-based approach (in this case, to landing site selection) can provide a way to quantitatively study issues in planetary science and can make using data from various sources more feasible. Most importantly, this approach has led to unexpected but defensible results, such as revealing Amundsen, rather than Shackleton, to be the most promising south polar location for studying lunar volatiles (see [13] for details).

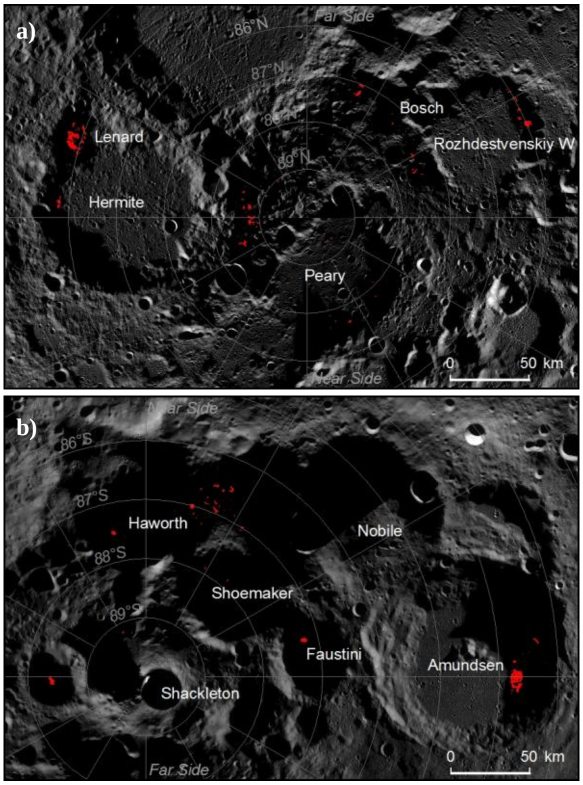

Figure 2. (a) north and (b) south polar regions that possess the best potential for studying lunar volatiles.

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