DIFFERENTIAL DISTRIBUTION OF WATER ICE AND DRY ICE IN THE MOON'S SOUTH POLAR REGION: IMPLICATIONS FOR RESOURCE POTENTIAL.

David A. Kring[1,4], Matthew A. Siegler[2,4], and David A. Paige[3], [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston TX 77058 USA (kring@lpi.usra.edu), [2]Planetary Science Institute, Tucson AZ 85719 USA, [3]Dept. Earth and Space Sciences, University of California, Los Angeles CA 90095 USA, [4]NASA Solar System Exploration Research Virtual Institute.

Introduction: Science objectives for exploration of the Moon [1] include a study of polar volatile compositions and sources; their transport, retention, alteration, and loss processes in permanently shadowed regions (PSRs); their host regolith physical properties; and a measure of the ancient solar environment as derived from implanted volatiles. Volatile species are also being targeted for *in situ* resource utilization (ISRU) that supports long-term exploration of the lunar surface and other deep space destinations.

Site Prospects: While science and ISRU objectives are often discussed in the context of the same lunar surface sites, a dichotomy between them may exist. Science objectives require surveys of sites with different environmental conditions, including the coldest PSRs where the most volatile species may exist. In contrast, ISRU operations may favor warmer PSRs where water is uncontaminated with other volatile species (e.g., NH_3 & CO_2), making it easier to process any ice into components for crew consumption and rocket propellant. Warmer conditions may relax requirements for rovers and other assets devoted to ISRU.

Model Calculations of Ice Distribution in the South Polar Region: Using previously developed methods (e.g., [2]), the possible stabilities of water ice (H_2O) and dry ice (CO_2) in the upper 50 cm and 1 m of the regolith were calculated. Water ice is stable within those near-surface zones over a greater geographic area than is dry ice (**Fig. 1**). Thus, as one approaches a PSR, near-surface water ice might be recoverable without dry ice and other volatile species. Scattered detections of surface water ice and dry ice have been made in the uppermost few mm of the same regions [3]. To illustrate the model results, we highlight three locations (Cabeus, Shackleton, and Amundsen).

Cabeus Crater: Cabeus crater has a region (**Fig. 1**) where water ice, dry ice, and other volatile species may be found. An impact experiment into that region, LCROSS, suggests water ice is comingled with H_2S, NH_3, SO_2, C_2H_4, CO_2, and other species [4]. While it will be important to sample those ices to address science issues [1] and, potentially, for some ISRU purposes, initial ISRU exploration may favor the outer margins of Cabeus where water ice may be enriched relative to those other species.

Shackleton Crater: Artemis III, the first Artemis lunar surface mission, is designed to land near the south pole, which is located on the rim of Shackleton crater. The crater hosts a large PSR that calculations suggest may have a near-surface environment with water ice (**Fig. 2**). Shackleton may also have been produced after the most intense delivery of impactor and volcanically-vented volatiles, so ices may be dominated by a solar wind source [5].

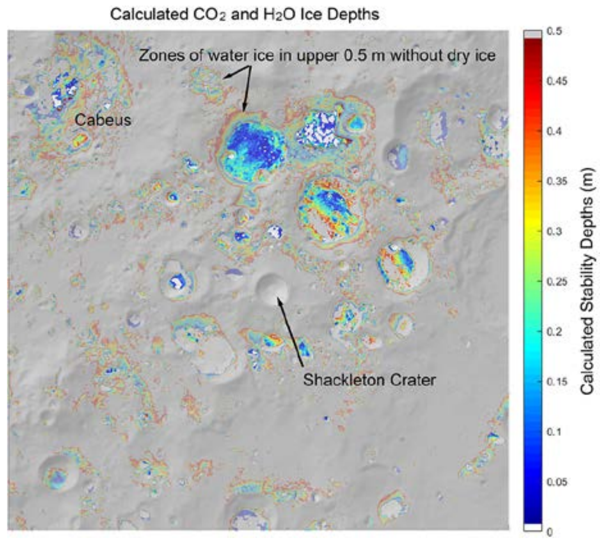

Fig. 1. *Semi-transparent map of calculated dry ice stability depths on top of a map of calculated water ice stability depths for the upper 50 cm of regolith.*

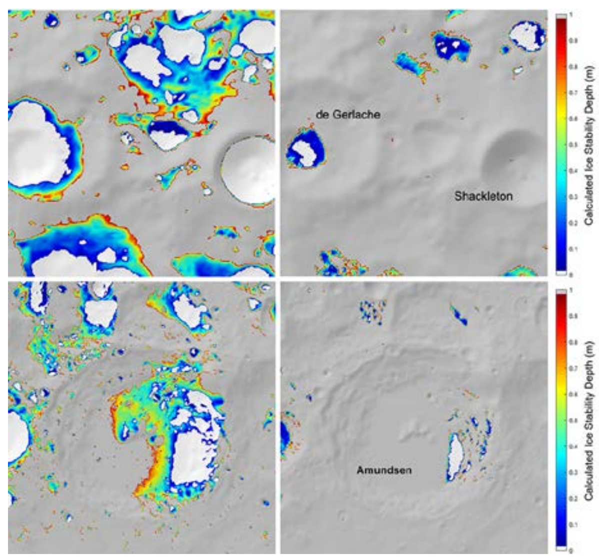

Fig. 2. *Maps of calculated stability of water ice (left) and dry ice (right) in the upper 1 m of regolith in Shackleton (top) and Amundsen (bottom) craters.*

Amundsen Crater: A previous analysis [6] of landing sites suitable for addressing lunar science objectives [1] suggested the floor of Amundsen crater is a high-priority target. An analysis [7] of the International Space Exploration Coordination Group (ISECG) design reference mission [8] also pointed out that Amundsen is a good place for a telerobotic subsurface survey for water ice. Calculations presented here (**Fig. 2**) illuminate the advantages of that type of location: it contains a diversity of ice types, on an easily traversable crater floor, in close proximity to sunlight and the power it provides.

Model Calculations of Resource Potential: Near-surface deposits that do not require energy for the removal of overburden may be attractive ISRU targets. Using the calculated ice distributions described herein, the potential resource tonnage was calculated in the upper 1 m (**Fig. 3**). Resource tonnage is derived assuming 5.6 ± 2.9 wt% H_2O in the regolith, as determined from the LCROSS experiment [4]. Because that experiment targeted Cabeus crater, the resource tonnage calculated for Cabeus (**Fig. 3**) should be viewed with a higher confidence than that for other sites (e.g., Haworth, Shoemaker, Faustini, and Shackleton crates). We note that the 5.6 wt% value is strictly applicable only to the coldest portion of Cabeus, where dry ice is stable at the surface. Thus, we also provide the potential resource tonnage for lower proportions (0.1, 0.5, and 1.0 wt%) of H_2O in the regolith.

Model calculations suggest 2×10^{10} kg to no more than 5×10^{10} kg water ice could be recovered from the uppermost 1 m of regolith in Cabeus crater. Similar values for Haworth, Shoemaker, Faustini, and Shackleton are 9×10^9 to 3×10^{10} kg, 9×10^9 to 3×10^{10} kg, 6×10^9 to 2×10^{10} kg, and 1×10^9 to 4×10^9 kg, respectively. For the coldest regions of the PSRs, where dry ice is stable at the surface, the potential resource tonnage of other ices (OH, CH_4, CH_3OH, CO_2, C_2H_4, SO_2, NH_3, and H_2S) is calculated (**Fig. 4**) assuming they occur in the same proportions as observed by the LCROSS experiment [3]. Additional tonnage can be recovered at deeper (>1 m) horizons. Depending on the resource recovery methodology, it may be more efficient to access deeper ice at a single location than surface ice at geographically distant sites. In either case, it will be important to evaluate sublimation rates of subsurface ices as overlying regolith is removed.

Conclusions: The sites where ISRU may initially be attractive and where the most interesting science can be addressed are not necessarily in the same locations. The outer margins of PSRs, which may be encountered first, may be attractive for ISRU, while science objectives may favor deeper excursions into the PSRs. Both types of sites will, of course, be important in a robust science and exploration program, but a trade may exist between them when designing mission architectures. An initial assessment of resource potential suggests millions of metric tons of water ice may be available within the uppermost 1 m in several locations in the south polar region of the Moon. While the model calculations are consistent with orbital detections of water and dry ices [3] and the single-point probe of LCROSS [4], an *in situ* exploration effort is needed to test the model calculations. If *in situ* measurements can be provided in a few representative sites, then the model calculations can be refined further.

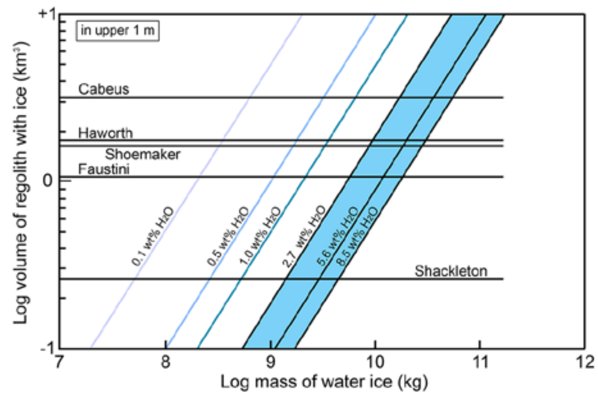

Fig. 3. *Calculated masses of water ice in several south polar craters with a regolith water abundance (5.6 ± 2.9 wt%, blue zone) measured by the LCROSS experiment. A log mass value of 9 on the horizontal axis is equivalent to a million metric tons.*

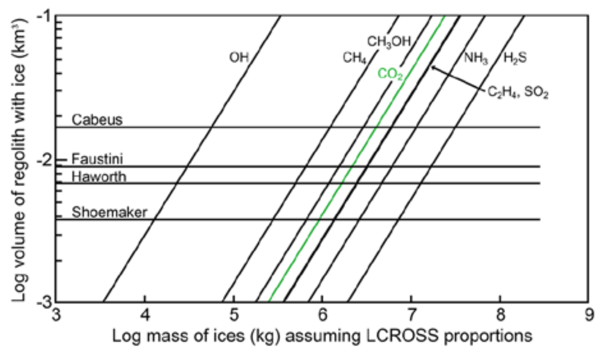

Fig. 4. *Modeled ice masses in the upper 1 m of regolith for species detected in the LCROSS experiment.*

References: [1] NRC (2007) *The Scientific Context for Exploration of the Moon*. [2] Siegler M. A. et al. (2016) *Nature*, *531*, 480–484. [3] Li S. et al. (2018) *PNAS*, *115*, 8907–8912. [4] Colaprete A. et al. (2010) *Science*, *330*, 463–468. [5] Kring D. A. (2019) *NASA Exploration Science Forum*. [6] Lemelin M. et al. (2014) *Planet. Space Sci.*, *101*, 140–161. [7] Allender E. J. et al. (2019) *Adv. Space Res.*, *63*, 692–727. [8] Hufenbach B. et al. (2015) *International Astronautical Congress*, Paper #IAC-15-A5-1-1-X30756.