SCIENCE-RICH SITES FOR LUNAR IN SITU RESOURCE UTILIZATION CHARACTERIZATION AND END-TO-END DEMONSTRATION MISSIONS.

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Introduction: Recent increased interest in the development of commercial space infrastructure, offers an opportunity for advancing basic lunar science questions parallel to technology development. Given that a limited number of locations on the Moon have been visited, investigated, and sampled, there are numerous locations on the Moon where basic scientific instrumentation could provide critical insight for scientific questions outlined in numerous reports [e.g., 1-5]. Many sites are also compatible with space development goals, such as the testing and implementation of in situ resource utilization (ISRU) technologies.

For example, regional pyroclastic deposits (e.g., NW of Taurus Littrow, ilmenite-bearing; Aristarchus plateau, Fe^{2+}-bearing) have been of interest for their ISRU resource potential for decades. Landed studies of bulk chemistry/mineralogy, volatile contents, and geotechnical properties at previously unsampled types of pyroclastic deposits would allow us to address strategic knowledge gaps for ISRU, as well as advance our understanding of lunar volcanic/thermal evolution.

ESA Strategy and Activities: Recent European Space Agency activities related to the expansion of expertise and capabilities in the area of space resources [e.g., 6,7] involves a program entitled "Commercial In-Situ Resource Utilization Demonstration Mission Preparation Phase". The aim of the study is to assess and develop commercial capabilities for processing of lunar regolith to produce oxygen and other resources. Participants are developing and testing resource extraction techniques ranging from hydrogen- and methane-reduction [e.g., 8] to application of the FFC-Cambridge electrochemical process for lunar materials [9]. Commercial lander providers are involved to investigate and coordinate potential ESA/industry partnerships for delivery of ISRU payloads to the Moon.

Our Study Goals: In the course of this ISRU project, led by OHB Italia under ESA contract, we reviewed potential ISRU resource types and evaluated potential lunar landing regions/sites for feedstock characterization mission(s) and/or end-to-end ISRU plant demonstration(s). We focused on mid-latitude nearside regions, where commercial lander providers will most easily be able to land and operate.

The evaluation of potential sites involved analyses of high-resolution and stereo image coverage, digital terrain models, illumination conditions, spectral/compositional maps (e.g., TiO_2, FeO, indigenous water), and maps of physical properties (e.g., radar/thermal characteristics, rock abundance). Combined within GIS, along with geological maps, crater/boulder size-frequency distribution measurements, and hazard assessments (e.g., slopes, rock abundance), these datasets allow the selection of both scientifically and technically relevant landing sites.

Characterization Sites: For our analysis of potential ISRU characterization sites, we combined locations discussed in [4], sites relevant to ISRU oxygen production from those discussed and summarized in Flahaut et al. (2012)[10] and Kring and Durda (2012)[11], and regions of interest for the cancelled NASA Constellation program [12]. We then limited the selections to those which the two participating lander providers can currently reach with their technology.

Different materials of interest generally fall into four groups: (1) high TiO_2 pyroclastics with affinity to the Apollo 17 landing site, (2) high FeO, low TiO_2 pyroclastics characterized by the Aristarchus plateau materials, (3) high TiO_2 basalts (e.g., type M2 [10]), and (4) high FeO, low TiO_2 basalts (e.g., the P60 basalt [13]). Group 1 regions include Sinus Aestuum, Rima Bode, Mare Vaporum, Sulpicius Gallus, Montes Harbinger, and Montes Carpatus. High TiO_2 pyroclastics were sampled at the Apollo 17 landing site, but it is unknown how these deposits compare to the others which have only been observed via remote sensing [e.g., 14]. Group 2 is primarily represented by the low TiO_2 and high Fe^{2+} compositions inferred from the remotely-sensed spectral properties of the largest lunar pyroclastic deposits on the Aristarchus plateau. High TiO_2 basalts of type M2 within group 3 are not present in our sample collection [10]. Group 4 includes low TiO_2, high FeO basalts, such as the P60 basalt, which is one of the youngest basalts on the Moon [4,13], and a potential site for either sample return or in situ age-dating missions [e.g., 15 and references therein].

The first two groups also exhibit potentially high concentrations of indigenous H_2O [16]. Given the need for groundtruth of these values and the potential use of indigenous water as an ISRU resource, it may be beneficial to select a landing site within such deposits. These locations are, for group 1: Sulpicius Gallus, Rima Bode, or Humorum/Doppelmayer; and group 2: the Aristarchus plateau.

The selection of a site on the Aristarchus plateau would allow the characterization of previously uncharacterized materials, whereas a mission to Rima Bode or Sulpicius Gallus would allow groundtruthing of how similar these materials are to Apollo 17 pyroclastics. Characterization at any of these sites would allow the evaluation of the reported high concentrations of indigenous water in some pyroclastic deposits. Key measurements of bulk chemistry and mineralogy, volatile contents, and quantification of geomechanical regolith properties would address both scientific themes and SKGs for potential ISRU materials [e.g., 4].

End-to-End Demonstration Sites: For a standalone end-to-end (E2E) ISRU demonstration mission, a fuller understanding of the physical and compositional characteristics of the resource deposits is required to reduce overall risk for the demonstration. As a result, either precursor or "characterization" missions are required, or an E2E site could be selected near prior landing sites. Thus, we examined locations near Apollo and Luna landing sites, to allow extrapolation of groundtruthed knowledge to nearby deposits. Because Ti-rich pyroclastic deposits appear to be most advantageous for initial E2E plant operations from both beneficiation and compositional perspectives, we selected an example landing site for an E2E demonstration to the northwest of the Taurus Littrow valley, south of Clerke crater (***Fig. 1***). Given that some ISRU methods require the presence of ilmenite, but others do not, this location offers an opportunity to test more than one ISRU approach in a single location.

We mapped landing regions that maximize both the Ti and Fe contents of the regolith, as well as offering slopes of <5° and accumulated illumination approaching 50% (~14 days)(e.g., ***Fig. 2***). The next steps for selecting a landing site within this region include more detailed hazard analyses. The selection of an E2E landing site near a prior Apollo landing site does not provide as great an opportunity for scientific advancement as small missions to characterize materials previously not groundtruthed.

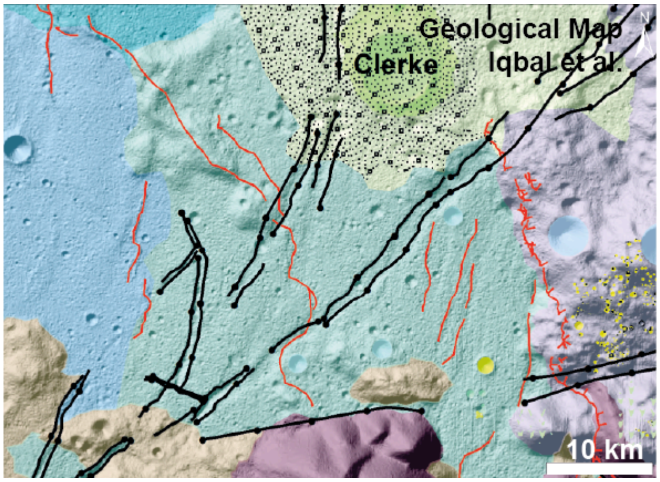
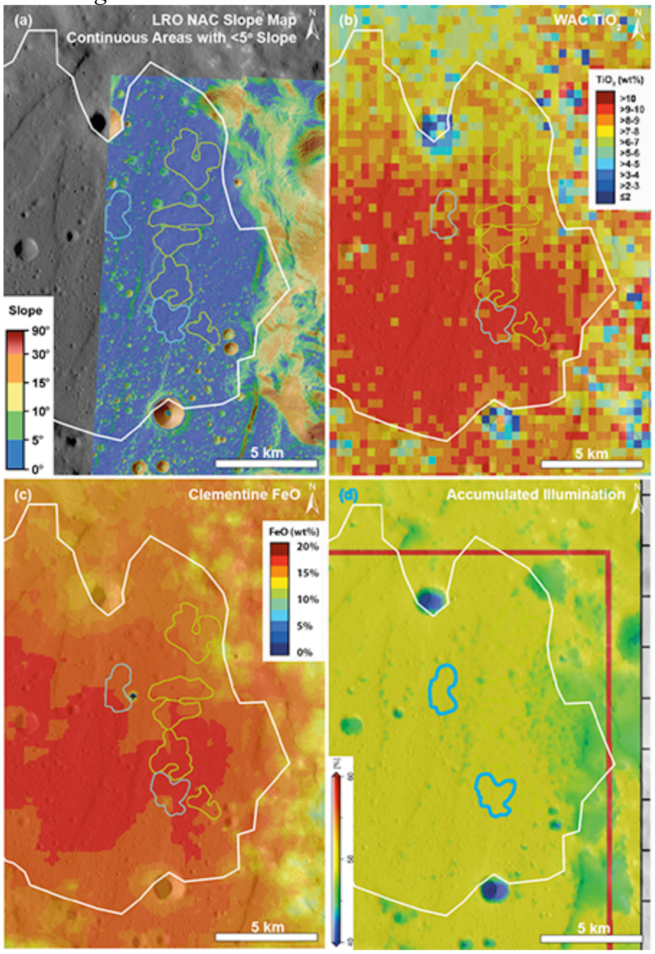


Figure 1. *Geological map of [17] showing the region around a potential end-to-end ISRU demonstration site NW of Taurus Littrow valley and south of Clerke crater.*

Figure 2. *Assessment of potential end-to-end ISRU demonstration sites combines analyses of (a) slopes, (b,c) Ti and Fe compositions, and (d) accumulated illumination, to select regions (e.g., cyan areas) that meet both engineering and technological constraints.*



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