EXAMINING THE RESERVE POTENTIAL OF LUNAR POLAR VOLATILES. R. V. Patterson*[1] and H. C. O'Brien*[2], L. E. Galien[3], J. L. Valenciano[3], C. R. Neal[3]. [1]Astralytical Consulting (ruby@astralytical.com), [2]NASA JSC JETS II (hannah.c.obrien@nasa.gov), [3]University of Notre Dame.

Introduction: In order to sustain humans on the lunar surface for extended periods, potential resources on the Moon must be defined, extracted, and refined on the lunar surface. There is also a potential future market for lunar resources to be exported back to Earth for profit [1]. However, the data currently available regarding these resources is not sufficient to define their reserve potential. In an effort to assess the reserve potential of polar volatiles, we discuss current standards and the data fidelity required to make a quantitative estimation of potential reserves within three lunar terrain types.

Establishing the difference between *Reserves* and *Resources* is key, as these terms have been used interchangeably in describing potential natural assets on the Moon. 'Resources' is a broader term, where materials that *may or may not be discovered* might be feasible for economic extraction. 'Reserves' is a specific term that implies *assured recoverability of a commodity* through *economic* and *legal* extraction [2]. Therefore, determining the reserve potential of lunar resources is vital for scientific and commercial exploration of the Moon, as well as the development of a cislunar economy, because the data obtained will inform multiple stakeholders (Fig. 1). In order to define such reserves, one proposed set of use standards is the Lunar Ore Reserves Standards (LORS) [3].

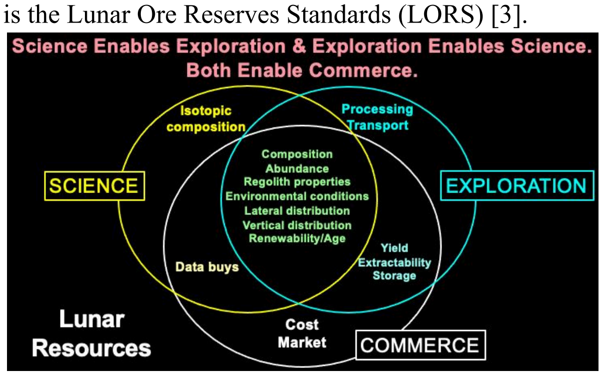

Fig. 1. Prospecting for lunar resources produces data that inform multiple stakeholders. Modified from [2].

The Lunar Ore Reserves Standards (LORS) provide a framework through which lunar reserves may be classified and communicated to interested parties wishing to explore, extract, and engage in the commercial transaction and use of space resources [3]. We utilize these standards as well as available data to answer two questions: (1) Where do current datasets place polar water-ice deposits in the LORS resource-reserve hierarchy? and (2) What new data are needed to quantify the reserve potential of lunar resources?

The current state of lunar resource evaluation falls into the United Nations Framework Classification (UNFC) E3 subclass. This classification scheme uses geologic knowledge, socio-economic viability, and project feasibility to define reserves. The LORs also utilizes this classification as a frame of reference. The E3 subclass is defined by the UNFC as: *Extraction and sale is not expected to become economically viable in the foreseeable future or evaluation is at too early a stage to determine economic viability* [4]. The present terrestrial standard is based on financial gain and economic viability, whereas it has been proposed that extra-terrestrial standards should be based on mission success [5]. The only non-financial based reserve terrestrial standard we have is the UN standard, which is limited. Reserve potential classification has largely been left to industry to define for their own use. If LORS is to be utilized for the Moon, mission success terms need to be included, as we aim for better data so that economic gain can be measured and the LORS standard further refined.

Future Relevant Missions: At present, over sixty lunar missions are slated to launch in the next six years [6]. This work focuses on those identified in [2] as part of a coordinated international campaign to prospect polar resources.

A Note on Scale: When producing geologic maps for economic exploration of a region, it is crucial to select the proper scale or resolution of maps/datasets. To illustrate this, we contrast the resolution and scale between proven successful terrestrial economic maps and current and planned resource prospecting missions to the lunar surface.

The resolution of data to be collected in current and upcoming missions ranges from 10 m/px to 10,000 m/px (Fig. 2). This roughly translates to 1:20,000 to 1:20,000,000 (using a 2000 dpi equivalent quality paper map) [7]. For reference, a useful terrestrial lode gold prospecting map would have a scale of < 1:24,000 [8]. This underscores the need for instruments to collect the finest resolution possible if we are to proceed with high-fidelity, economically profitable mining operations on the lunar surface.

Polar Ice Deposit Terrain Types: We relate the LORS classification schema to the 3 potential water-ice bearing lunar terrain types (TT) from [9]. These are hypothesized to represent different stages in the evolutionary pathway of the ice deposits on the Moon, where thick ice is deposited on the surface (TTI) via impacts, then the thick ice layer is broken up and ice is dispersed into shallow regolith (TTII), and eventually ice is buried at depth (TTIII).

Terrain Type I. Represented as the thick ice layers deposited in macro cold traps (regions that are cold enough to trap water ice, and is the model standard of a PSR - Permanently Shadowed Region - such as large craters at the south pole). TTI represents the beginning of the evolutionary path of lunar water-ice. As a surficial TT, infrared and microwave heating could potentially be used to prospect. Evaluating the top meter of the lunar surface can be achieved by PROSPECT [10] and PRIME-1 [11].

Terrain Type II. Continued impacts on the surface act as erosive agents, 'gardening' the ice and burying it deeper into the regolith layers [9]. TTII (and III, below) are micro cold traps, or small areas in rough terrain that are shadowed and cold enough to trap water-ice in otherwise non-shadowed regions. As this TT is ≤1m below the surface, instruments specializing in subsurface measurements are ideal [12]. If ice were mixed with regolith, this could be a more difficult case but radar could detect these [12]. TTII would benefit from ground truth measurements (e.g., ground-penetrating radar, drilling, etc.) from a mission such as LUPEX [13].

Terrain Type III. Impact gardening pushes ice deeper still, mixing it with dry regolith, and the seismic shaking that accompanied impacts compresses the ice-rich regolith into layers >1m beneath the surface [9]. Due to the depth, analyses would require higher data resolution than TTI and TTII. If ice was interbedded with regolith, the difficulty in this case would depend on the thickness of the beds. Thicker beds would be detected with radar, but deeper, thinner beds likely would not be detected by neutron measurements, although ground penetrating radar instrument development is ongoing at the University of Notre Dame that may resolve this. However, surface drilling >1 meter is a technology development that is necessary to quantify water-ice deposits at such depths. Data collected from missions that have the capabilities to drill into the lunar surface, such as VIPER's TRIDENT and LUPEX, would be useful in investigating at depth [11,13].

Discussion: For economically-viable water-ice reserves to be defined for the Moon, a concerted international effort must be launched. The surface area of the top ten targets of lunar polar volatiles exceeds 6000 km^2 [14] and is too large an undertaking for one nation or organization to attempt alone [2]. Coordinating existing missions is a way to undertake a resource prospecting campaign that can involve multiple nations without diverting valuable resources to establish such a campaign [cf. 2]. Current data fidelity is not at a sufficient level to assess the reserve potential of lunar polar volatiles. Until the feasible resources test line is crossed to stimulate commercial involvement (transition from "inferred" to "indicated" resources [3]), demand for commodities on the lunar surface is undefined and uncertain. Without demand, the extent of reserves cannot be determined. The first step towards understanding reserve potential of water-ice is high fidelity orbital and ground data acquisition at the meter-decameter scale. Further lunar exploration also needs to consider what levels of data are needed for determining the "extractability" of ice on the Moon - i.e., the geotechnical properties of the ice deposits.

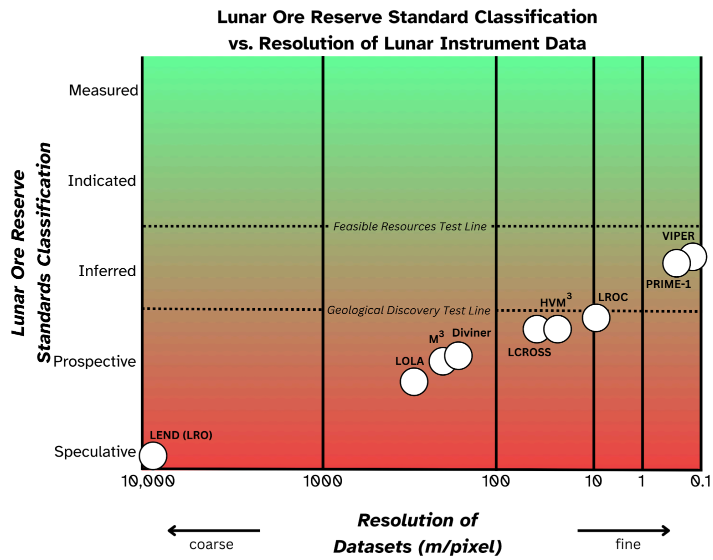

Figure 2. LORS classification [3] versus resolution of datasets from various orbital and surface lunar missions from [2]. 'Geological Discovery Test Line' indicates a resource is inferred. 'Feasible Resource Test Line' signifies a resource is indicated and may be a candidate for economic extraction.

Conclusion: Current and scheduled lunar missions are supplying data that are needed to define indicated polar water ice resources. Future landed missions to other areas are needed to continue this progression.

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