LUNAR PYROCLASTIC DEPOSITS: AN ACCESSIBLE AND QUANTIFIABLE LUNAR RESOURCE

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Introduction: In light of current NASA plans to return humans to the Moon sometime in the next decade [1], it is logical to take advantage of the new information being returned by current and projected robotic lunar precursor missions in order to reassess the location, quantity, and accessibility of available lunar resources, which are essential for maintaining and increasing the scope of a permanent human space presence [2,3]. Planning and studies performed now can enhance the chosen human lunar return architecture, as well as influence future missions and site selection for the Lunar Robotic Precursor Program.

Of the commonly cited possibilities for lunar resources, one of the most easily accessible and numerous resources are lunar pyroclastic deposits. These lunar volcanic products are scattered about the lunar surface and can be effectively characterized using remote sensing techniques (e.g., [4-8]). New global lunar datasets, such as the global imaging expected to be returned by the Lunar Reconnaissance Orbiter Camera instrument [9] and global hyperspectral data from instruments such as the M3 instrument on the Chandrayaan spacecraft [10] are currently projected to exist within the next several years. These new data will permit considerable improvement in the assessment of the resource potential of lunar pyroclastic deposits, including their location, volume, composition, and accessibility.

Background: Lunar pyroclastic deposits are among the most common and most accessible potential lunar resources, as outlined in [11-12] and many other references. Also referred to as dark mantle deposits, these materials are low-albedo deposits that subdue and mantle the adjacent terrain. Investigators agree that these materials are of pyroclastic origin and a product of processes resembling a terrestrial fire-fountaining volcanic eruption [e.g., 13-14, 4].

There are two kinds of lunar pyroclastic deposits. *Localized Dark Mantling Deposits* are associated with endogenic dark halo craters. These craters lack obvious rays, are non-circular in shape, and aligned along floor fractures and lineaments [15]. Localized pyroclastic deposits are compositionally diverse and can be divided into three distinct groups: Class 1 localized dark mantling deposits are composed of highlands materials with minor olivine and volcanic glass. Class 2 localized dark mantling deposits are composed of fragmented mare basalts. Class 3 localized dark mantle deposits are comprised of mafic materials and dominated by olivine and pyroxene. Because of this compositional variability, the localized deposits are considered to be less immediately useful as a direct resource, but more studies are clearly needed in order to more fully evaluate their resource potential.

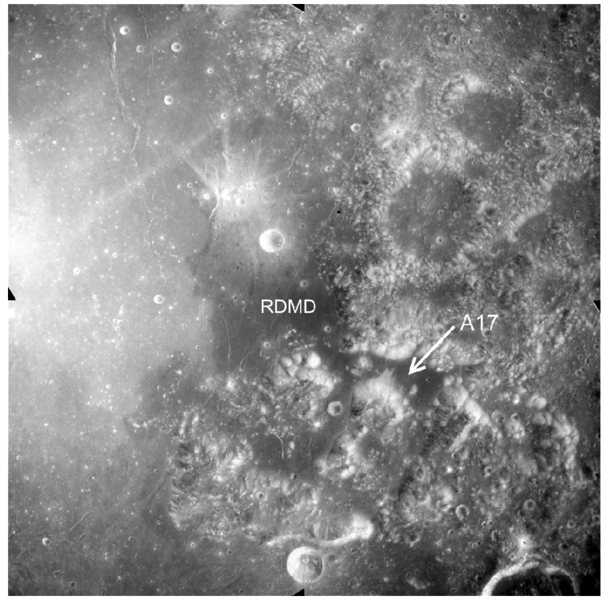

Figure 1: Apollo 15 metric mapping photograph AS15-M-0972, showing the Taurus-Littrow region and the large regional pyroclastic deposit located to the northwest of the Apollo 17 landing site. This is the only regional dark mantling deposit (RDMD) which has been directly sampled, and it is currently unknown whether its composition is representative of other RDMDs [NASA/JSC/Arizona State University].

The second major group of lunar pyroclastic deposits are the *Regional Dark Mantling Deposits*, or RDMDs. RDMDs are predominantly composed of picritic glasses of volcanic origin. These glasses represent the most primitive (i.e., unfractionated) materials in the lunar sample collection. Therefore, chemical analyses performed concurrently with the large-scale resource processing of pyroclastic materials will be uniquely useful for improving our understanding of both the composition and evolution of the lunar interior and lunar rocks [16-19].

Two kinds of RDMDs can be discerned based on currently available spectral data. The first type of RDMD is characterized by broad, long-wavelength absorption features and probably contain Fe^{2+}-bearing volcanic glasses. The large RDMD near the Aristarchus plateau [4] is an example of this type of deposit. The second class of RDMD is dominated by ilmenite-rich black spheres of pyroclastic origin. Examples of this kind of pyroclastic deposit include the RDMDs located near Taurus-Littrow (shown in Figure 1), Rima Bode, Southern Mare Vaporum, and Southern Sinus Aestuum [4]. RDMDs cover very large areas (up to 50,000 km^2), are tens of meters thick, and overlie both highlands and mare substrate. RDMDs are essentially uniform in composition and are generally not contaminated by surrounding highlands materials, an important consideration for designing both industrial processes and flight hardware. RDMDs were directly sampled at the Apollo 17 landing site at Taurus-Littrow, but it is currently unknown how representative the samples collected at that site are of other RDMDs.

Resource Potential: The economic utility of lunar pyroclastic deposits have been outlined by many previous workers (e.g., [11], [20]) and can be generally divided into short-term and long-term resource applications. Briefly, lunar pyroclastic deposits have several short-term advantages as locations for permanent lunar outposts. Pyroclastic deposits are fine-grained, well-sorted, and boulder-free (or nearly so). This means that machinery and processing equipment can be designed to meet narrowly-defined performance parameters, which will reduce development time and cost. This uniform grain size (approximately 40 µm, based on studies of Apollo samples) also means that pyroclastic materials can be easily moved and used as cover in order to rapidly provide the necessary radiation and thermal protection for lunar habitats, with a minimum of processing and equipment. Since at least 3m of protection is believed to be required to effectively shield a lunar outpost from the ambient radiation environment, this rapid *in-situ* shielding capability is an important consideration for crew health and safety.

As detailed in many studies, lunar pyroclastic deposits can also be used to produce oxygen [e.g., 21-22]. This is a useful capability in the event that the hypothesized lunar polar ice deposits prove to be inaccessible, or present in economically non-useful quantities. Oxygen production from ilmenite-rich pyroclastic materials using hot hydrogen reduction processes has been extensively studied, the processes behind it are well-understood, and the process itself produces the most oxygen of currently proposed lunar oxygen-production processes [23-25]. In the long-term, *in-situ* lunar oxygen production is a key enabling technology for the continuing development of cislunar space [26] and reducing the costs of a lunar outpost.

Other long term resources that could be potentially extracted from RDMD materials include solar-wind implanted volatiles such as H, He, He-3, N, C, and other noble gases ([9],[11],[20]), which would provide important life support materials as well as agricultural nutrients for a lunar outpost. Studies of lunar volcanic glasses returned by the Apollo missions also revealed sublimates including Zn, Pb, Cu, K, Na, Cl, and Ga coating the grain surfaces [27-28]. These sublimate products are important, since they could easily be extracted through heating and are therefore the most accessible currently-known lunar ore ([28],[9],11]). Identification of large concentrations of sublimates from orbit is therefore high priority of future investigations [20].

Future Work: **T**he datasets from forthcoming lunar precursor missions should be aggressively used to more fully characterize lunar pyroclastic deposits. Future efforts will include placing further constraints on the composition of lunar pyroclastic deposits, assessing possible compositional diversity within and between pyroclastic deposits, and determining the resource potential of localized dark mantling deposits.

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