SCIENTIFIC EXPLORATION OF MARE IMBRIUM WITH ORBITBEYOND, INC.: CHARACTERIZING THE REGIONAL VOLCANIC HISTORY OF THE MOON.

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Introduction: OrbitBeyond, Inc., a new US-based lunar transportation company [1], plans to send its first mission to the Moon in 2020. In collaboration with TeamIndus and their other partners, OrbitBeyond will touch down their Z-01 lander on smooth lunar volcanic plains. Among other payloads, the lander will carry the *Ek Choti si Asha* (ECA) rover [2]. The micro-class ECA rover, weighing only 7.5 kg, was engineered primarily to safely traverse the lunar surface while acquiring high-definition images and video; the rover was not designed with particular scientific goals and objectives in mind. However, the ECA rover will be traversing across Mare Imbrium, an ancient impact basin that has a rich and diverse volcanic history [e.g. 3-5], and thus the OrbitBeyond Z-01 mission offers an opportunity to perform science operations that can increase our understanding of lunar geologic history.

A group of students at Brown University have been working closely with engineers at OrbitBeyond and its partners through a collaborative project that stemmed from the SSERVI-sponsored class, "Origin and Evolution of the Moon" [7] that was offered at Brown University in the Fall 2018 semester. Because the Z-01 mission is going to a location that contains critical information for understanding the origin and evolution of the Moon, we have set out to explore ways to optimize the scientific return of the mission through the development of a Design Reference Mission (DRM) to Mare Imbrium. Our goal is to characterize the Z-01 landing site from a scientific and geologic perspective and define key scientific goals that can be accomplished by the lander and rover during the 10-Earth-day mission lifetime. The scientific return is analyzed for two cases: Case 1, in which we consider the current, nominal rover payload [1], and Case 2, in which we consider the addition of one instrument to the rover.

Landing Site: The landing site (29.521°N, 25.680°E) is located within Mare Imbrium, an impact basin that has been flooded and resurfaced by multiple volcanic events over a period of ~1.5 Gyr (Fig. 1) [e.g. 3,4]. The regional volcanic history is notoriously complex; over 30 distinct mare units have been mapped within Mare Imbrium based on a variety of orbital data, such as Clementine composition maps, radar data, and color images [e.g. 3,4,6]. The landing site is located within one of the youngest mare units on the Moon, estimated to be ~2.3 Gyr old (Fig. 1) [4]. Some flow fronts can be observed in the vicinity of the landing site in low-illumination images and detrended topographic data [8]. Thus, the Z-01 mission and exploration of this region of Mare Imbrium has the opportunity to help us understand the characteristics and dynamics of degassing of magma late in lunar history [e.g. 9].

Additionally, the landing site is located in a region of anomalously high-Ti basalts [5]. High-Ti basalts are believed to be strongly connected to the overturn and remelting of early lunar deposits [10]; exploration of the younger Ti-rich flows in Mare Imbrium offers the possibility to better understand the evolution of lunar melts and mantle heterogeneity through time.

Understanding the reasoning for the anomalous characteristics of this region, including the young flows and high TiO_2 signature, can also provide important insight into geologic variations between this location and other locations that have been visited by previous lunar missions.

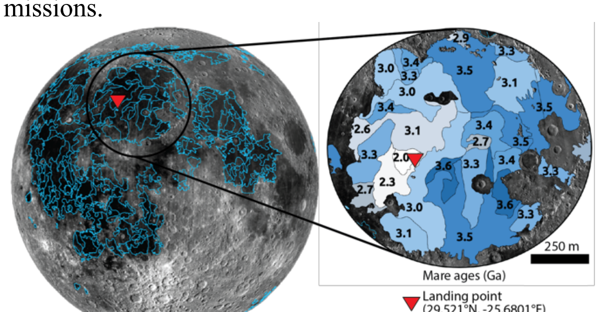

Fig. 1. Landing site is marked by a red triangle with respect to the nearside (left) and Mare Imbrium (right). All mare units are outlined in blue on the left [4]. On the right, mare units within Mare Imbrium are colored with respect to age, where older terrains are in blues and younger terrains are in grays [4].

Overall, the exploration of Mare Imbrium can improve our understanding of (1) the generation, ascent, and eruption of magma on the Moon, (2) the thermal evolution of the Moon, and (3) regional geologic variations. We label these three topics as the key scientific goals of the mission (Table 1) and explore possible ways to accomplish these goals with our DRM.

Scientific Returns: For the first part of our DRM, we outlined the scientific return the lander and rover can achieve for both Cases 1 and 2.

Case 1: Nominal Payload. Table 1 outlines scientific objectives that the lander and rover can address to fulfill the key scientific goals of the mission. These objectives can be achieved using the lander and nominal rover instrumentation, primarily through utilization of the navigation (mast, hazard, and rear-facing) cameras onboard the rover [e.g. 11]. Cameras can be used for (a) local geomorphic and geological analyses, (b) investigation of macro-scale geologic and petrologic textures,

(c) analysis of grain sizes and shapes, and (d) quantitative measurements of surface features using stereo-derived digital elevation models. Other instruments can also be used to accomplish the objectives and enhance scientific return: (e) lander accelerometer to monitor meteorite bombardment or moonquakes, (f) lander descent cameras to repeatedly image the surface for change detection analysis after landing and for the duration of the mission, (g) rover wheels to study material underlying displaced regolith, and (h) rover wheels for measurements of required torque levels for movement to gauge physical properties of the regolith.

Case 2: One Additional Instrument. We propose the integration of an x-ray fluorescence spectrometer (XRFS) onto the rover, which can evaluate bulk chemistry at pin-point locations, requires little additional cost, space, or power, and is currently in development for spaceflight [12]. Additional objectives that the rover can address with an XRFS are outlined in Table 1 in italics.

Goals	Objectives
Generation, ascent, and eruption of magma on the Moon	1. Characterize vertical stratigraphy and sequence of the flows using impact craters and excavated material. 2. Measure thickness of individual flows. 3. Characterize variation in flow extent, topography, and geometry of flows. 4. Characterize regolith and protolith and compare to previous mission data.
The thermal evolution of the Moon	1. Measure distribution, shape, and size of vesicles in flows. 2. Measure texture and grain size in flows. *3. Use in-situ chemical analyses to determine the age of individual lava flows in the region.* *4. Determine bulk composition of flows.* *5. Determine mineralogy of flows.*
Regional geologic variations	1. Place results in context of past mission data. 2. Collect diagnostics on hardware performance and environmental conditions throughout the mission. *3. Determine any vertical and lateral variations in the major element chemistry and mineralogy of flows.* *4. Characterize space weathering effects on flows and in nearby areas.* *5. Characterize bulk petrology and mineralogy of individual rock samples, outcrops, or suites that may be of historic interest, or of similar composition and origin to returned samples.*

Table. 1. Key scientific goals and objectives to complete with Cases 1 and 2 in our DRM. In the objectives column, regular text is for objectives possible in Case 1, italics for Case 2.

Traverse Algorithm: With the key scientific goals and objectives defined (Table 1), as the second part of the DRM we identified specific targets to visit and observations that must be made at these targets in order to address the scientific goals and objectives. The targets are fresh craters, crater ejecta, volcanic flows, and regolith. Specific observations include (a) imaging crater stratigraphy to identify exposed lava flows and then make specific measurements to constrain characteristics of lava emplacement through time, such as the role of volatiles, depth of magma generation, and viscosity of magmas, (b) imaging disturbed regolith along wheel tracks to characterize grain size and cohesion of the regolith, and (c) imaging contacts between crater ejecta and nearby regolith to characterize variations between fresh and degraded material. To ensure completion of many of these observations, the targets are inputs for the rover traverse algorithm (e.g. Fig. 2), which also takes into account engineering constraints such as slope, driving direction, and presence of hazards.

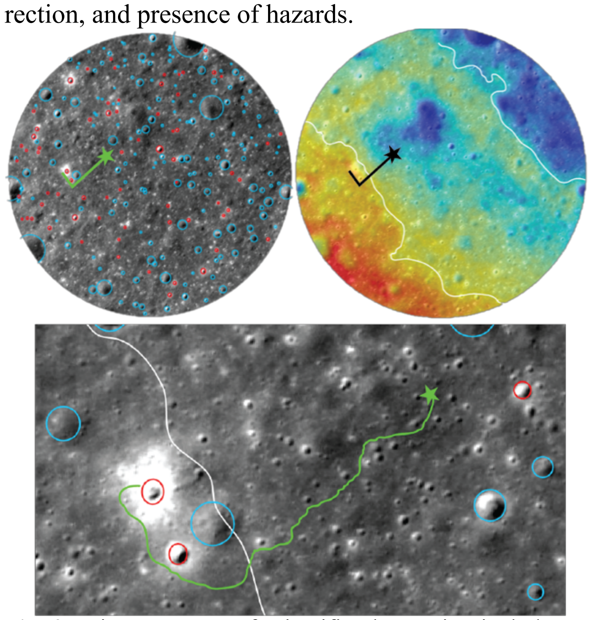

Fig. 2. Primary targets of scientific observation include craters, ejecta, volcanic flows, and regolith. Example landing spot as star and traverse path as lines. (top, left) All craters >10 m in diameter are circled in blue and those that appear morphologically fresh are circled in red. (top, right) Putative lava flows identified in topography and NAC low-illumination images are traced in white. (bottom) Zoom on potential traverse, avoiding craters, traversing lava flows, and approaching a fresh crater rim.

Conclusions: In this new, exciting wave of private investment and partnerships, our abilities to explore the Moon are growing. In this work, we present an example of scientists and engineers working together to explore the lunar surface and address key scientific goals. The science and engineering synergism between Brown University and OrbitBeyond provides a unique collaborative framework for future commercial scientific space exploration.

References: [1] www.orbitbeyond.com [2] www.teamindus.in [3] Bugiolacchi, R. and Guest, J. (2008), *Icarus*, *197*, 1-18. [4] Hiesinger, H. et al. (2010), *JGR Planets*, *115(E3),* E003380. [5] Zhong, S. et al. (2000), *EPSL, 177,* 131-140. [6] Morgan, G. et al. (2016), *JGR Planets*, *181(8),* 1498-1513. [7] www.planetary.brown.edu/html_pages/geo2870_2018-2019.html [8] Kreslavsky, M. et al. (2017), *Icarus, 283,* 138-145. [9] Wilson, L. and Head, J. (2018), *GRL, 45,* 5852-5859. [10] Shearer, C. et al. (2006), New Views of the Moon, p.365-518. [11] Virmontois, C. et al. (2016), *LPSC47,* Abstract 2862. [12] Kraft, R. et al. (2018) *AGU*, P21E-3403.