Identification of Science-rich Mission Sites Designed to Test the Lunar Magma Ocean Hypothesis.

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Introduction: One of the eight concepts identified by the NRC for NASA's Vision for Space Exploration is that the crustal diversity can be used to further comprehend the key processes that shaped the moon, as well as constrain evolutionary models [1]. Key planetary process especially include differentiation, volcanism and impact craterization [2].

Concept 3 of the NRC report is subdivided into 5 goals, the first of which is to 'Determine the extent and composition of the primary feldspathic crust, (ur)KREEP layer, and other products of differentiation'. This goal constitutes one of the top-eleven priority science goals of the NRC report [1]. Primordial rock types, which are thought to be products of the magma ocean solidification and differentiation, are indeed key samples to collect as they would bring crucial information on the Early Moon and its formation. To help implement that exploration program, we surveyed lunar surface locations that will meet that objective.

The Lunar Magma Ocean (LMO) hypothesis: According to most widely-accepted lunar formation models, the Moon was completely molten to a depth of hundreds of kilometers right after its accretion [3]. As inferred from studies of Apollo lunar samples, the cooling of this magmatic ocean led to the process of planetary differentiation, with denser crystallized material like pyroxene and olivine sinking, and lighter material like plagioclase-rich cumulates floating to form the upper crust. According to this hypothesis, the resulting Moon is expected to be layered in a plagioclase-rich upper crust, a more mafic-rich lower crust, an incompatible-rich (ur)KREEP layer, a mafic-rich mantle, and a possible core [4]. Moreover it has been suggested that the composition and extent of these different layers may also vary laterally, as regions of different geochemical signatures (or terranes) have been identified on the Moon [5]. Determining the vertical and lateral heterogeneity of the Moon is key to the understanding of lunar formation, and can even provide insight onto similar processes on other terrestrial bodies. However, thorough investigation of the lunar structure requires multiple sample locations.

Requirements for sites selection: We need to target sites with potential to yield representative samples of planetary differentiation products (primordial anorthositic crust, lower crust, urKREEP, mantle). The variety of lunar highlands types and the existence of several distinct geochemical terranes have to be taken into account. The extent and variability of layer thickness may also play an important role in the formation process. In particular, the urKREEP layer might be patchy in scope rather than ubiquitous, possibly providing an explanation to the asymmetry of the lunar crust [6]. For such reasons, sites likely to contain urKREEP material are targeted in priority [5].

Suggested landing sites: The best sampling sites were determined for each of the differentiation products, and then integrated to identify the best landing sites to test the entire LMO hypothesis.

Primordial feldspathic highlands material: The primary feldspathic crust is expected to be a ferroan-rich anorthosite, with very high and nearly pure plagioclase content [4, 7, 8]. Therefore sites to investigate are the highland areas and the recent purest anorthosite (PAN) detections. PAN detections are abundant in almost all the fresh craters that are larger than 30 km in diameter, leading to the idea that there might be an ubiquitous PAN layer buried under the mixed and breciated surface material, at least in the highland area [9]. This PAN layer might represent remnants of the ancient upper crust. Highlands are also expected to be made of feldspathic material derived from the ancient upper crust. However, recent studies of the feldspathic highlands [10, 11] suggest that not all highlands material is derived from the LMO; other formation processes may have led to various highland types. *Chevrel et al.* [10] identified and mapped at least 5 highland types; the types 'H1' and 'H2', abundant in the FHT terrane defined by [5] may correspond to the most pristine highland material. Highland samples are rare in the Apollo collection, and correspond mainly to highland types H3 and H5, which are Thorium-rich units. Sampling H1 and H2 material in their original geological context is consequently needed and could be done in young craters impacting those highland types, as we expect fresh outcrops of exposed material there.

Lower crust and mantle material: As the lower crust and mantle layers should not typically be exposed on the lunar surface, the best way to observe material from depth is through impact cratering processes [8]. There are 3 locations in the vicinity of an impact crater where this material could be sampled: the ejecta, the central peak (or peak rings), or the melt sheet. To determine where the lower crust or mantle could be sampled on the surface of the Moon, impact excavation depth and melt depth were calculated using equations from [12, 13]. Excavation depth provides information on the depth of origin of ejecta material. Conversely, melt depth estimates the depth of origin of material contained within impact melt, and also provides a minimum limit to the depth of origin of the uplifted central peak/peak ring material. Values were compared with the crustal thickness estimates from [14] to infer where the mantle or lower crust should have been sampled and could be exposed at the surface on the Moon. These calculations are similar to proximity calculation of *Cahill et al.* [15, 16]. Results shows that there are hundreds of craters that could have tapped into the lower crust, containing some of this material in their melt sheet or central peaks; on the contrary, less than 40 craters (all basins) might contain mantle material in their melt or peak rings [2]. LOLA data was used to find out which of these craters or basins have preserved central peaks or peak rings, and can be considered as good sampling sites. Recent olivine detections from the Kaguya mission [17] were also considered as they might indicate mantle outcrops. More mafic detections with recent high-resolution spectral-imagers are to come and could also be good indicators of the presence of lower crust or mantle.

urKREEP material: The concept of an urKREEP layer was first introduced after the return of the Apollo samples and the emergence of the magma ocean theory [18]. The urKREEP layer is believed to correspond to the last liquid that crystallized from the magma ocean, and is expected to be rich in incompatible elements. Pristine urKREEP material has never been sampled, though the Apollo collection does contain many KREEP basalt samples, believed to be mafic cumulates which assimilated urKREEP material. As the urKREEP layer is expected to have been sandwiched between the lower crust and mantle, all basins excavating mantle material should also have excavated urKREEP material, assuming that the urKREEP layer is global. If not, other methods were developed to determine the layer's composition and extent [2, 6]. In particular, basins with KREEPy geochemical signatures (primarily based on Th abundance) should be higher priority targets as they are more likely to contain urKREEP material.

Final science-rich mission sites: Assuming a 10 or 20 km traverse range for a mission on the lunar surface, there is not a single place where all the differentiation products can be sampled for sure. Finding locations that will yield representative samples of each of the differentiation products implies multiple landings at different sites. Moreover, assessing the structural heterogeneity of the Moon's interior is key to its understanding, and requires samples originating from a diverse range of depths and varied geographical distribution. Generally speaking, impact craters, and especially central peaks, are best locations to assess the LMO hypothesis. A list and corresponding map of all the possible final landing sites should be presented at the conference.

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