LUNAR LANDING SITES TO EXPLORE THE EXTENT OF KREEP AND ITS SIGNIFICANCE TO KEY PLANETARY PROCESSES.

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Introduction: As part of the nation's Vision for Space Exploration, the National Research Council (NRC) published a report in 2007 entitled *'The Scientific Context for the Exploration of the Moon'* [1]. This report outlines 8 main concepts of lunar science that are to be addressed by further human and robotic exploration. One of those concepts (#3) states that "key planetary processes are manifested in the diversity of crustal rocks" and lays out the objective to determine the extent and composition of a potential K, REE, and P-rich (KREEP) layer that was produced by global differentiation and subsequently modified by magmatism and impact cratering [1]. To help the program achieve that objective, we conducted a global survey of the Moon to locate potential landing sites where the extent of KREEP can be evaluated.

Relevance of KREEP: Analysis of returned samples from the Apollo missions led to the discovery of a material enriched in incompatible and heat-producing elements, named KREEP [2]. Since its discovery, KREEP has been implicated as a critical marker of several key planetary processes.

Significance to Lunar Magma Ocean. The Lunar Magma Ocean (LMO) hypothesis states that the Moon was molten to great depths directly after accretion [3]. As material cooled, planetary differentiation processes triggered a segregation of chemical constituents, leaving a thin layer rich in incompatible elements wedged between an anorthositic crust and a mafic mantle. This (ur)KREEP layer (the ur- prefix meaning primitive or original) represents the last liquid to crystallize from the lunar magma ocean [2]. Though it occupies < 1% of the lunar magma ocean by volume, the urKREEP is thought to have contained about half of the Moon's incompatible elements [2] and is nevertheless a very important part of the LMO model.

Lateral and vertical extent of KREEP. The urKREEP layer has been estimated to be approximately 2 km thick, assuming an average crustal thickness of about 40 km and initial global distribution [2]. However, remote sensing results from recent missions such as Lunar Prospector and Clementine question the global extent of this theoretical layer [4]. Observations of patchy incompatible element abundances on the lunar surface may suggest an asymmetrical distribution of urKREEP [5], making it a regional attribute of the aptly named Procellarum KREEP Terrane (PKT) (e.g., [4, 6]). The primordial urKREEP layer has not been sampled by any missions or meteorites, making urKREEP material a priority sample in order to constrain its putative existence and debated distribution.

Significance to Magmatism and Impact Processes. On the other hand, the analyses of Apollo samples (especially from Apollo 14, 15, 12) [7, 8] did show the existence of KREEP-basalts with unique mineralogy [5] and a different geochemical signature than the hypothetical primordial urKREEP material [9]. KREEP-basalts are thought to originate from deep mantle plumes that plowed through the urKREEP layer, thus assimilating some urKREEP material along the way [9]. Therefore we define urKREEP as the primordial remnant of the LMO hypothesis, and KREEP-basalts as a product of later lunar magmatism.

The large abundance of heat-producing elements in KREEPy material may have led to slower crystallizing rates or partial melting of crustal material [6]. In addition, a patchy extent of the urKREEP layer primarily existing in the PKT region of the lunar nearside could explain the crustal dichotomy of mare flooding [6]. Large impacts into KREEP-rich regions redistribute the KREEP material across vast distances, acting as a tracer for the material's origin. It is also possible that large impacts have probed deep enough to expose primordial remnants of the urKREEP layer.

Methodology: We present two methods to identify landing sites with potential to yield important information about the extent and composition of KREEP.

'Top-down' method. We analyze geochemical maps of thorium, samarium, and potassium, which are indicators of KREEP-rich material [4, 7], and locate regions where these elements show the strongest signature. We target well-preserved craters, such that samples may be representative of that area.

'Bottom-up' method. In the case of a global urKREEP layer sandwiched between the crust and mantle, it is safe to hypothesize that all impacts that tap into the mantle should also sample any overlying urKREEP unit. Thus, we identify craters from the Lunar Impact

Crater Database that potentially sampled material from the ancient urKREEP layer, either by excavating it intact or incorporating it in impact melt [11, 12].

Results: The 'top-down' method yields a map of KREEP-rich regions on the Moon, mostly occurring within the PKT. In addition, there are some small scattered areas of high KREEP signature within the South Pole-Aitken Terrane, and an anomalous region near Compton crater. Utilizing the 'bottom-up' method of exploring the extent of the urKREEP layer, we identify 43 craters that may have sampled urKREEP material and incorporated it within their central peaks or melt sheets.

Discussion: Potential landing site locations have been determined through a combination of the 'top-down' and 'bottom-up' methods. In the case of a global urKREEP layer, the identified craters should all show geochemical evidence of KREEP either in the central peak or within the melt sheet. We find that interestingly, not all of the craters from the 'bottom-up' method show high KREEP signatures. This may confirm a patchy lateral extent of the urKREEP layer, in support of heterogeneous urKREEP models (e.g., [5, 12]). However, it is possible that the features are covered by layers of regolith, therefore hiding the urKREEP signature. We categorize craters of interest into two groups: features with a KREEPy geochemical signature, and features with no distinct KREEP signature.

The high-KREEP-bearing craters (bright red circles in Fig. 1) could provide representative samples of KREEP-rich material, possibly even pristine samples of urKREEP. Craters outlined with light pink lines in Fig. 1 represent areas that do not show incompatible material in the superficial layer, yet are thought to have excavated urKREEP material from the proximity model in the 'bottom-up' method. Such craters are of interest to explore the patchy nature of the urKREEP, and to identify what exists at the crust-mantle boundary if not a layer of KREEP-rich material.

Conclusion: In choosing landing sites for the goals within Concept 3 of the NRC report [2, 8, 13], we target sites that help constrain the thermal, physical, and chemical models of KREEP. Our survey identifies a sufficiently large number of landing sites that are so geographically distributed that candidates can be further down-selected based on their ability to address other objectives of [1]. Sites in Fig. 1 that are on the farside, however, have a higher priority than those on the nearside, as Apollo has provided nearside data.

Acknowledgements: This work is part of the 2010 LPI Lunar Exploration Summer Intern Program funded by the NLSI through the LPI-JSC Center for Lunar Science and Exploration. We are especially grateful to the LPI staff for their help and support throughout the program.

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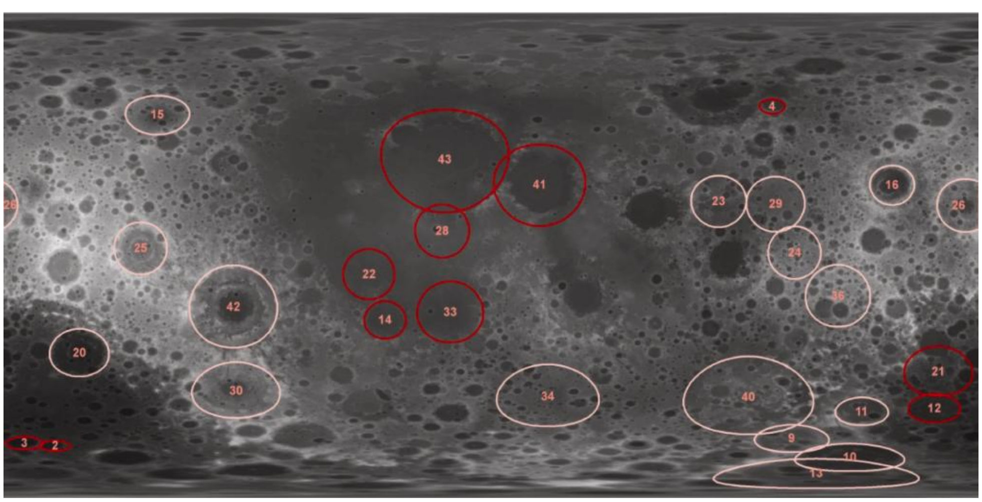

Figure 1. Map of sites for determining the extent of KREEP. Bright red indicates high KREEP signature, light pink indicates low. Background: LOLA topography.