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Identification and characterization of science-rich landing sites for lunar lander missions using integrated remote sensing observations

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Abstract

Despite more than 52 years of lunar exploration, a wide range of first-order scientific questions remain about the Moon's formation, temporal evolution, and current surface and interior properties. Addressing many of these questions requires obtaining new *in situ* analyses or return of lunar surface or shallow subsurface samples, and hence rely on the selection of optimal landing sites. Here, we present an approach to optimize science-rich lunar landing site selection studies based on the integration of remote sensing observations. Currently available remote sensing data, as well as features of interest published in the recent literature, were integrated in a Geographic Information System. This numerical database contains geographic information about all these findings, which can be consulted and used to simultaneously display multiple features and parameters of interest. To illustrate our approach, we identified the optimal landing sites to address the two top priorities (or goals) relative to Concept 3 of the National Research Council of the National Academies (2007), namely to 'Determine the extent and composition of the primary feldspathic crust, (ur)KREEP layer, and other products of differentiation' and to 'Inventory the variety, age, distribution and origin of lunar rock types'. We review site requirements and propose possible landing sites for both these goals. We identified 29 sites that best fulfill both these goals and compare them with the landing sites of planned future lunar lander missions. Finally, we detail two of these science-rich sites (Aristarchus and Theophilus craters) which are particularly accessible through their location on the nearside.

Keywords: Moon; Landing sites; Exploration; Remote sensing; Database; Crustal diversity

1. Introduction

In the wake of the publication of the NASA Vision for Space Exploration (January, 2004), major publications by Jolliff et al. (2006) and the US National Research Council of the National Academies (NRC, 2007) highlighted the main remaining scientific challenges and opportunities for future lunar exploration missions. The NRC report provided a clear overview of priorities and recommendations for scientific lunar exploration, summarized in Table 1. Many of the scientific priorities listed in Table 1 require performing *in situ* analyses of lunar surface or shallow subsurface samples, and hence rely on the selection of optimal landing sites. Successful missions by the USA (Clementine,

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Table 1
List of the top 11 lunar science priorities (NRC, 2007).

Priority	Goal	Title
1	1a	Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins
2	1b	Anchor the early Earth–Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin)
3	1c	Establish a precise absolute chronology
4	4a	Determine the compositional state (elemental, isotopic, mineralogical) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions
5	3A	Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation
6	2a	Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales
7	2b	Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle
8	8a	Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity
9	2c	Determine the size, composition, and state (solid/liquid) of the core of the Moon
10	3B	Inventory the variety, age, distribution, and origin of lunar rock types
11	8b	Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy

Lunar Prospector, Lunar Reconnaissance Orbiter LRO/LCROSS), Europe (SMART-1), China (Change'E-1 and Chang'E-2), Japan (SELENE), and India (Chandrayaan-1), and state-of-the-art analyses of Apollo-era samples and data are rapidly expanding the database that can be used for landing site selection studies. In the coming years, the quantity and quality of lunar remote sensing data is expected to increase even further through institutional agency science missions such as LADEE, GRAIL, Luna-Glob 1, and Chandrayaan-2. In addition, several agencies are developing lunar lander missions (*e.g.,* ESA Lunar Lander, Chang'E-3 and -4, Luna-Glob 2, Luna-Grunt, SELENE-2), and there is the distinct possibility of non-agency missions to the lunar surface carrying small scientific payloads, for example through teams vying to win the Google Lunar X-Prize (GLXP) (http://www.googlelunarxprize.org).

The widening range and improving quality of recent and upcoming remote sensing data form an ideal basis for performing landing site selection studies. Here, we show how the integration of a large range of available datasets (obtained at different spatial resolutions from different missions) can be employed to identify lunar landing sites with maximum scientific potential. We gathered, processed, and geo-referenced many available datasets from previous lunar orbital missions into a Geographic Information System (GIS) which provides mapping and calculation tools. We also included information from sections of as yet unreleased datasets that were published in recent literature, as well as estimates of the depth of origin of material found in impact craters. The GIS provides a complete numerical database of older and recent lunar findings, which can be consulted and used to display features and parameters of interest.

In principle, our methodology can be applied to the selection of optimal landing sites for lunar landing missions of any type and size (i.e. lander only, lander plus rover, manned landings), and for addressing any of the prioritized NRC report goals listed in Table 1. We illustrate our

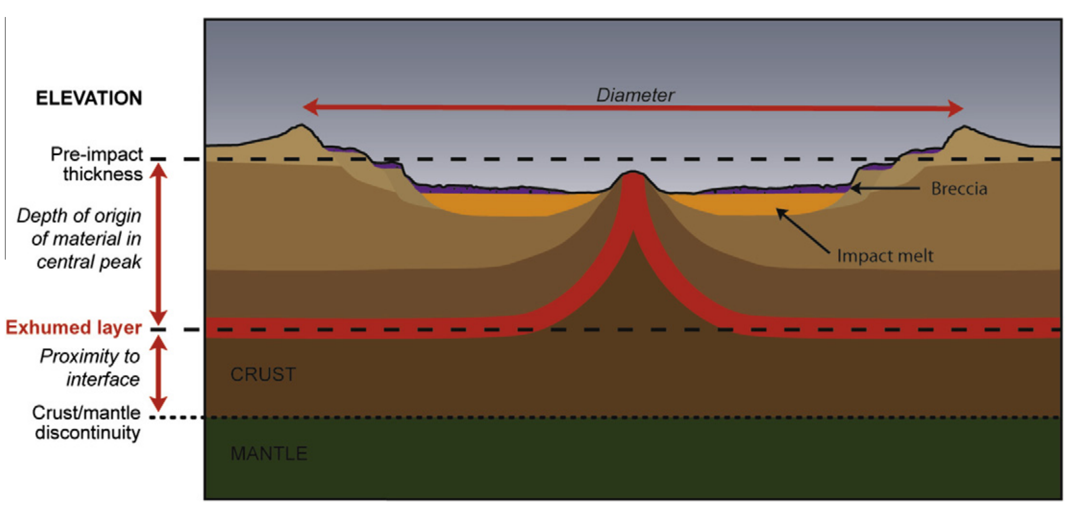

Fig. 1. Schematic cross section of a complex impact crater exhuming deep layers in its central peak. For each of these craters the proximity to the lunar crust-mantle boundary was calculated by subtracting the depth of origin (D_e or D_m, excavation depth and melting depth, respectively) from the crustal thickness (T). Here proximity to the crust-mantle boundary (P_m, melt proximity) via the maximum depth of origin is illustrated.