LUNAR CRUSTAL ROCK TYPES, GLOBAL DISTRIBUTION, AND TARGETING.

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Introduction. The Apollo samples provide a first-order understanding of the makeup of the lunar crust - its composition, mineralogy, and rock types [1-3]. On the basis of these samples, much has been inferred about the conditions under which these materials formed within the crust as well as the early evolution of the Moon's crust and mantle. Crustal rocks are dominated by three silicate mineral groups: olivine, pyroxene, and plagioclase. Lunar rocks are virtually anhydrous and crystallized at low oxygen fugacity and relatively low pressure. The dominant igneous crustal rock types are thus anorthosite, norite, troctolite, and intermediate types (e.g., anorthositic norite). In lunar crustal rocks, low-Ca pyroxene (orthopyroxene and pigeonite) is more abundant than high-Ca pyroxene (augite) although gabbroic rocks do occur among the samples. Rocks enriched in alkali elements and phosphorous, including alkali anorthosite, alkali norite, alkali gabbronorite, monzogabbro, and granite, are not abundant but are found, especially in samples from the western Apollo sites. Owing to known physicochemical conditions of the lunar crust, these are the rock types expected to occur throughout the Moon's upper crust, even in locations not directly sampled. This inference is supported by the observed mineralogy of lunar meteorites, which arguably provide a random sampling of the Moon's near-surface rock types, and by mineralogical remote sensing of the lunar surface.

Rock compositions, mineral chemistry, and isotopic characteristics allow subdivision of crustal igneous rocks into (1) the ferroan-anorthositic suite (early, primary crust, complementary to the mafic mantle that produced basaltic volcanism later in the Moon's history), (2) the magnesian suite (similar to the products of terrestrial layered mafic intrusives), and (3) the alkali suite, which represents more evolved chemical differentiates of magmatic processes. From these characteristics, an interpretation emerged of a relatively simple lunar crustal formation, with a post-accretion magma ocean solidifying rapidly to produce the ultramafic and dense lunar mantle, and a less dense, plagioclase-rich, buoyant crust. Remelting in the lunar mantle generated partial melts that rose into the crust, ponded, and formed layered mafic intrusions. Extended fractionation of some of these magma bodies produced chemically evolved alkaline rocks, and some may have erupted to form the compositionally distinctive but related KREEP basalts. Impact basin and crater formation melted and mixed these crustal rock types into a variety of impact-melt, fragmental, and granulitic breccias, along with the fine-grained debris that constitutes the regolith.

Global Remote Sensing. Global remote sensing missions of the 1990s – Clementine and Lunar Prospector – extended what was known from the Apollo and Luna landing sites and the narrow swaths of Apollo remote sensing to a global perspective, and the paradigm of the lunar crust changed significantly. These missions filled in details only hinted at by Apollo remote sensing. The data showed that surface expressions of crustal composition vary strongly and broadly across the lunar surface. The northern far-side highlands were found to be highly anorthositic (low-Fe, high-Al), even more so than the "type" highlands landing site, Apollo 16. The region where most of the Apollo landing sites occurred lay within the compositional influence of the Imbrium basin and its ejecta, and the global view provided by Lunar Prospector showed this region to be anomalously rich in chemically evolved crustal components and characterized by the compositionally distinctive KREEP signature. Further studies of the Apollo samples revealed a relationship between the magnesian- and alkali-suite rocks, and the suggestion arose that perhaps these rocks formed mainly in the Procellarum-Imbrium region, or the *Procellarum KREEP Terrane*. This area also appears to be a locus of crustal magmatism and extended volcanic activity, featuring some of the youngest surfaces on the Moon [4].

Another major terrane of the Moon is the area of the southern far side that is associated with the giant South Pole-Aitken Basin. Remote sensing shows that the interior of the basin still retains a distinct compositional signature that is relatively mafic (rich in Fe and Mg) and exhibits modest Th concentrations, although the latter are significantly less than concentrations found in the Procellarum KREEP Terrane. According to the size of the SPA Basin, we might expect contributions from upper-mantle as well as crustal components in its rocks, which may be impact-melt rocks or differentiated products of deep impact melt that now resemble rocks of igneous derivation.

Remote Sensing Approaches. Multispectral data from Clementine were used to investigate rock types in fresh exposures across the Moon in the form of central peaks of impact craters that mainly sample the upper crust [5]. Spectral characteristics of immature surfaces have also been used to map mineralogy globally [6]. These approaches complement global compositional remote sensing (gamma-ray) and provide a framework for the global distribution of crustal rock types. These methods rely heavily on the Fe^{2+} content of mafic silicates; however, Mg is not determined directly, and this is important to determine the distribution of ferroan vs. magnesian rock types. Recently spectral modeling by Lucey and Cahill [7,8] has been used to estimate Mg' globally; although promising, these results need further validation.

Despite efforts to deconvolve Mg contents (or Mg/Fe) from the remotely sensed data, the distribution of *ferroan* vs. *magnesian* rocks remains poorly known and one of the key remaining petrologic problems. Ferroan anorthosite as a rock type is well known; however, magnesian anorthosite, which is found mainly as a clast component in lunar meteorites, is much less common among the samples and its mode and place of origin in the lunar crust is not known [9]. Similarly, the origin (location and igneous rock precursors) of magnesian granulitic breccias, which are common among the Apollo samples, is not well understood [10]. Furthermore, most of the crustal rocks types appear to have shallow origins, so the composition of deep crustal rocks is not well known, either.

Another key lunar petrologic mystery is the distribution and extent of the more chemically evolved lunar crustal magmatic differentiates, the alkali-suite rocks, including granite and monzogabbro. To date, these rock types are found only as minor components in breccias and small rocks or rock fragments in regolith, mainly from Apollo 12, 14, and 15. Whether these rock types are concentrated in areas such as the Aristarchus region [11,12] and nonmare volcanic domes or spectral "red sots" [13,14] remains speculative.

What can the Lunar Reconnaissance Orbiter do to improve knowledge of lunar crustal rock types and their distribution? The main advances in furthering knowledge of rock-type distribution from fresh rock exposures is coming from high spectral- and spatial-resolution remote sensing by multi- and hyperspectral imagers (on Kaguya and Chandrayaan). LRO, through its camera systems, will contribute to these advances. The narrow-angle cameras (NACs) will provide the highest spatial resolution terrain imaging to date (0.5 m/pixel in targeted locations and perhaps 2 m/pixel global resolution if there is an extended mission with an appropriate orbit). These images will provide context for remote compositional data that can be used to better understand and deconvolve sources of variation in the data. Stereo images will enable high-resolution slope determinations and normalization of slope-induced illumination geometry effects [15]. Images taken at the boundaries between distinctive units will aide efforts to better understand mixing relationships.

The wide-angle camera (WAC) will extend multispectral data at a similar spatial scale to Clementine throughout the visible region (415 to 680 nm) and into the UV (315 and 360 nm); however, these data will be mainly applicable to the mineralogy of basaltic rocks (better determination of ilmenite content and possibly improved olivine detection, and to mapping out the distribution of volcanic glass deposits that span a range of Tiand color). WAC coverage will be global and targeted NAC images will include WAC color for context imaging. The main concern here is for targeting the NACs so as to best support compositional remote sensing of geologic features that are key to understanding compositional diversity of the lunar crust.

Important targets for the NACs in this regard include crater structures that reveal fresh rocks such as central peaks, crater walls and terraces, melt sheets, and impact ejecta deposits. Of particular interest are massifs that occur in the ring structures of impact basins as these – along with central peaks – reveal rock types exhumed from some depth in the crust. Other important targets include nonmare volcanic domes and contacts between compositionally distinctive units.

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