

THE COMPOSITION OF THE LUNAR CRUST AND SOME UNANSWERED QUESTIONS. B. L. Jolliff.
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Introduction: A great deal is known about the Moon's crust, first through direct sampling of surface materials from known locations by six Apollo and three Luna missions, and secondly, through geophysical, geochemical, and mineralogical remote sensing. The samples provide ground truth and highly accurate information about age, lithology, and petrogenesis of crustal rocks, and remote sensing permits extrapolation from areas of ground truth to the entire globe. The effectiveness of impact mixing is both a boon and a bane: ejecta deposits obscure bedrock surface with regolith and megaregolith but provide a regional diversity to local samples. Owing to detailed exploration during Apollo missions, we know much about how to read the diversity in rocks and soils and relate it to local and regional geology. Even so, the constrained central-nearside locations of sample-return sites limits the extent to which we can fully understand the crust on a global basis from the returned samples, alone. Recent orbital remote-sensing missions have provided a global context within which to better understand the Moon through the growing set of lunar meteorites. These new samples, in turn, provide additional information about unsampled parts of the Moon. This abstract reviews some of the key things that we know about the lunar crust as well as some that remain only poorly known, awaiting future exploration.

Lithologic diversity: Three major suites of crustal rocks make up the majority of the sample collections (excluding basalts). These are ferroan-anorthositic-suite rocks (FAS), magnesian- and alkali-suite rocks, and impact-melt rocks and breccias. Fragmental and regolith breccias, though abundant in the samples, incorporate these three main rock groups. The mineralogy of crustal rocks is well understood from the samples, including compositions and conditions of formation such as P, T, fO_2 , and (nearly nonexistent) water activity [1,2]. The diversity of crustal rock types is less well known and is more biased by where the samples came from. Apollo landing sites are all on the central nearside and are biased toward rocks excavated and deposited by the latest of the large nearside basins, Imbrium and Serenitatis [3]. Samples of the FAS, which represent the primary feldspathic upper crust derived from magma-ocean crystallization occur at all the sample sites, but are most common in the eastern highlands sites that are distant from Imbrium and Serenitatis, especially Apollo 16 samples excavated by North Ray Crater. These materials are mainly anorthositic but include examples of related, more mafic rock types such as norite and gabbro-norite [4]. Samples of magnesian- and alkali-suite rocks are more common among samples of the western near-

side sites, which suggests an east-west dichotomy [5] that is now better understood in the context of global data (see below). These rock suites appear to represent remelting of deep-seated rocks and intrusion to shallow crustal levels, followed by crystallization and differentiation. Careful analysis of these rocks indicates the importance of concentration of radiogenic elements in producing the heat needed for melting. A relationship between magnesian- and alkali-suite rocks is suggested by fractionation trends observed in KREEP basalts, but the alkali-suite rocks (alkali anorthosite and norite or gabbro, granite, monzogabbro) are found mainly as small rocks or clasts in breccia and their geologic context is not known. The extent of these rocks at depth and globally is also not well known but can now be inferred from global remote sensing. From the distribution of thorium [6], arguments have been made that perhaps the magnesian- and alkali-suite rocks are largely confined to specific regions of the crust where early planetary differentiation produced concentrations of the radiogenic elements [7]. Among the limitations of what is known from the sampled rocks is that most appear to have derived from shallow depths of the upper crust [8]. The impact-melt rocks and breccias produced by basin-forming impacts may have excavated materials from deeper in the crust, but much of the sampled material has been thoroughly brecciated or melted so as to obscure the lithology of the deep crust.

Craters and basins as probes of deeper crust:

The early bombardment of the Moon by basin- and large-crater-forming impacts is responsible for the distribution of most of the lithologic and compositional diversity seen in crustal materials, especially in views from orbit. This characteristic and the fact that the megaregolith produced by the early bombardment did not produce a homogenized surface layer permits assessment of the compositional variation of the crust both laterally and with depth on a broad scale. Basin ejecta tend to be more mafic than the surrounding surface materials, thus the crust appears to be more mafic with depth; however, this is not a simple relationship and some parts of the crust such as the northern farside are thick and highly feldspathic. In some locations, the "stratigraphy" inferred from impact-basin massifs points to a layer of anorthosite beneath a more mafic megaregolith [9]. The largest of the recognizable impact basins, the South Pole-Aitken basin, produced a mafic geochemical anomaly that persists today and may represent the best "view" of lower crustal materials. Remote sensing also opened up the central peaks of large impact craters to examination and permitted an inventory of

crustal rock types from the upper few tens of km of the Moon [10]. The variety of rock assemblages so indicated includes anorthosite and more mafic olivine- and pyroxene-bearing variations, but it remains difficult to place these fully in petrologic context without knowledge of the Fe/Mg of the mafic components.

Terranes concept and lunar meteorites: Following the advent of global data sets from Clementine and Lunar Prospector, it became evident that despite the effects of heavy impact bombardment of the Moon, several broad areas remain that have distinctive compositions that reflect fundamental aspects of the early crustal differentiation. Wieczorek et al. [in 2] considered three main regions primarily on the basis of Fe/Al and thorium contents: the Feldspathic Highlands Terrane, especially the northern farside highlands, the Procellarum KREEP Terrane, including much of the central-western near side, and the South Pole-Aitken Basin, which because of its size created a clear geochemical anomaly and influenced the topography and composition of the entire southern far side [11].

The Feldspathic Highlands Terrane is best characterized by thick, anorthositic crust of the northern far side. The growing body of lunar meteorites includes many highly feldspathic regolith breccias whose low FeO and Th indicate that these are samples – although from random locations – of the Feldspathic Highlands Terrane, many of which lack contamination from the large nearside basins that makes the Apollo 16 regolith not so representative. Importantly, many these meteorites are dominantly (but not exclusively) composed of ferroan-anorthositic components, indicating that most of the feldspathic highlands consist of FAS rocks and not magnesian-suite rocks. Those regolith-breccia meteorites with magnesian components, including magnesian anorthosite, may correspond to localized regions such as near Crisium where orbital remotely sensed data suggest magnesian compositions, but the distribution of such materials remains poorly known and awaits more accurate and higher-resolution Mg data. Although some of the more mafic lithologies within these breccias may reflect deeper crustal components, the composition and lithology of the deep crust remains open to debate.

The Procellarum KREEP Terrane (PKT) is fairly well represented by samples, but because of extensive resurfacing by basalts and the fact that most of the rocks are found as part of basin ejecta deposits and impact breccias, little geologic context exists. Remote sensing and the composition of basin ejecta indicate that the entire region may be fairly mafic and lack the anorthosite-dominated upper crust found elsewhere [12]. Remote sensing also points to locations where some of the more chemically evolved and unusual rock types occur in geologic context such as the possible shallow igneous

complex excavated by Aristarchus and silicic volcanic domes located in the PKT [e.g., 13,14].

The SPA basin contains the remnants of deeply excavated materials of the lower crust and possibly including some upper-mantle material. Much work has been done to interpret the remotely sensed data over the basin [15-17], but determining the diversity of crustal materials and relationships to known samples remains a challenge. The surface composition and ejecta of SPA arguably represent the “typical” lower crust of the FHT and differ from what we might infer about the crustal section excavated by Imbrium and Serenitatis, and characteristic of the PKT. Although arguments can be made that the average composition of the basin floor materials is ferroan, consistent with a mafic (e.g., gabbroanorthite), FAS-dominated lower crust, and significantly less Th-rich than the PKT, improved compositional data, especially accurate Fe and Mg concentrations of basin materials, are needed. Until samples are returned from the SPA basin, it will remain difficult to untangle the mixture of possible mantle components, lower- and mid-crustal rocks, and basaltic materials.

Unanswered questions: Much remains to be learned to understand the lunar crust globally and to pursue questions of bulk-crust composition and further test hypotheses for the Moon’s origin and differentiation. Accurate global crustal thickness and variations, constrained by improved gravity and seismic-network data, are sorely needed along with better knowledge of the materials, compositions, and variability of the lower crust, which is key to mass-balance models for elements such as thorium. Additional samples of basalts and crustal rocks of known provenance are needed to further test models for coupling crustal thermal and magmatic history with variations in the lunar mantle.

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