

LUNAR CRUSTAL COMPOSITION, HETEROGENEITY, AND EVOLUTION: IMPLICATIONS FOR EXPLORATION. B. L. Jolliff, R. L. Korotev, and R. A. Zeigler, Department of Earth and Planetary Sciences and the McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130 (blj@wustl.edu)

The view from Apollo. Many volumes have been written on the basis of what the Apollo lunar samples revealed about the makeup of the lunar crust - its composition, mineralogy, and rock types – and its formation and evolution (see [1] and references therein). Rock compositions, mineral chemistry, and isotopic characteristics discriminate crustal rocks into (1) the ferroan-anorthositic suite (early, primary crust, complementary to the mafic mantle that produced basaltic volcanism later in Moon's history), (2) the magnesian suite (similar to the products of terrestrial layered mafic intrusives), and (3) the alkali suite, which are more evolved chemical differentiates of magmatic processes. Ages of these rock types were shown to overlap, but generally the ferroan-anorthositic rocks were oldest, dating from very soon after the Moon's formation, the magnesian-suite rocks covered a broader range, extending to about the age of large basin formation (3.8-4.0 Ga), and the alkali-suite rocks covered a somewhat younger average age, extending to about 3.8 Ga on the basis of Apollo samples. Nearly all of these rocks have been shown through studies of mineral assemblage and chemistry to have crystallized at relatively shallow depths.

A picture emerged of a relatively simple and early 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. Generic cross sections of the Moon showed concentrically layered zones and a more-or-less uniform intrusion of the early crust by later, mafic intrusive magmas, followed by basaltic volcanism, presumably formed as melting zones extended deeper into the Moon. Mafic impact-basin ejecta and melt rocks from deeply penetrating impact events, sampled at the rims of Imbrium and Serenitatis, indicated that the lower crust is more mafic (Fe- and Mg-rich) than the surface and shallow crust.

Clementine and Lunar Prospector. Global remote sensing missions of the 1990s changed the paradigm of the lunar crust significantly. These missions filled in details only hinted at by Apollo remote sensing. They showed that surface expressions of crustal composition varied strongly and broadly across the lunar surface. The northern farside 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 tagged by the compositionally distinctive signature of KREEP. New 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, which has been termed the Procellarum KREEP Terrane. This area is also known as a locus of crustal magmatism and extended volcanic activity, featuring some of the youngest surfaces on the Moon.

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 [2]. Immature surfaces have been used to map global mineralogy [3]. These approaches complement global compositional remote sensing and provide a framework for future exploration objectives. These methods rely heavily on the Fe^{2+} content of mafic silicates, however, such that the distribution of ferroan vs. magnesian rock types, which is central to understanding early crustal petrogenesis, remains poorly known.

The Clementine mission also provided improved definition of lunar topography and, in particular, illuminated the giant South-Pole Aitken basin (SPA) in the southern lunar far side. This basin represents the largest and oldest recognizable impact feature on the Moon. Despite its great size, however, the SPA event did not excavate lower crustal materials that were strongly enriched in differentiated magmatic residua as was seen in the Procellarum KREEP Terrane. This observation led to the realization that the Moon is strongly asymmetric with respect to its crustal evolution corresponding in part to its broad geophysical asymmetry [4].

Lunar meteorites. A new set of samples in the form of meteorites found on Earth but recognized to be pieces of the Moon have provided new information that is mostly consistent with global remote sensing, namely that the Apollo sample suite, while providing fundamental information about the Moon's crust and origin, was a highly biased sample set [5]. The lunar meteorites in contrast, represent the Moon's surface fairly well. Many are highly feldspathic regolith breccias that represent materials like the anorthositic, northern-farside highlands. Many are low-Ti basalts or related rocks, which the remotely sensed data indicate should be more abundant than they are in the Apollo collections. Even a few of the KREEP-rich samples, such as would repre-

sent the Procellarum KREEP Terrane, have been found. To date, however, no lunar meteorites have been reported that have the compositional or mineralogical characteristics inferred for deeply exhumed materials of the South Pole-Aitken basin-forming event.

Ages of igneous components of the lunar meteorites have revised the lunar chronology, extending known dates of volcanism and intrusive rocks to as young as 2.8 Ga [e.g., 6]. Petrogenetic relations among these younger materials further suggest an association with the Procellarum KREEP Terrane, supporting the notion that volcanism and igneous activity there was not only spatially extensive, but also extended in time.

South Pole-Aitken Basin: Key to several major problems in planetary science. Because it is so old in the scheme of lunar basin chronology, the SPA basin and rocks exhumed by its formation hold one of the remaining keys to understanding how lunar crustal structure and compositional heterogeneity came to be on a global scale, and thus some of the critical details about how the Moon's early differentiation occurred. If the radiogenic heat-producing elements such as thorium and uranium were strongly concentrated within the region of the Procellarum KREEP Terrane as is presently indicated, that would have had fundamental implications for how the Moon differentiated and what drove later heating to produce its volcanism. The cause of such global-scale asymmetry is unknown; it could have developed by processes associated with early magma-ocean solidification, or it could have been triggered by an early giant impact for which no firm geophysical evidence remains. In addition to holding one of the most important remaining keys to lunar crustal formation processes, the SPA basin is at the center of a great debate about the impact history of the early Solar System, i.e., the "Cataclysm." Samples of materials exhumed by the basin are needed for age dating and for detailed compositional and mineralogical studies in order to answer these questions.

Global Composition of the Moon. Cosmochemical models stemming from an understanding of the geochemistry of the lunar crust and mantle in comparison to Earth, and based on direct knowledge gained from the lunar samples, are central to current understanding of comparative planetology [7]. Implications of compositional mass balance for crustal and global distribution of elements within the Moon are consistent with the view that radiogenic heat-producing elements were strongly concentrated early in the Moon's history. Questions relating to why and how such fundamental asymmetry exists on the Moon are relevant to understanding how and why such processes did or did not occur on other planets. Mars, Venus, and Earth exhibit pronounced asymmetries in the distribution, thickness, and/or composition of their crustal components, and Mercury probably does, too.

Future Exploration Objectives. To make significant gains in knowledge of the lunar crust and its evolution, we must sample materials from the unexplored and poorly explored regions of the Moon. Some of the potential key targets include:

South Pole-Aitken Basin: major unsampled geochemical "Terrane"- interior of basin lies 500-1000 km from South Pole; key to early lunar and inner solar-system history.

Aristarchus region: Locus of igneous and volcanic (pyroclastic) activity of extreme compositions.

Youngest mare volcanism: regions such as the basalts near Crater Lichtenberg and in Crater Flamsteed P [8]; determine temporal extent of volcanism; constrain planetary cooling history.

Central peaks of several large impact craters in key locations, e.g., Tycho, Copernicus, Tsiolkovsky; direct samples of bedrock in known locations.

"Red Spots" and volcanic domes: a form of lunar volcanism and rock types from evolved magmatic processes [9].

A key unknown for understanding the Moon's crust is its thickness. At present, only relative thickness is known and multiple geophysical crustal-thickness models exist based on seismic, gravity, and topography data. Improved gravity and topography from orbiters will improve knowledge, but a global seismic network is needed to constrain these models adequately.

Implications for Polar Outpost Exploration. Polar regions lie far distant from the sampled Apollo and Luna sites and will provide important new samples for understanding the crust. However, human and/or robotic access to multiple and widely distributed sites for sampling, as described above, is needed to advance understanding of the extent of magmatic and volcanic activity and its variety of rock types. Sorties with global access; robotic, automated sample-return excursions, or very-long-range roving capabilities are needed.

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