LUNAR ANORTHOSITE: A GLOBAL LAYER. . C. A. Peterson[1], B. R. Hawke[1], P.G. Lucey[1], G. J. Taylor[1], D.T. Blewett[1,2], P.D. Spudis[3], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822. [2]Innovative Technical Solutions, Inc., 2800 Woodlawn Dr., #192, Honolulu, HI 96822 USA. [3]Lunar and Planetary Institute, Houston, TX 77058.

Introduction: Evidence suggests that Earth's Moon was formed as a result of the impact of a body the size of Mars or larger with the early Earth [e.g., 1,2]. Material that derived from both the impactor and the proto-Earth reacreted in Earth orbit to form the Moon. The heat generated by the impacts may have created a global magma ocean hundreds of kilometers deep on the newly formed Moon.

As the magma ocean cooled, olivine and pyroxene crystals that formed would have been denser than the remaining melt and would eventually have settled to the bottom. When the magma ocean became saturated with plagioclase feldspar, this mineral would have been less dense than the magma and would have floated to the top. This flotation crust, composed primarily of anorthosite (rock containing at least 90% plagioclase feldspar), may have formed the original crust of the Moon.

At first, the anorthosite crust may have been frequently breached during bombardment by debris generated by the Moon-forming impact or by other material not yet incorporated into any of the young solar system's planets or their satellites. Impacts that penetrated the growing crust would have emplaced magma atop the crust, and further impacts could have mixed this more mafic material into the upper portions of the crust. As the flotation crust thickened over time, it would have become more and more difficult for any impactor to penetrate the complete thickness of the crust, and a layer of pure anorthosite would have grown.

If the Moon's crust formed in this manner, what has happened to it? We have been investigating this question for a number of years [e.g, 3,4,5,6], and the answers are becoming clearer.

Method: The Moon is a nearly ideal target for study using remote sensing techniques. The great majority of the Moon's surface is composed of only a few minerals, and these are easily distinguishable using reflection spectroscopy utilizing wavelengths from the UV through visible light and into the near infrared. The mafic minerals pyroxene and olivine contain iron which causes the minerals to absorb light with a wavelength near 1 µm [e.g., 7]. Pyroxenes have a single absorption band near 1 µm while olivines display a more complex 3-lobed absorption feature. In contrast, plagioclase feldspar does not absorb light near 1 µm, although plagioclase can show absorption of light near 1.25 µm if it has not been highly shocked by impacts.

The Moon's almost complete lack of atmosphere and water has allowed the surface materials to remain unaltered by weathering of the type found on Earth. Impacts by bodies of various sizes cause most of the changes that lunar surface rocks undergo. For example, impact melt produced by the constant rain of micrometeoroids quenches to glass, which accumulates over geologic time and tends to reduce the spectral contrasts among lunar minerals. For this reason, fresh impact craters that have exposed crystalline rocks provide material that can be identified with the greatest confidence. Rocks composed of anorthosite can be identified by the absence of any discernible 1-µm absorption features in their spectra.

In 1994, the Clementine spacecraft orbited the Moon for about two months and returned a nearly complete global data set. One of the instruments carried by Clementine was the UVVIS camera that imaged the surface in five wavelengths from the UV to the near infrared [8]. These wavelengths were chosen specifically to allow for identification of minerals found on the Moon. This data set has now been well calibrated, and the results can be used with some confidence. Resolution is about 125 m per pixel near the sub-spacecraft points.

This data set may be used in a number of ways to search for anorthosite on the lunar surface. Ratios of images taken at different wavelengths (750 and 950 nanometers) provide a simple but effective method for identifying anorthosite in fresh craters. While all fresh craters are bright at 750 nanometers, fresh anorthosite reflects more light at 950 nanometers than does rock containing higher proportions of mafic minerals. In 750/950 nanometer ratio images, fresh mafic craters appear brighter than their more mature surroundings while fresh craters composed of anorthosite are almost indistinguishable from the more mature material surrounding them.

Lucey *et al.* developed a more sophisticated technique combining the 750/950 nanometer ratio and absolute reflectance at 750 nanometers to derive the weight percent FeO in materials on the Moon's surface [9]. Blewett *et al.* subsequently refined the accuracy of this technique by comparing Clementine data with the results of analyses of samples from individual Apollo landing site stations [10]. Lucey *et al.* recently presented a revised set of algorithms based on the final calibration of the Clementine data [11]. This technique yields results with a standard deviation of less than ± 1.5 wt. % FeO.

Tompkins and Pieters have utilized the Clementine data to investigate the composition of 109 central peaks in craters ranging in diameter from 40 to 180 kilometers [12]. Their technique uses the "key ratio" of the 750 nanometer band to whichever of the 900, 950, or 1000 nanometer bands contrasts most strongly with the 750 nanometer band. In addition, they use a measure of "spectral curvature". These measurements are used to identify a number of lunar rock types, including anorthosite.

Results: Our group and others collected ground-based telescopic near-infrared reflection spectra for numerous locations on the lunar nearside throughout the 1980s and early 1990s. Several outcrops of anorthosite were identified, mostly in a narrow band that stretches from the inner Rook Mountains in the west to the crater Petavius in the east. These outcrops were usually associated with the inner rings of impact basins. In all cases, the anorthosite had been exposed from beneath a more mafic surface layer.

With the return of data from the Clementine spacecraft (and also from the Galileo spacecraft, which obtained data in similar wavelengths during two flybys of the Earth-Moon system), it was possible to search for anorthosite on the lunar farside. Confidence in the applicability of the Lucey iron-mapping technique to the identification of anorthosite was established by examining all nearside anorthosites that had been previously identified from ground-based telescopic studies. In every case, the anorthosite outcrops exhibited very low FeO values that contrasted strongly with values for the surrounding terrain. When the technique was applied globally, it revealed exposures of anorthosite in the inner rings of such basins as Hertzsprung and Korolev that were reminiscent of such exposures previously identified from ground-based telescopic data at Orientale, Grimaldi, Humorum, and Nectaris basins on the lunar nearside. However, in the far northern farside, vast areas of anorthosite lay exposed at the surface. Clementine data also revealed the presence of anorthosite deposits in some parts of the far northern nearside.

The work of Tompkins and Pieters [12] examined the composition of crater central peaks in order to determine the composition of subsurface deposits brought to the surface by the crater-forming impacts. Of the 109 peaks studied, 68 contained anorthosite, either alone or in combination with other rock types.

Discussion: The continuing discovery of anorthosite outcrops, many of which have been lifted to the surface by crater- or basin-forming impacts events, is revealing an extensive distribution of this rock type. The role of the giant South Pole-Aitken (SPA) impact basin on the far side is significant in explaining the pattern we see today. Enormous quantities of SPA ejecta must have been emplaced near the basin rim on the central farside and southern nearside, covering any of the original flotation crust that was still intact. Anorthosite was subsequently exposed from beneath this ejecta only by basins large enough to penetrate it. Further from the SPA rim, where ejecta was more thinly emplaced, smaller impacts could expose anorthosite. This is the case in the far northern farside.

Extensive deposits of mare basalt on the nearside and a paucity of large impact basins in the highlands of the southern nearside have acted to obscure the extent of the buried anorthosite that may also exist on the nearside. It has been argued that the putative Procellarum impact event removed all the original flotation crust from the Procellarum basin. However, identification of anorthosite in the central peaks of craters such as Aristarchus and Eratosthenes argues for a continued presence of buried anorthosite in Procellarum and perhaps other mare-filled basins. In fact, anorthosite has even been reported in the interior of South Pole Aitken basin itself in craters such as Mendell (51° S, 250° E) and O'Day (31° S, 157 ° E) [12].

While it is possible that any individual exposure of anorthosite may have derived from a differentiated pluton, it is likely that most of the identified anorthosites are remnants of the Moon's original plagioclase flotation crust. If much of the original crust remains intact at depth, that fact may have important implications for questions regarding the flux of impactors early in the Moon's history. One thing is clear: a layer of (mostly subsurface) anorthosite of greater extent than previously recognized remains on the Moon today.

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