REMNANTS OF THE ANCIENT LUNAR CRUST REVEALED BY CLEMENTINE. C. A. Peterson[1], B. R. Hawke[1], P.G. Lucey[1], G. J. Taylor[1], D.T. Blewett[1], P.D. Spudis[2], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822 [2]Lunar and Planetary Institute, Houston, TX 77058.

INTRODUCTION

Soon after the return of the first lunar rock samples by the crew of Apollo 11, it was recognized that the lunar highlands crust could have been produced by the flotation of plagioclase feldspar which had crystallized from a magma ocean [e.g., 1]. More recently, the origin of the Moon has been attributed to a giant impact of a Mars-size or larger body onto the proto-Earth [e.g., 2]. An impact of this scale could have ejected material, much of it molten or vaporized, into space, where some of it could then have accreted to form the Moon. The rapid accretion of this material may have generated enough heat to produce a deep global magma ocean. The original flotation crust should have been composed primarily of anorthosite (rock containing at least 90% plagioclase feldspar). However, most of the highlands crust on the lunar nearside, as sampled by the Apollo crews and as analyzed using ground-based near infrared reflection spectroscopy, has been shown to contain significant amounts of more mafic minerals. This indicates that much of the original crust has been substantially modified since its original emplacement. While some of the Moon's anorthosite may have been produced subsequent to the formation of the crust, such as by differentiation of a pluton, the great majority of anorthosite present on the lunar surface today may well be remnants of the primordial flotation crust.

Until recently, only the Earth-facing hemisphere of the Moon has been available for investigation into the fate of the original flotation crust. This situation changed in 1994 when the Clementine spacecraft returned the first nearly global multispectral data set for the Moon. Analysis of this data set has provided intriguing insights into the fate of the original crust of the Moon.

METHOD

Earth's 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., 3]. 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 which have exposed crystalline rocks provide surface material which can be identified with the greatest confidence. Rocks composed of anorthosite can be identified by the absence of any discernible 1 µm absorbtion 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 which imaged the surface in five wavelengths from the UV to the near infrared [4]. 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 [5]. Blewett *et al.* recently refined the accuracy of this technique by comparing Clementine data with the results of analyses of samples from individual Apollo landing site stations

[6]. This technique yields results with accuracy of about ± 1.5 wt. % FeO.

It should soon be possible to combine the UVVIS data set with the data from Clementine's near infrared camera (which is nearing the final stage of calibration) which will allow better comparison with ground-based spectra (which cover approximately the combined wavelength range of the two Clementine cameras). In addition, the NIR data include a 1.25 µm bandpass which allows an independent means for identifying anorthosites which have not been subjected to high levels of shock pressure [e.g. 7].

RESULTS

Over the past two decades or so, our group and others have collected numerous ground-based near infrared reflection spectra for areas on the Moon's nearside [8-11]. Anorthosite has been identified in several locations, but most of the surface of the lunar nearside highlands is certainly not composed exclusively of anorthosite. Outcrops of anorthosite occur primarily in a narrow band which stretches from the inner Rook Mountains in the west to the crater Petavius in the east. More recently, a few other isolated outcrops of anorthosite have been identified outside of this region, for example in the central peak of Aristarchus crater and in the far northern nearside highlands [e.g. 7].

In the majority of cases, the anorthosite appears to have been exposed after being brought to the surface from considerable depth. Many nearside anorthosites are associated with the rings of large impact basins, particularly the inner rings of basins such as Orientale, Grimaldi, Humorum, and Nectaris. Material in these locations is thought to rise from depth by rebound during the basin-forming impact event. In other cases, anorthosite is exposed in the peaks or walls of large craters which excavated the anorthosite from beneath a more mafic-rich surface layer.

Analysis of the Clementine data shows it to be in good agreement with the ground-based spectral data. Every anorthosite outcrop identified from ground-based spectra which has been compared with the best resolution Clementine data displays an appropriately low iron value in the Clementine data set. This provides good confidence in the accuracy of the technique presented by Lucey *et al.* for the determination of iron values and allows the analysis to be extended to the lunar farside.

The distribution of anorthosite on the farside is quite distinct from that on the nearside. Vast stretches of the northern farside, for example near the crater Fowler (43° N, 145° W) and in portions of the Coulomb-Sarton basin (52° N, 123° W), appear to contain nothing but anorthosite. There is a general trend towards higher iron content to the south of this region, but very low iron values can also be found in the inner rings of such basins as Hertzsprung.

DISCUSSION

The pattern of anorthosite distribution on the lunar farside appears to be in large part related to the giant South Pole-Aitken (SPA) basin. With a diameter of 2500 km, SPA is the largest known impact basin in the solar system. It is also the oldest unambiguously identified impact basin on the Moon. The SPA impact event must have deposited enormous quantities of ejecta, much of it derived from the more mafic lower crust, beyond the basin's rim. Near the basin, the ejecta would have covered the primordial crust to a great enough thickness that only large basins such as Orientale and Hertzsprung could have penetrated through it to reveal the anorthosite below. Further to the north, the SPA ejecta blanket would have been much thinner. Moderate sized basins such as Birkhoff and Coulomb-Sarton could have stripped away nearly all of the SPA ejecta to reveal the anorthosite crust.

This simple scenario appears to go far towards providing an understanding of the fate of the original lunar farside crust. The geologic history of the nearside does not appear to be so simple. It has long been known that there is an asymmetry between the lunar nearside and farside. For example, the farside crust is thicker, and far more of the nearside is covered by mare basalt. A better understanding of the fate of the Moon's original crust may lead to a better understanding of this asymmetry.

Analysis of the Clementine data is continuing, and it will soon be possible to compare it with the data now being collected by Lunar Prospector. These data sets should complement each other well and allow for a better understanding of the Moon's geologic history than either set alone could provide.

REFERENCES: [1] Heiken, G.H. *et al.* eds. (1991), *Lunar Sourcebook*, Cambridge Univ. Press; [2] Hartmann, W.K. *et al.* eds. (1986), *Origin of the Moon*, LPI; [3] Pieters, C.M. and Englert, P.A.J. eds. (1993), *Remote Geochemical Analysis*, Cambridge Univ. Press; [4] Nozette, S. *et al.* (1994), *Science*, **266**, 1835; [5] Lucey, P.G. *et al.* (1995), *Science*, **268**, 1150; [6] Blewett, D.T. *et al.* (1997) *JGR*, **102**, 16,319; [7] McEwen *et al.* (1994), *Science*, **266**, 1858; [8] Spudis, P.D. *et al.* (1984) *PLPSC*, **15,** C197; [9] Hawke, B.R. *et al.* (1991) *GRL*, **18**, 2141; [10] Hawke, B.R. *et al.* (1993) *GRL*, **20**, 419; [11] Peterson, C.A. *et al.* (1995) *GRL*, **20**, 3055.