THE MANTLE OF THE MOON: EXPOSED AND SAMPLED? M. A. Wieczorek[1], J. T. S. Cahill[2], P. G. Lucey[2], C. K. Shearer[3]; [1]Institut de Physique du Globe de Paris (wieczor@ipgp.jussieu.fr), [2]University of Hawaii at Manoa, [3]University of New Mexico.

Introduction. The mantles of the terrestrial planets account for more than 90% by volume of the silicate materials in the inner solar system. Nevertheless, as a result of an overlying protective crust, exposures and samples of planetary mantle materials turn out to be exceedingly rare. Only on Earth has plate tectonics resulted in the obduction of oceanic lithosphere onto the continental crust, and only on Earth has mantle-derived xenoliths been identified in volcanic materials. In contrast, no samples or exposures of mantle material have yet been conclusively identified on any of the other terrestrial planets. Such samples, if found, would prove extremely valuable in deciphering the thermal and geochemical evolution of the corresponding parent body.

Could the lunar mantle be exposed? Seismic data collected during the Apollo era originally suggested that the crust of the Moon was on average more than 60 km thick. Since impact craters excavate materials to depths of about one-tenth of their diameter, only a few of the largest impact basins would have been expected to have excavated through the entire crustal column, bringing mantle materials to the surface. Of those that did, the percentage of mantle material in the basin's ejecta would have been rather small [1]. Recent reanalyses of the original lunar seismic data, however, suggest an average crustal thickness that is about one half of the Apollo-era determination [2], and this opens the possibility that exposures and samples of the lunar mantle might be more prevalent than once thought.

One manner to search for sites where the crust is thin, and perhaps absent, is by the construction of a crustal thickness model using gravity and topography data [2]. While such maps are limited in spatial resolution by the quality of the data (~100 km), recent analyses suggest that the crust might be completely absent (with the exception of a thin veneer of mare basalts) within the Orientale and Crisium impact basins [3]. Based on the size of the Nectaris, Smythii, Serenitatis, and Imbrium basins, these impact events might have excavated through the entire crust as well.

In addition to the excavation of large quantities of mantle material by impact basins, it is also possible that the mantle could be exposed in the central peaks of some smaller complex craters. Central peaks are thought to be derived from depths of about one-tenth of the crater's diameter, or perhaps even deeper if the underlying crust was impact melted [4]. If a complex crater formed at a locale where the crust was previously thinned, under favorable conditions, the central peak could perhaps sample the underlying mantle.

To search for central peaks that might sample the mantle, two different crustal thickness models [2] and two different central peak depth of origin criteria were considered. For the peak's depth of origin, a minimal estimate was assumed to be one-tenth of the crater's diameter, and a second estimate was taken to be equal to the maximum expected depth of impact melting beneath the crater [4]. Crater diameters and locations were taken from [5], and the presence of peak materials in these craters was determined by visual inspection of Clementine images. If the depth of origin of the peak was within 5 km of the crust-mantle interface (a rough estimate of the accuracy of the crustal thickness maps) or deeper, the peak was considered to be a potential outcrop of the lunar mantle.

Figure 1 shows the locations of potential mantle-sampling central peaks. In total, 49 central peaks are found that satisfy at least one of the above four possible criteria, with most of these being located within the South Pole-Aitken basin. The central peaks of only four craters are found to satisfy all four criteria: Minnaert, Antoniadi, Von Karman, and Leibnitz.

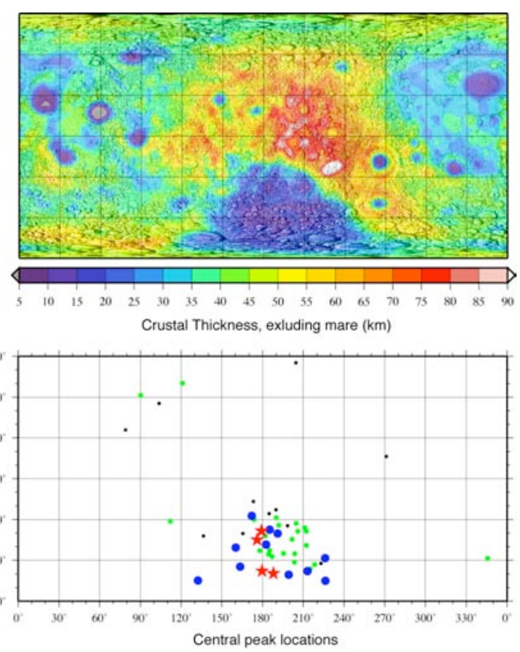

Figure 1. (Top) Estimated crustal thickness, excluding mare fill, assuming a uniform density crust and mantle. (Bottom) Locations of central peaks that might sample the lunar mantle using four different criteria. Those peaks satisfying one through four of these criteria are plotted in black, green, blue, and red, respectively.

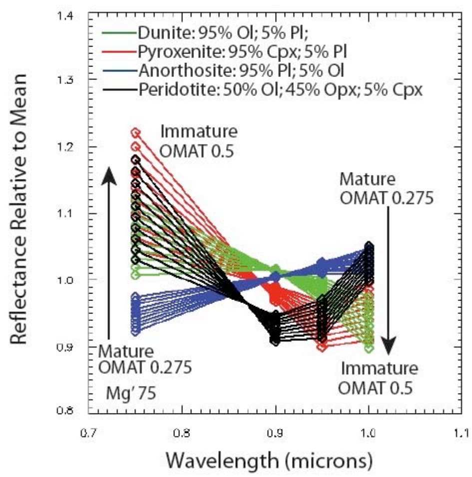

Figure 2. Modeled relative reflectance spectra at Clementine wavelengths for a dunite, clinopyroxenite, peridotite, and anorthosite, each with a Mg# of 75. Each suite of lines for a given composition illustrates the effects of space weathering.

Can mantle materials be detected from orbit? The reflectance spectrum of lunar surface materials is indicative not only of the material's mineralogy, but also the amount of space weathering the material has been subjected to. By using measured mineral optical constants and the radiative transfer theory of Hapke, it is possible to predict the reflectance spectrum of lunar surface materials as a function of modal mineralogy, magnesium number, and optical maturity [6]. Figure 2 shows the results of such modeling for four different lithologies. As is seen, even with the four-color Clementine spectra, it should be possible to invert for, or at least place bounds on, modal mineralogy.

For the purpose of distinguishing mantle from crustal materials, we will use the total plagioclase abundance as a proxy. In general, modal plagioclase abundances less than 15% are representative of mantle materials, whereas abundances greater than 25% are representative of crustal materials. While some ultramafic crustal rocks have been identified in the lunar samples, they are somewhat rare. If ultramafic lithologies turn out to be identified exclusively in the central peaks suspected of having a mantle origin, but not in others, this would give confidence to the hypothesis that these peaks sampled the mantle, and not just ultramafic cumulates of a crustal pluton. The composition and abundance of the mafic lithologies will also help in distinguishing crustal from mantle materials.

We have developed a method for inverting Clementine four-color spectra for mineralogy, magnesium number, and optical maturity. The approach is detailed in *Cahill et al.* (this volume) and results of potential mantle-derived central peaks will be presented at the 39th LPSC.

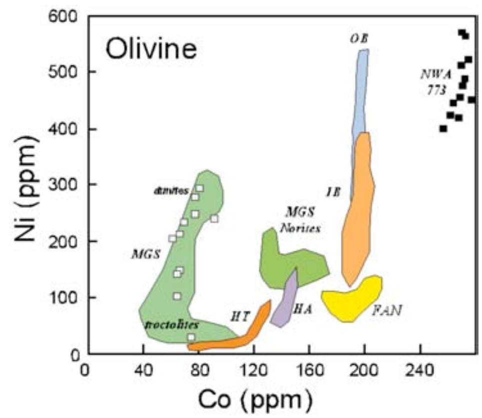

Figure 3. Nickel and cobalt concentrations in olivine from various lunar lithologies: Magnesian suite (MGS), high-titanium basalt (HT), high-aluminum basalt (HA), Apollo 16 ferroan anorthosite (FAN), Apollo 12 olivine basalt (OB), ilmenite basalt (IB). Open squares are for olivine clasts present in the Apollo 17 impact melts.

Have we sampled the lunar mantle? Forsteritic olivine clasts have been identified in both the Apollo 15 and 17 impact melts, as well as the Luna-24 soils. As the adjacent Imbrium, Serenitatis and Crisium basins could have excavated through the entire crust, the possibility exists that some of these clasts might be derived from the mantle.

One manner to distinguish crustal from mantle samples is to investigate the systematics of compatible elements, such as nickel and cobalt, that are fractionated during magmatic processes. We have measured the abundances of these two elements in the olivines of a variety of crustal rocks and mare basalts. Figure 3 shows that the major compositional groupings are easily distinguished on this two-element plot. We note that hypothetical mantle olivine compositions that would be in equilibrium with the primitive pyroclastic glass compositions would plot at significantly higher nickel abundances (greater than 1000 ppm).

We have obtained samples of the olivine clasts present in the Apollo 17 impact melts that were previously suggested to have a potential mantle origin [7]. These samples are plotted in Figure 3 (open squares), which shows that they overlap with the compositional field of the magnesian suite dunites and troctolites. These samples are thus consistent with having a crustal origin. We have also obtained samples of the olivine clasts in the Apollo 15 impact melts, as well as the Luna-24 soils. Results from the analyses of these samples will be presented at the 39th LPSC.

References. [1] P. Spudis, *The Geology of Multi-Ring Impact Basins*, 1993; [2] M. Wieczorek, et al., in *New Views of the Moon*, 221, 2006; [3] H. Hikida and M. Wieczorek, *Icarus*, **192**, 150, 2007; [4] M. Cintala and R. Grieve, *MaPS*, **33**, 889, 1998; [5] J. McDowell, Lunar crater database, http://host.planet4589.org/astro/lunar/; [6] J. Cahill and P. Lucey, *JGR*, **112**, 2007; [7] G. Ryder, et al., *GCA*, **61**, 1083, 1997.