Radiative transfer modeling of geophysically targeted lunar impact crater central peaks

J.T.S. Cahill[1], M.A. Wieczorek[2], P.G. Lucey[1], C.K. Shearer[3], [1]University of Hawaii at Manoa (jcahill@higp.hawaii.edu), [2]Institut de Physique du Globe de Paris, [3]University of New Mexico.

Introduction: Lunar materials thought to potentially be from the lower crust or upper mantle are rare [1]. To date, other than lunar basalts (transported from mantle to surface via melting) no samples returned from the Moon are actually confirmed to be of mantle origin [2]. However, if samples of this type are identified remotely, they would be valuable for further deciphering lunar evolution.

Complex impact crater central peaks provide perhaps the best location to find samples that may be from lower crust or mantle depth [3]. Studies of terrestrial impact craters show that central peaks are composed of materials from significant depth [4]. The materials exhumed are usually postulated to be from depths roughly equivalent to 1/10th the diameter of a given crater [4]. This inherent property of impact crater central peaks makes them a good place to look for these materials. *Tompkins and Pieters* [5] used this approach to investigate the compositional structure of the crust. That study divided their crater sampling into "basin related" and "highland" populations, but no clear patterns were identified. *Wieczorek and Zuber* [6] refined this analysis using a model of crustal thicknesses and found their results were compositionally consistent with a dual-layered stratified model (upper and lower crust).

In this study we further refine the approach of [5] using geophysical constraints on material depths of origin, and a quantitative spectral analysis model to return compositional data. Here impact craters that have the highest potential of exhuming materials from the lowest possible depths of the lunar interior are quantitatively determined using gravity and topography data. These craters are then evaluated for the potential presence of exhumed material in the form of a central peak and are subsequently analyzed via radiative transfer modeling of Clementine reflectance spectra for mineralogy and geochemistry.

Choosing craters to analyze: We constructed two crustal thickness models using gravity and topography data in order to determine crater localities that occur where the lunar crust is thin or possibly absent. Crater diameters and locations were taken from [7]. Craters inputed into this model have a diameter range that covers that of complex craters. Further details of these geophysical models are documented by [2, 8].

Results from these models produced a ranked list ~160 craters by their theoretically calculated depth of exhumation. With visual inspection of these craters using Clementine data, we culled this list of craters to ~50 with central peak material (Fig. 1). The majority of craters with peak material fitting our geophysical criteria described in [2] are located within South Pole-Aitken (SPA) basin.

Method of Analysis: Model spectra are computed using radiative transfer theory developed by [9-11] and use optical constant data of [12]. This model is similar to that implemented by [13] and explained in detail by [14, 15]. In general, the model uses the optical constants (real, *n*, and complex indices, *k*, of refraction) of minerals to calculate single scattering albedo (the probability a photon will survive an encounter with a material) for each component at a specified particle size, maturity, and mineral chemistry. Single scattering albedo of each mineral component is added linearly, weighted by abundance, and converted to reflectance. Mineral modes used for this study span a plagioclase-olivine-orthopyroxene-clinopyroxene system at 1 vol% intervals (176,851 modal combinations). Mafic mineral chemistry is varied in the form of Mg' (i.e., molar Mg/(Mg+Fe)·100) ranging from 50-95 in increments of 5.

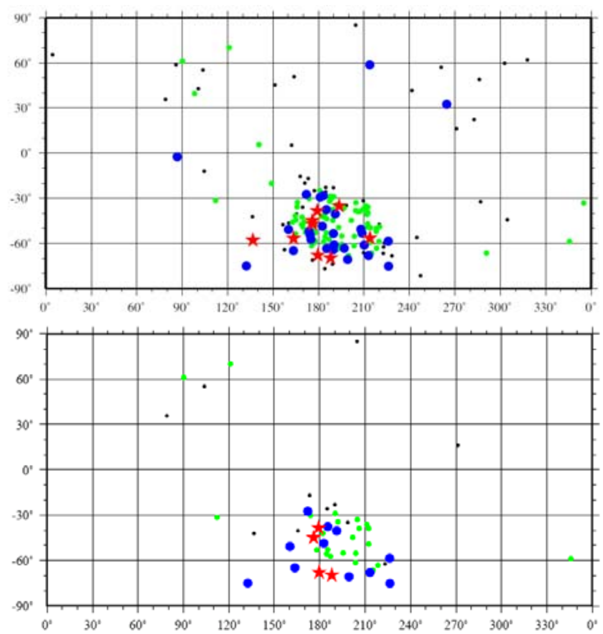

Figure 1. (Top) Locations of craters initially identified to potentially excavate or mantle material. (Bottom) Locations of craters that were confirmed to have central peak material. Peaks satisfying one through four of [2]'s criteria are plotted in black, green, blue, and red, respectively.

We account for space weathering by using the optical maturity method of [16] and compute our models based upon the full range of immature compositions. *Lucey et al.'s* [16] optical maturity parameter (OMAT) quantifies optical maturity combining the reflectance and spectral contrast of each spectrum in a manner that is largely insensitive to composition. At 1 km spatial resolution the Moon ranges from .2 (highly mature) to .5

(immature) in this parameter. Here we force our models to cover 46 levels of maturity from 0.275 to 0.5 OMAT in increments of 0.005, which covers the full range of immature compositions on the surface of the Moon.

Model candidates having a 950/750 nm ratio within ±.0005 of each Clementine spectrum are selected. Next, models are compared to a Clementine spectrum in relative reflectance. The best model is chosen based upon the least amount of difference per spectral band from the Clementine spectrum. This selection process is applied for each pixel ten times (once for each modeled Mg'), giving ten best-fit possibilities for each Clementine pixel.

With these final ten possibilities, Mg' is determined by calculating the difference between Clementine derived FeO, via the method of [17], and the stoichiometric FeO computed from our modeled mineralogy to yield ΔFeO. The model with the smallest difference in FeO from the Clementine spectrum is chosen as the matching spectrum. The Mg' is chosen where ΔFeO is zero.

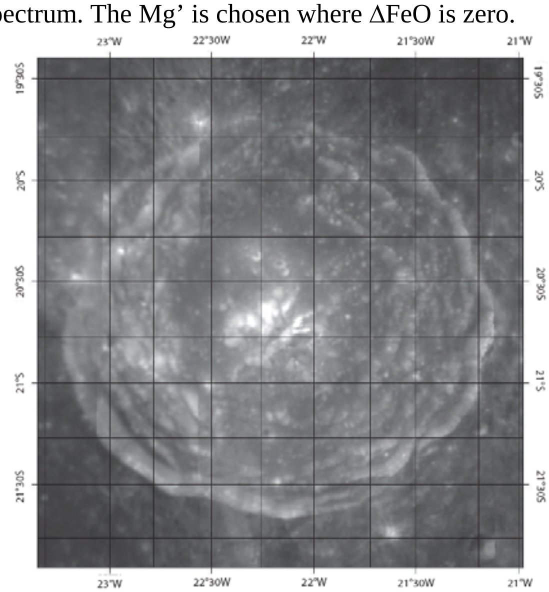

Figure 2. A Clementine 750 nm mosaic of Bullialdus crater.

Analysis of Bullialdus central peak: Here we illustrate our analytical method using the crater Bullialdus (Fig.2). With geophysical modeling of the lunar crust, [6] make the case that Bullialdus crater may consist of lower crustal material. Mineralogically, Bullialdus stands out as the only large crater on the nearside of the Moon with a central peak documented with norite mineralogy [5, 15, 18]. The only other central peaks documented with this composition are within SPA basin (e.g., Birkeland, Bhabha, Finsen, Lyman, and White). However, results from [15] also indicate that the spectral classes of [5] do not compositionally classify all the immature spectra present on Bullialdus central peak. Furthermore, Bullialdus spectra that are compositionally classified using these classes may be more mafic than previously interpreted. Thus, further study of Bullialdus' central peak may prove useful for more accurately inferring composition of lower crustal material.

Previous study of immature material on Bullialdus central peak documented the spectral classes AN, N, and AGN [15]. Here, modeling indicates Bullialdus to be very mafic with pyroxenite, peridotite, norite, gabbronorite lithologies (Fig. 3). Anorthositic-norite and noritic-anorthosite lithologies are also present but not in high abundance. Mg' for all lithologies range from ferroan to moderately magnesian (40-75) compared to the lunar sample collection.

Using plagioclase abundance as a convenient proxy we can infer the likelihood of whether we may be looking at lunar crustal or mantle materials (crustal 25 vol.%; mantle <15 vol.%). Our mineralogical results indicate that Bullialdus may have a significant percentage (73%) of lithologies expected to originate from the lunar mantle. This includes a 44% fraction of lithologies that do not contain plagioclase.

In essence we don't know the Mg' of the upper mantle. However, two possibilities exist. If fractional crystallization took place, the magma ocean may have given rise to a ferroan composition (Mg' similar to FANs). This theory is more consistent with our results from Bullialdus. However, if the mantle overturned, the first forsteritic olivines to crystallize from the magma ocean could have risen to upper mantle levels and we would expect to see more magnesian materials. In either case, Bullialdus appears to have a central peak that potentially exhumed lower crust or mantle material. Similar analyses of central peaks plotted in Figure 1 are ongoing.

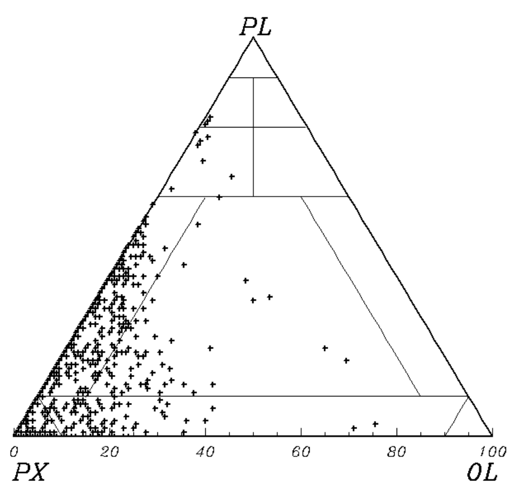

Figure 3. Modeled results for immature materials on Bullialdus peak.

References: [1] Ryder et al. (1997), *GCA*, 61 [2] Wieczorek et al. (2008), *LPSC*, 39 [3] Pieters (1986), *RG*, 24 [4] Cintala and Grieve (1998), *MaPS*, 33 [5] Tompkins and Pieters (1999), *MaPS*, 34 [6] Wieczorek and Zuber (2001), *GRL*, 28 [7] McDowell J. host.planet4589.org/astro/lunar/ [8] Wieczorek et al. (2006), *NVM*, 60 [9] Hapke (1981), *JGR*, 86 [10] Hapke (1993) [11] Hapke (2001), *JGR*, 106 [12] Lucey (1998), *JGR*, 103 [13] Clark et al. (2001), *MaPS*, 36 [14] Lawrence and Lucey (2006), *JGR*, (in press) [15] Cahill and Lucey, (2007), *JGR*, 112 [16] Lucey et al. (2000), *JGR*, 105 [17] Le Mouélic et al. (2000), *JGR*, 105 [18] Tompkins et al. (1994), *Icarus*, 110