SHOCKED ANORTHOSITE: PUZZLING OVER ITS WHEREABOUTS.

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Introduction: The surface of the Moon provides evidence of a long history of bombardment in the inner solar system from the multi-ring basins that dominate the nearside down to millimeter-scale craters due to micro-meteorite impacts. Early telescopic observations and orbital measurements of the lunar surface at low spatial and low spectral resolutions identified exposures thought to be evidence of the Moon's primary anorthositic crust that had been shocked during the impact process [e.g. 1-5]. These identifications were based on observations of high albedo regions with featureless spectra, which are characteristics believed to be consistent with shocked or non-crystalline plagioclase, the dominant mineral phase in anorthosite. The spectrum of Fe-bearing, crystalline plagioclase has a diagnostic absorption band at 1.25 μm due to minor amounts of Fe^{2+} being incorporated into the crystal structure. The strength of plagioclase's diagnostic absorption at 1.25 μm can be weakened, to the point of disappearance giving the spectrum a featureless shape, by at least two known surface processes: space weathering and shock metamorphism. At relatively low shock pressures (between ~10 and 30 GPa), internal fragmentation occurs in feldspars [e.g. 6], which can create fine scale discontinuities within the transparent media resulting in light being scattered out of the media before achieving a sufficient path length through the media [7]. At shock pressures near ~25 GPa, plagioclase begins to lose its crystal structure and diaplectic glass starts to form and by ~35 GPa 100% of the plagioclase has been transformed to diaplectic glass, or maskelynite [6,8-10]. As the amount of maskelynite increases, the 1.25 μm absorption band widens and weakens as seen in plagioclase shocked naturally [11-12] and in the laboratory [13].

However, recent high spatial and high spectral resolution measurements of regions previously identified as shocked anorthosite or plagioclase have unambiguously identified Fe-bearing, crystalline plagioclase units within these regions [e.g. 14-20]. Currently, very little evidence exists for intact shocked blocks of primary anorthositic materials. So where is all of the shocked anorthositic material that is expected due to impact bombardment of the lunar surface, what is its geologic setting, and how should it be identified for future lunar sample return? Dhingra et al. [21] used a combination of high spatial and high spectral resolution Moon Mineralogy Mapper (M^3) data along with the geologic context from the Kaguya Terrain Camera to identify shocked anorthositic material within the central peak of Theophilus crater.

Here we analyze data from M^3 and the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) for a suite of highland craters in an effort to (1) identify shocked anorthositic material and its relationship to crystalline anorthositic material within each crater and (2) map the distribution of shocked anorthosites across the lunar surface in an effort to better understand their systematics of occurrence, preservation, and relationship with each other on the regional scale.

Data and Methods: Individual M^3 data strips from a single optical period (OP) [18] were mosaicked together for craters of interest. To identify crystalline plagioclase within the M^3 data, an integrated band depth (IBD) across the broad 1.25 μm absorption band is calculated. This 1.25IBD was developed to specifically highlight crystalline plagioclase-rich areas from mafic-rich areas and the details of its calculation are provided elsewhere [19-20]. Pixels exhibiting prominent Fe-bearing, crystalline plagioclase absorptions will have higher 1.25IBD values (absorption band strengths > 1-2%) while pixels with "featureless" spectra have lower 1.25IBD values and lack perceptible (spectral contrast < 1-2%) absorption features near 1, 1.25 and 2 μm. M^3 spectra are extracted from each classified unit to confirm the identifications as crystalline or "featureless" anorthosite. Featureless spectra could result from blocks and/or outcrops of shocked anorthosite, regions of well-developed lunar soil or a mixture of shocked and featureless material observed at an insufficient spatial resolution as discussed by Ohtake et al. [22]. Further evaluation of each of these scenarios requires detailed characterization of the surface using high-spatial resolution imagery like images from the LROC Narrow Angle Camera (NAC). Thus, for this analysis LROC NAC images covering the central peak of Theophilus were acquired and M^3 spectral maps highlighting crystalline and "featureless" anorthosite were overlaid to identify "featureless" pixels that contain boulders and/or outcrops.

Results and Discussion: Previous work by Dhingra et al. [21] documented a traverse across a portion of the central peak of Theophilus crater (region outlined in blue in Figure 1C) as containing three distinct units rich in: Mg-spinel, crystalline anorthosite, and

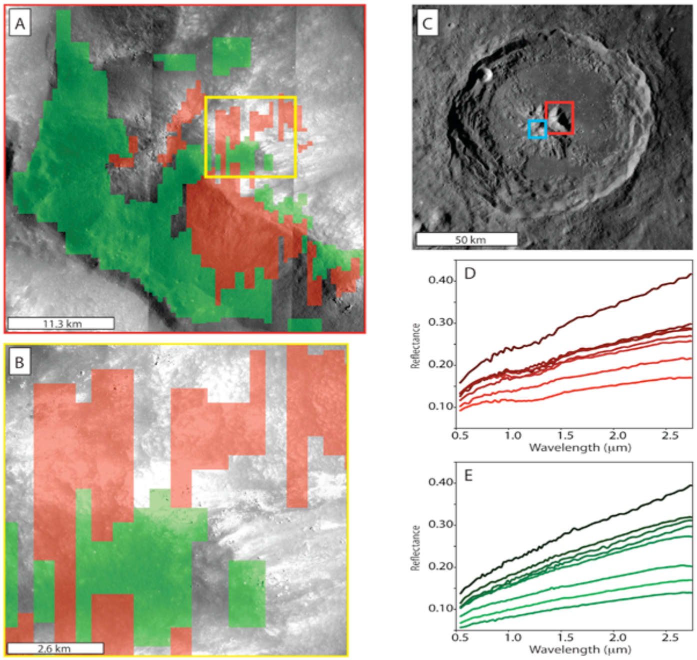

Figure 1. (A) LROC NAC albedo images covering the eastern portion of Theophilus' central peak (outlined by the red square in figure C). Red pixels highlight units with high 1.25μm IBD values and are rich in crystalline anorthosite. Green pixels highlight units with "featureless" spectra. (B) Zoomed in portion of the eastern central peak (outlined by the yellow square in figure A). Again green pixels highlight units with "featureless" spectra. (C) LROC WAC albedo image of Theophilus crater. The red rectangle highlights the region analyzed in this study. The blue rectangle highlights the region analyzed in the previous study by Dhingra et al. [20]. (D) M^3 reflectance spectra for units identified as crystalline anorthosite (red pixels) in figures A and B. (E) M^3 reflectance spectra for units identified as "featureless" (green pixels) in figures A and B.

shocked anorthosite. The shocked anorthosite unit was observed to have a high albedo, a "featureless" spectrum, and an association with a well-defined rock outcrop.

In this work, we focus our analysis on the eastern portion of Theophilus' central peak (region outlined in red in Figure 1C). Crystalline anorthosite units are indicated by red pixels in Figure 1A and B. M^3 reflectance spectra from random locations across the crystalline anorthosite units are plotted in Figure 1D and confirm the presence of crystalline anorthosite by the broad 1.25 μm absorption band diagnostic of crystalline plagioclase. The lack of 1 and 2 μm absorption bands due to mafic minerals like pyroxene, olivine and spinel suggest these units are highly pure (> 98 vol% plagioclase). Most of the crystalline anorthosite is located on the southern slope of the peak and is associated with a large outcrop visible in LROC NAC images. Other crystalline units seem to be associated with bright boulders scattered on the northern slope of the peak. "Featureless" units are indicated by green pixels in Figure 1A and B. M^3 reflectance spectra from random locations across the "featureless" units are plotted in Figure 1E. Most of the "featureless" material is located on the southern and western slopes of the peak, which appear to be outcrop and boulder-free. However, some "featureless" material is located on the northern slope of the peak. Further examination of the LROC NAC images of this portion of the central peak (Figure 1B) shows high albedo boulder fields. These shocked anorthositic boulders are adjacent to the crystalline anorthositic boulders also observed on the northern slope. Thus, we observe further evidence of shocked anorthositic material in the central peak of Theophilus crater.

Future Work: Further detailed analysis of other portions of Theophilus crater will be performed. This work will be expanded to a suite of highland craters to understand the general distribution of shocked anorthositic materials within complex craters, especially in relation to the distribution of crystalline anorthositic material. Understanding this distribution of shocked materials will provide a better understanding of impact induced shock systematics in materials on planetary surfaces, our natural laboratory.

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References: [1] Spudis P. D. et al. (1984) *JGR, 89*, 197-210. [2] Pieters C. M. (1986) *Rev. Geophys., 24*, 557-578. [3] Hawke B. R. et al. (1991) *LPS XXII*, 539-540. [4] Hawke et al. (2003) *JGR 108*. [5] Peterson C. A. et al. (1995) *GRL, 22,* 3055-3058. [6] Stöffler D. (1971) *JGR, 76*, 5541-5551. [7] Pieters C. M. (1983) *JGR, 88*, 9534-9544. [8] von Engelhardt W. et al. (1967) *Contrib. Mineral. Petrol. 15*. [9] von Engelhardt W. and Stöffler D. (1968) *Shock Metamorph. Natural Mins.*, p. 159. [10] Gibbons R. V. and Ahrens T. J. (1977) *Phys. Chem. Mins., 1,* 95-107. [11] Adams J. B. et al. (1979) *LPS X*, 1-3. [12] Bruckenthal E. A. and Pieters C. M. (1984) *LPS XV*, 96-97. [13] Johnson J. R. and Hörz F. (2003) *JGR, 108*. [14] Matsunaga T. et al. (2008) *GRL, 35*. [15] Ohtake M. et al. (2009) *Nature, 461*. [16] Pieters C. M. et al. (2009), *LPS XXXX*, Abstract #2052. [17] Yamamoto S. et al. (2012) *GRL, 39*. [18] Boardman J. W. et al. (2011) *JGR, 116*. [19] Cheek L. C. et al. (2013) *JGR, 118*. [20] Donaldson Hanna K. L. et al. (2013) *JGR, submitted*. [21] Dhingra D. et al. (2011) *GRL, 38*. [22] Ohtake M. et al. (2013) *Icarus, 226*, 364-374.