INVESTIGATING THE NATURE OF CRYSTALLINE AND SHOCKED ANORTHOSITE ON THE MOON. E. R. Bamber[1], K. L. Donaldson Hanna[2], N. E. Bowles[2], J. T. S. Cahill[3], B. W. Denevi[3], and B. T. Greenhagen[3], [1]Department of Earth Sciences, University of Oxford, Oxford, UK (Emily.Bamber@spc.ox.ac.uk), [2]Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK, and [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

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 micrometeorite impacts. Early telescopic observations and orbital measurements of the lunar surface at low spatial resolutions identified exposures of material within craters and basins thought to be evidence of the primary anorthositic crust that had been shocked during the impact process [e.g. 1-3]. These identifications were based on observations of high albedo regions with featureless near infrared (NIR) spectra, which are characteristics believed to be consistent with shocked or non-crystalline plagioclase (the dominant mineral phase in anorthosite). However, recent high spatial (20 to 500 m/pixel) and high spectral resolution (9 to 296 spectral bands) remote observations have confirmed the presence of crystalline anorthosite using the diagnostic absorption band near 1.25 µm indicative of plagioclase in these regions [e.g. 4-7]. While the spectrum of crystalline plagioclase has a diagnostic absorption band, the strength of this band can be weakened by at least two known surface processes (1) space weathering and (2) shock metamorphism [e.g. 1, 2, 6, 7]. This results in a spectrum nearly devoid of its initially observed absorption feature.

As multiple processes can remove the diagnostic NIR absorption of plagioclase, shocked anorthosite cannot be unambiguously identified based solely on NIR spectra. Recent investigations [6, 8, 9] have used a combination of the high spatial and high spectral resolution Moon Mineralogy Mapper (M^3) data along with geologic context from the Kaguya/SELENE Terrain Camera and Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) to identify shocked anorthositic blocks of material within the central peak of Theophilus crater and the Inner Rook Mountains of Orientale Basin. In addition, Denevi et al. [10, 11] recently demonstrated that crystalline anorthositic material can be distinguished from shocked and/or melted anorthositic materials across ultraviolet (UV) wavelengths in laboratory measurements and in global observations of the Moon by the LROC Wide Angle Camera (WAC). However, a detailed investigation into the observed characteristics of shocked anorthosites across a wide spectral range has yet to be completed. In this initial investigation, we combine remote sensing observations across a wide spectral range, from UV through to thermal infrared (~0.3 to 25 µm; TIR) to characterize shocked anorthositic material in impact craters and basins on the Moon.

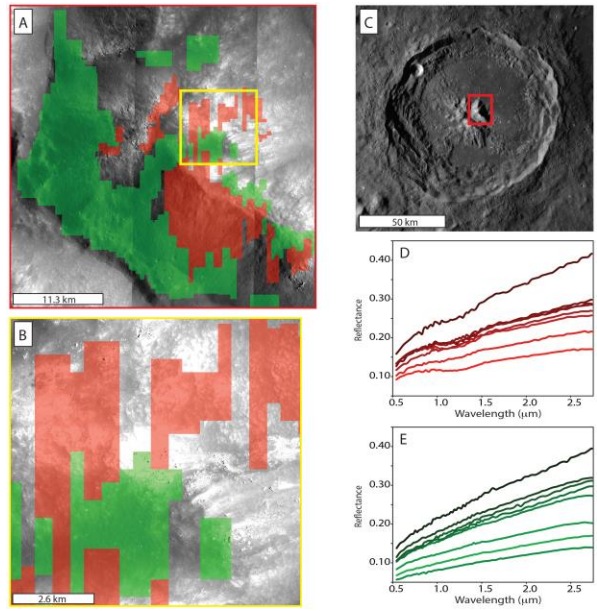

Figure 1. LROC WAC and NAC images of Theophilus crater **(11.4° S, 26.4° E; A, B, and C)** and M^3 spectra **(D and E)**. Red pixels and spectra highlight crystalline anorthosite units and green pixels and spectra highlight shocked anorthosite units.

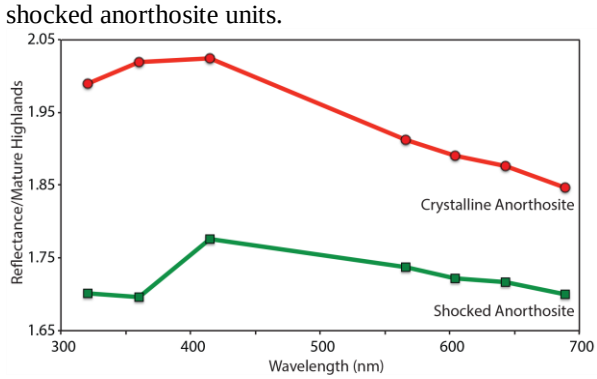

Figure 2. LROC WAC spectra extracted from crystalline anorthosite (red) and shocked anorthosite (green) regions that were identified in M^3 data (Figure 1).

Data and Methods: This initial study integrates M^3, LROC, and Diviner Lunar Radiometer (Diviner) observations for Theophilus and Jackson craters as well as Orientale Basin. Level 2 M^3 reflectance data across

the 0.4 – 3.0 μm spectral range for each optical period (OP) are utilized to prepare color composite maps using integrated band depths (IBD) at 1 μm, 1.25 μm, and 2 μm to highlight areas spectrally dominated by mafic minerals (e.g. pyroxene and olivine) and crystalline plagioclase [e.g. 6, 7]. M^3 spectra are extracted for relatively high and low 1.25 μm IBD areas to confirm the presence of crystalline plagioclase-rich units and possible shocked units with featureless NIR spectra, respectively.

Seven-band LROC WAC UV mosaics are used in the investigation of each crater and Orientale Basin. Color composite images utilize 321 nm/415 nm and 321 nm/360 nm ratios thought to highlight the different spectral features of crystalline and shocked and/or melted anorthosite [10, 11]. Spectra are extracted for regions with (1) high 321 nm/415 nm and low 321 nm/360 nm values and (2) low 321 nm/360 nm and low 321 nm/415 nm values to confirm the identification of crystalline anorthosite and shocked and/or melted anorthosite regions, respectively. To assess the nature of each anorthosite lithology WAC observations are compared with M^3 observations.

Finally, Diviner four-band TIR emissivity spectra and Christiansen Feature (CF) maps over each crater and Orientale Basin are derived from Diviner daytime radiance data. Data are binned and averaged at 128 pixels per degree and converted to emissivity spectra and CF maps as described in [12]. During this process, Diviner emissivity spectra and CF positions are corrected for local lunar time, latitude, and topography [13]. Additionally, the space weathering correction of Lucey et al. [14] is applied to remove the albedo effects caused by maturity. These are then used to characterise the TIR spectral changes due to shock by comparing with WAC and M^3 analyses.

Results: Here we initially focus on Theophilus crater as portions of the central peak were previously analyzed in detail and observed to have units of shocked and crystalline anorthosite [8, 9]. As seen in Figure 1, the northeastern part of the central peak shows clear distinction between the crystalline (red pixels) and shocked (green pixels) lithologies.

As seen in Figure 2, WAC spectra were extracted from the areas identified as shocked anorthosite using M^3 data. These UV spectra show a downturn at 415 nm thought to be characteristic of shocked anorthosite, although the up-turn at 360 nm is unlike lab spectra of shocked samples which continue to steepen relative to mature highlands spectra [10, 11]. WAC spectra taken from areas identified as crystalline anorthosite in M^3 are slightly different from their corresponding lab spectra and spectra of crystalline areas in other craters, with a down-turn starting somewhere between 360 and 415 nm for Theophilus as opposed to at 360 nm for lab spectra [10, 11]. Better spectral resolution is required to confirm that this is a real difference.

After comparison to the WAC color composite map it appears that the disparities may simply be due to the comparatively lower spatial resolution in WAC compared to M^3 data (400 m/pixel vs. 140 to 280 m/pixel, respectively), which leads to poor sampling over each area, obscuring features in the acquired spectra. The size of specific areas identified as either shocked or crystalline anorthosite is relatively small adding to the difficulty. Closer observation of the WAC color composite map does indicate small (<5 pixel) clusters of crystalline anorthosite in the same areas as those identified by M^3 (with spectral features of these areas closely matching those obtained from laboratory spectra of crystalline anorthosite samples [10, 11]).

Diviner CF data for the central peak of Theophilus crater shows no obvious difference in CF values for shocked and crystalline anorthosite units as identified in the M^3 and WAC data. These initial results corroborate earlier laboratory studies that showed no change in the CF position as anorthositic materials were shocked to varying degrees of pressure [e.g. 15, 16].

Future Work: Future work will focus on the integrated analyses of Jackson crater and Orientale Basin to begin to characterize shocked anorthosites across a wide spectral range (UV, NIR and TIR). In addition, detailed characterizations are needed to understand the general distribution of shocked anorthositic materials within impact craters and basins, 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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