RAPID (<2 MA) LUNAR SPACE WEATHERING PRODUCTS INDICATED BY APOLLO 16 'BIG MULEY' SAMPLE 61016.

C. M. Pieters[1], G. R. Osinski[2], T. Hiroi[1] [1]Brown University, Dept. Earth, Environmental, and Planetary Sciences, Providence, RI, 02912 USA (Carle_Pieters@brown.edu), [2] Institute for Earth and Space Exploration, University of Western Ontario, Canada

Introduction: The lunar highlands are dominated by feldspathic breccias that are believed to be the result of an extensive impact history of anorthositic crustal products derived largely from a primordial magma ocean. Global remote sensing of the lunar crust confirms that the highlands contain a lower abundance of mafic minerals than the younger (and darker) mantle-derived mare basalts emplaced across the Moon's battered surface. Returned samples and meteorites nevertheless reveal a complex diversity of feldspathic crustal rock types involving different concentrations of olivine, pyroxene, spinel, accessory minerals and radiogenic and rare-earth elements (KREEP). Although it is well known that the optical properties of lunar materials alter when exposed to the space environment [e.g. 1], the time scale for space weathering products to accumulate in a regolith is poorly constrained. We report coordinated spectroscopic and petrographic measurements from a well-documented Apollo 16 rock, 61016 'Big Muley', that suggest the weathering process can be relatively rapid for shocked anorthositic material exposed in the lunar environment.

Background: For several years we have been striving to make a stronger link between 'ground truth' spectroscopic measurements of lunar samples and remotely acquired spectra of feldspathic highland surfaces [2]. The pervasive presence and localized distribution in the highlands of relatively pure crystalline anorthosite has now been assessed with modern sensors based on the diagnostic absorption near 1.25 µm of plagioclase [3, 4]. Nevertheless, areas of bright, relatively freshly exposed highland materials often exhibit no identifiable spectroscopic features [4,5,6]. For the Moon, such highland areas without detectible mafic minerals have been interpreted to represent another form of anorthosite ('featureless' plagioclase) that has been altered by an extensive history of impact events and/or minor space weathering and mixing [6,7]. Although the strength of a diagnostic plagioclase absorption near 1.25 µm depends on the minor amount of iron present, the 1.25 µm absorption is prominent in samples with even 0.1% FeO [8]. On the other hand, no 'featureless' plagioclase has yet been identified in returned samples to verify an anorthositic interpretation of bright featureless highland material observed remotely.

Approach: We analyzed samples of individual lunar anorthositic lithologies. Particulate samples were prepared for spectroscopic analyses in RELAB and coordinated grain mounts were prepared for petrographic analyses at University of Western Ontario. For Apollo 16 sample 61016 we obtained an additional chip (,546) that retained a patina developed on the exposed surface. This 6 mm chip allowed spectra to be obtained for 2 mm areas across different lithologies.

Results: VNIR RELAB bidirectional reflectance (BDR) spectra for all samples are shown in **Fig. 1**, spliced with longer wavelength FTIR spectra at 2.5 µm. The location of samples from 61016 are shown in **Fig. 2**.

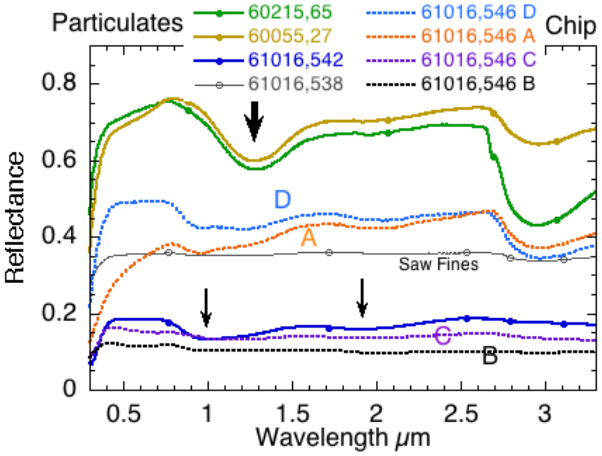

Figure 1. Reflectance spectra of particulate anorthositic lunar samples and four areas on the small chip of 61016. <u>Large arrow</u> indicates the absorption diagnostic of crystalline plagioclase and <u>small arrows</u> indicate the two glass absorption bands diagnostic of maskelynite (plagioclase diaplectic glass). [61016,538 saw fines are contaminated with minor fine grained metal.]

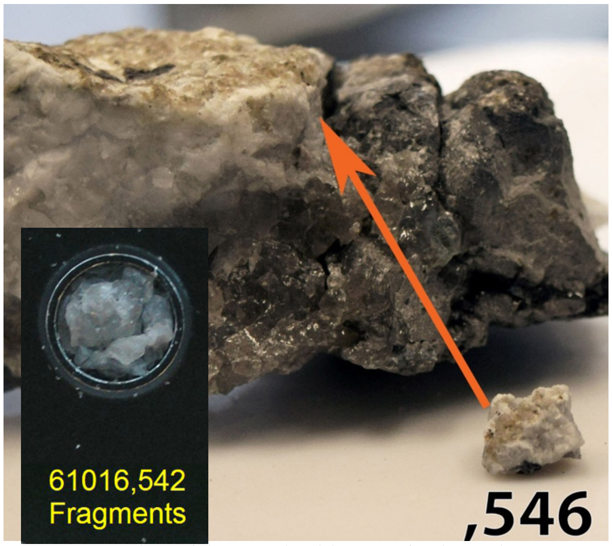

Figure 2. Portion of the anorthositic cap of 'Big Muley' 61016. The location of the ~6 mm 61016,546 chip from the shocked anorthosite is indicated. Particulate sample 61016,542 (shown in RELAB sample dish) was derived from the vitreous zone below the cap and contains abundant plagioclase diaplectic glass.

Sample 61016 'Big Muley' is a 11.7 kg rock collected by Charlie Duke at Apollo 16. It is believed to have been excavated by South Ray Crater, and dated at 2 Ma; it remained exposed to the environment since then [9].

Published FeO values for the plagioclase samples of Fig. 1 range from 0.15 to 0.33. The particulate samples of both **60215** and **60055** are bright and granular ~<200μm. 60215 contains several multi-grain particles up to 500 μm. These two samples are found to be almost entirely crystalline and grains exhibit only minor fractures. Both samples exhibit the well-defined 1.25 μm absorption diagnostic of crystalline plagioclase. In contrast, at least half the shocked **61016,542** particulate sample exhibits significant diaplectic glass with the remaining being crystalline plagioclase and partially isotropic material (i.e., incomplete transformation to diaplectic glass). The two bands at ~1 and 1.9 μm characteristic of diaplectic glass are well defined. The contribution of a superimposed 1.25 μm crystalline plagioclase band is also readily observed on expanded scale in **Fig. 3**.

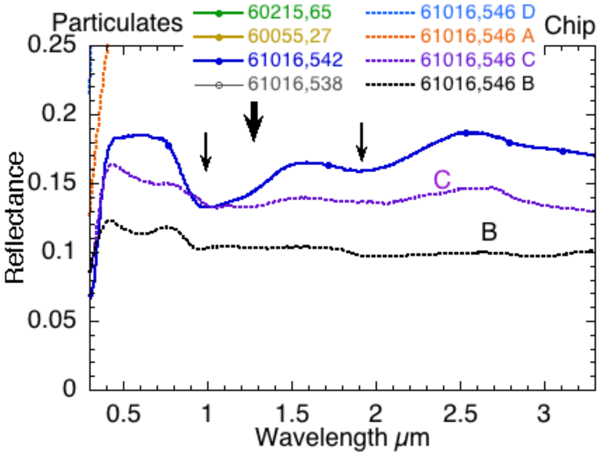

Figure 3. Expanded scale of Figure 2 illustrating the character of the diagnostic diaplectic glass absorptions (small arrows) and superimposed crystalline plagioclase band found in 61016,542.

The four areas measured on chip **61016,546** are ~2 mm across and are necessarily spatial mixtures. Areas **A** and **D** are part of the upper white feldspathic 'cap' seen in the small chip face shown in Fig. 2. Area **A** includes the uppermost surface that exhibits a patina, whereas the neighboring area **D** is slightly lower in the same unit, but without patina. Areas **B** and **C** are not seen from the view shown in Fig. 2. Area **B** is centered on an embedded unusual dark mineral clast, and area **C** occurs further toward the base of the 'cap' and consists of compact vitreous grains similar to those for 61016,542.

Discussion: Our coordinated analyses of 60215 and 60055 readily confirm the presence and character of the 1.25 μm absorption diagnostic due to crystalline plagioclase for these lunar samples. Similarly, the 1 and 1.9 μm absorption bands observed for the 61016,542 vitreous sample confirm the diagnostic absorptions of plagioclase diaplectic glass. Together, these observations allow direct interpretations of spectra for exposed areas A and D of the 61016 shocked anorthositic cap.

The spectra for 61016,546 areas A and D (Fig. 1) both exhibit the same combination of crystalline plagioclase (1.25 μm) and diaplectic glass absorption bands (1 and 1.9 μm) implying the presence of a highly shocked plagioclase mineralogy. However, the structure of the anorthositic 'cap' is much more friable and less vitreous than the larger grains immediately below (e.g., 61061,542). *Most notable* is that the exposed surface (A) that accumulated a patina after the rock was emplaced at Apollo 16 exhibits the classic optical properties of space-weathering npFe^0 products. Thus, this thin space weathering layer must have developed during the 2 Ma since South Ray Crater formation and emplacement of 'Big Muley'.

Remaining Issues: Although we have not yet confirmed that the 61016 observed patina in fact consists of npFe^0 (as expected from the spectra), 2 Ma must be a maximum time scale for its development. In reality, the patina most likely formed over a much shorter period since an exposed surface does not remain stable during millions of years due to constant micrometeorite erosion.

Another issue yet to be addressed is the origin of the iron necessary to create the observed npFe^0 on an anorthositic substrate. Although incomplete, most laboratory space-weathering experiments involving near iron-free minerals require an additional source for the iron [e.g. 10]. For the patina found on this 61016 anorthositic cap the iron might be provided by micrometeorites or redistribution of other local materials, but either source implies a tight coupling with some meteorite rearrangement of materials. Regardless, the observed npFe^0 patina cannot originate solely through solar wind interactions.

Acknowledgments: We are grateful for SSERVI support (NNA14AB01A) for this research.

References: [1] Pieters and Noble 2016, JGRP 121, 1865-1884. [2] Pieters et al., 2018, LPSC49 #1698; ---- 2019, METSOC Sapporo. [3] Ohtake et al. 2009, *Nature*, 461, 236. [4] Donaldson Hanna et al. 2014, *JGR* 119, 1516. [5] Hawke et al., 2003, JGR 108 E6. [6] Yamamoto et al., 2015, JGRP 120, 2190. [7] Lucey 2002, GRL 29, 1486. [8] Cheek et al., 2013, LPSC44 #2387. [9] Meyer 2009, 61016 Lunar Sample Compendium. [10] Gillis-Davis et al. 2012, LPSC43 #2664.