SPACE WEATHERING OF LUNAR ROCKS. S. K. Noble[1], L. P. Keller[2], R. Christoffersen[2] and Z. Rahman[2], [1]NASA GSFC Mail Code 691, Greenbelt MD 20771, sarah.k.noble@nasa.gov, [2]NASA JSC, Mail Code KR, Houston TX 77058.

Introduction: All materials exposed at the lunar surface undergo space weathering processes. On the Moon, boulders make up only a small percentage of the exposed surface, and areas where such rocks are exposed, like central peaks, are often among the least space weathered regions identified from remote sensing data. Yet space weathered surfaces (patina) are relatively common on returned rock samples, some of which directly sample the surface of larger boulders. Because, as witness plates to lunar space weathering, rocks and boulders experience longer exposure times compared to lunar soil grains, they allow us to develop a deeper perspective on the relative importance of various weathering processes as a function of time.

Samples: Building upon our earlier work on lunar rock 76015 [1,2] we have added observations from patina coatings on two other Apollo 17 rocks: 76237 and 72315. Both 76015 and 76237 originate from the Apollo 17 Station 6 boulders, which were emplaced approximately 22 million years ago based on cosmic ray exposure ages [3,4] (for comparison, a typical soil grain, has a lifetime of only ~10^4-10^5 years [5,6,7]). While the Station 6 rocks have the same exposure age, they differ in composition; 76237 comes from within a large plagioclase-rich clast.

Lunar rock 72315, from a Station 2 boulder, also has a space weathered patina, though its surface is considerably younger than the others, only about 0.1-0.3 Ma, based on cosmic rays, solar flares, and micrometeorite counts [8]. Looking at this younger, but still weathered, surface allows us to explore whether patinas quickly reach a steady state or if the products seen in our preliminary studies of 76015 require longer exposure times to develop.

Methods: After thoroughly examining the samples in SEM, regions of interest were selected for TEM analysis. Using a FIB (Focused Ion Beam) instrument, multiple cross sections through the weathered patina were produced from each of the samples and thinned for TEM analysis.

TEM work was done using the JEOL 2500SE 200 keV field-emission scanning-transmission electron microscope (FE-STEM) at JSC. The FE-STEM is optimazed for compositional spectrum imaging using a large-area, thin window energy-dispersive X-ray (EDX) spectrometer. Spectrum images of the sample were acquired with a 4 nm probe whose dwell time was minimized to avoid beam damage and element loss/mobilization during mapping.

Results and discussion: Similar sets of products are observed in all three samples (Fig 1) This includes: 1) solar wind irradiation surfaces 2) condensation of impact vaporized or solar wind sputtered material, 3) impact melt glass, 4) recrystallized grains, 5) and entrained grains and melt spherules.

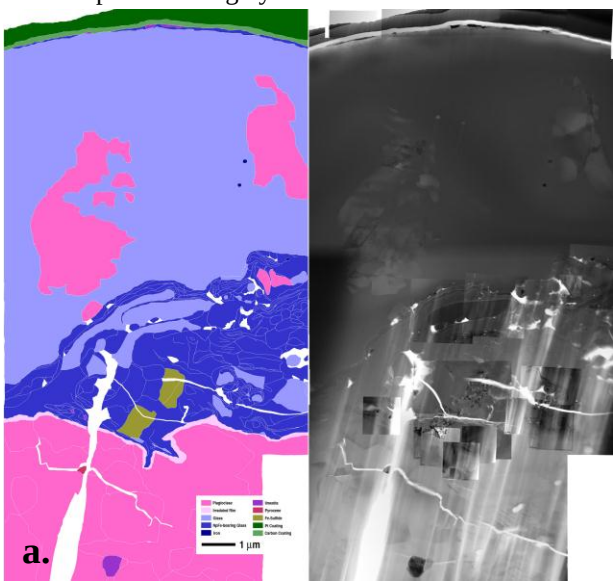
Immediately above the unaltered host rock, there is commonly an amorphous layer with an average thickness of ~100 nm, but ranging up to ~250 nm. This layer is derived by solar wind ion amorphization of the host rock's crystalline surface. Irradiation rims on lunar soil grains are typically thinner, (~20-100 nm thick [9]), likely owing to the shorter exposure time. Above this irradiation rim, the bulk of the patina coatings are composed of melt glass units, ranging in size from nanometers in thickness and diameter to several micrometers. The melt glass compositions vary widely, similar to the range seen in lunar agglutinates and spherules. There is no distinct difference in the average glass composition between 76015 and 76237 despite the differences in their substrates. This suggests that much of the melt is not locally derived and likely represents melts that were transported over distances as large as or larger than the size of the feldspathic clast (tens of centimeters).

Most of the glass units from all three rocks contain nanophase iron ($npFe^0$). In general, smaller melt units have higher modal concentrations of $npFe^0$ inclusions than larger ones. Vapor-deposited layers occur in several of the FIB sections, but are volumentrically a small component of the patina overall. The $npFe^0$ in the vapor deposited layers is typically smaller than in the melt glass, a distinction we have long recognized in lunar soils as well [10]. The size of $npFe^0$ has a predictable effect on the Vis/NIR spectra; smaller $npFe^0$ reddens while larger $npFe^0$ darkens [11]. Because of the surface area differences, vapor deposits should be less optically important for rock patina than in soils, which have much greater surface to volume ratios, thus we expect a weathered rock surface to be darker and less red than comparably weathered soils.

Several samples from all three rocks contained a notable thick iron-rich layer that appears to be a common feature of rock patina (Fig 2). In all cases the unit is high in Fe and Si and is loaded with $npFe^0$, typically larger blebs of $npFe^0$ than found in other glass units. The thickness, often elevated Ti contents, and the common schlieren-like features are consistent with deposition as a melt rather than vapor. The lack of nickel suggests a lunar, rather than meteoritic, origin.

These iron-rich units appear to be as common in the younger patina (72315) as in the older surfaces.

The patina is highly variable in thickness across even small distances; in some places it can be >10 μm thick (Fig 1a), in other places, bare rock is exposed (Fig 1b). This variability is a reflection of the stochastic nature of micrometeorite bombardment that both deposits and erodes. SEM analysis suggests that (not surprisingly), on average across the surfaces, the patina is thicker on the rocks with longer exposure times (76015 and 76237) than shorter (72315).



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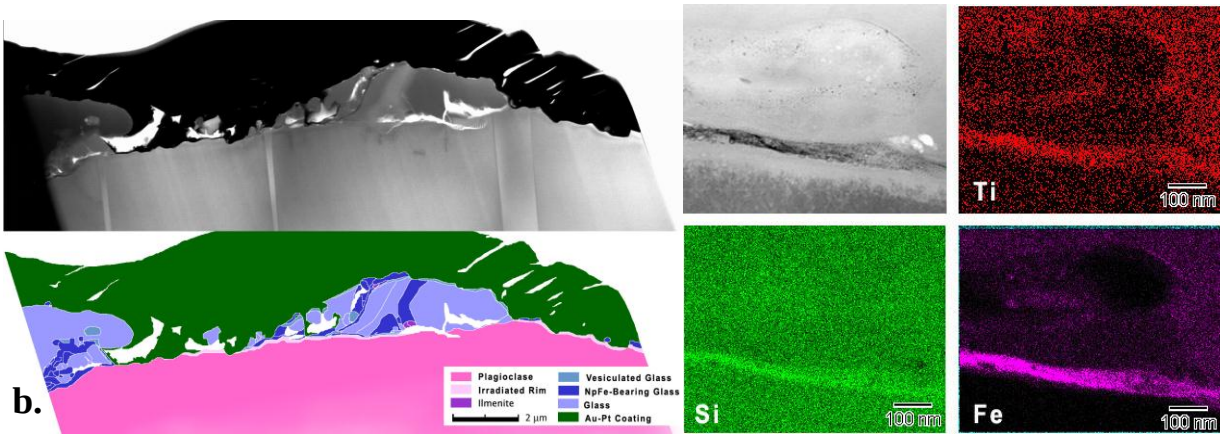

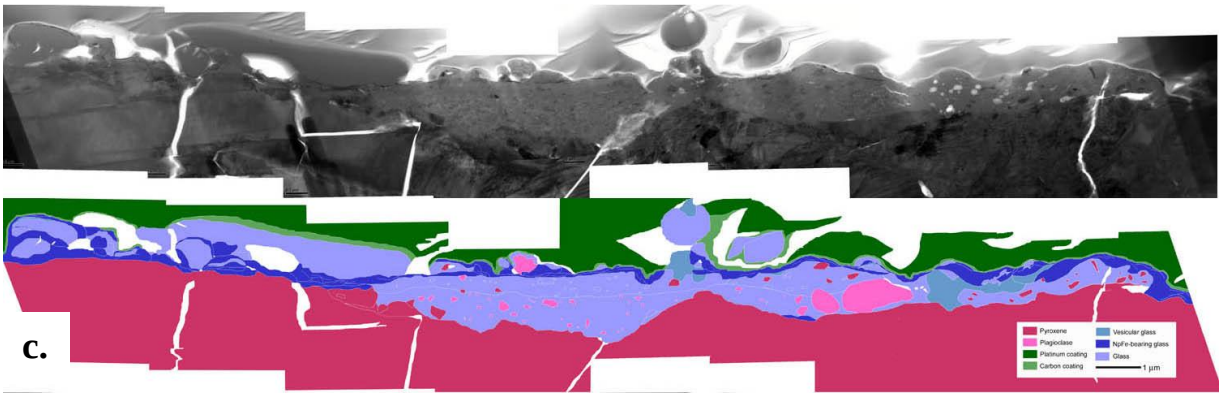

Fig 1. FIB samples from (a) 76237, (b) 76015, and (c) 72315. The thickness and composition of the patinas are highly variable, not only from sample to sample, but even across very small distances within a sample.

Fig 2. Chemical maps from a FIB sample of 76015 showing a melt layer enriched in Si and Fe, particularly $npFe^0$, these distinct layers are found in all three rocks.