CONTEXTING EXPERIMENTAL SPACE WEATHERING WITH LUNAR SOIL MATURITY.

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Introduction: Space weathering is a complex, multi-component process that occurs on atmosphereless bodies. Space weathering processes are most clearly understood for bodies where both spectra and samples have been obtained (i.e. the Moon and Itokawa). Having spectra and samples allows comparisons between the physical modifications and optical maturation of these bodies [e.g. 1,2,3].

Alternatively, experiments allows us to expand our understanding of space weathering to materials that represent other atmosphereless bodies not yet sampled by spacecraft. There are a wide variety of experimental methods aimed at reproducing space weathering trends (e.g. pulsed laser irradiation [4,5], ion bombardment [6,7], kinetic energy experiments [8]), but as of yet it is unclear how well each of these methods reproduce actual trends on atmosphereless bodies.

I_s/FeO values of lunar soils provide useful criteria to study the spectral variations of lunar soils as a fuction of exposure age (i.e. maturity) [9]. The Lunar Soil Characterization Consortium (LSCC; eg. [10]) also compared the spectral trends as a function of I_s/FeO values for a large suite of soils and found the optical properties are highly dependent on I_s/FeO.

The aim of this work is to study the effectiveness of experimental methods in reproducing the spectral trends observed in lunar soils. In particular, we compare the visible and NIR trends of Apollo soils to the trends from different types of space weathering experiments performed on lunar and lunar analog materials. Thus by using I_s/FeO values of 0-30 for immature, 30-60 for submature, and >60 as mature, we are able to characterize experimental trends in relation to the optical maturity of lunar soils.

Methods: We used a Nd:YAG, 1064 nm wavelength, pulsed laser to simulate micrometeorite impacts on San Carlos olivine (SCO), a lunar highlands analog (LHA), and an interior piece of an Apollo rock sample 68416 (A68416), which was crushed to make an immature regolith. The LHA was is composed of of 85% Stillwater plagioclase (An_{80}), 10% orthopyroxene ($Wo_1En_{69}Fs_{30}$), and 5% SCO (Fo_{90}). A68416 is predominately plagioclase (~80%), with accessory pyroxene (12-16%), minor amounts of olivine (<5%), and Al_2O_3 content of 28% wt.%. Each sample was crushed and dry-sieved to <75 µm. A 0.5g of SCO, and 0.2g each of the LHA and Apollo samples were irradiated using a laser spot size of 0.25 mm and an incident energy of 30mJ. A frequency of 20 Hz and a 6-8 nanosecond pulse duration was used to simulate timescales of 10 µm sized micrometeorite impacts [11]. SCO and the LHA samples were irradiated at intervals of 8.0, 8.0, 9.0, 7.0, and 8.0 minutes for a total of 40 minutes. A68416 was also irradiated for a total of 40 minutes except at intervals of 5.0, 5.0, 10.0, 10.0, and 10.0 minutes. Each of the samples were irradiated as uncompressed powers and under vacuum pressures of 10^{-5} to 10^{-6} mbar.

Spectral data were taken using a Vis/NIR (350-2500nm) ASD Fieldspec 4 spectroradiometer. Bidirectional reflectance spectra were acquired at a standard viewing geometry of i=30° and e=0°, and measured relative to a 99% reflectance LabSphere Spectralon Standard. We combine our spectra with Vis/NIR spectra of Apollo soils from the NASA RELAB facility [12] for which I_s/FeO values have been measured [9,10].

We employ principal component analysis (PCA) on the spectra to conduct a set of linear transformations and obtain a set of eigenvectors that allows us to best visualize the variance between our experimental data and Apollo soil spectra. In addition, we used previously published spectra of other space weathering ex-

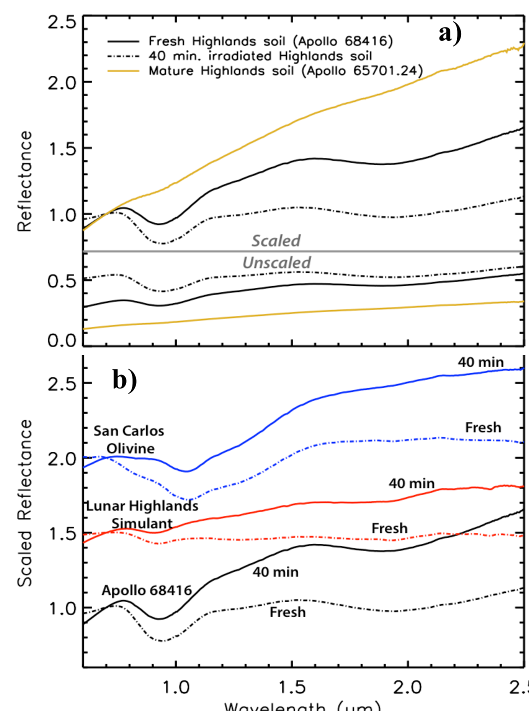

Figure 1: a) Spectra of a fresh and irradiated lunar highlands soil produced from A68416 and a mature highlands soil. b) Spectra scaled to values at 0.7 µm for each of the samples irradiated in this study. Spectra have been offset for clarity.

periments that have been conducted on SCO in our analysis. Interpolation was used to adjust each of the spectra to a consistent wavelength scale. Due to limitations in the wavelength coverage for some of the data, PCA analysis was restricted to a wavelength range of 0.6 to 2.5 µm. Each of the spectra was normalized to reflectance values at 0.7 µm prior to PCA.

Results: Figure 1a shows the albedo (unscaled) and slope (scaled to 0.7 µm) evolution of our fresh highlands soil as a function of irradiation time in comparison to a mature highlands soil (65701.24) that was collected in-situ. The irradiated A68416 soil shows a noticeable drop in reflectance, an increase in spectral slopes, and a reduction in absorption features after 40 minutes of irradiation. However, it is clear that even after 40 minutes, our sample is still much less optically mature compared to the 65701.24 highlands soil. Figure 1b shows the spectra of each of our laser irradiated samples that have been scaled to reflectance values at 0.7 µm. After 40 minutes of irradiation, the SCO and A68416 samples show similar degrees of reddening. Although the LHA has a similar mineral mode as the A68416 sample, it is clear from Fig. 1b that the fresh spectra are noticeably different. The fresh LHA is significantly flatter and brighter (not shown here) than the fresh A68416 sample and after 40 minutes of irradiation, the LHA shows a much smaller degree of reddening than the irradiatied A68416 sample.

Figure 2 shows the results of the PCA applied to the spectra of our irradiated samples, the Apollo soil

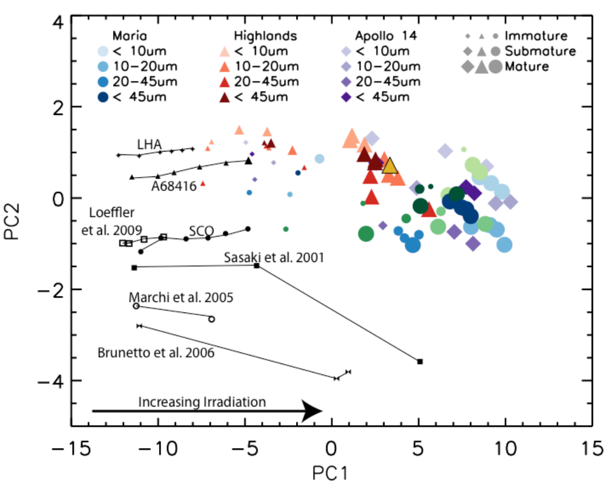

Figure 2: A comparison of the first two principal components of experimental data and Apollo soils. Immature refers to Apollo soils with I_s/FeO<30, submature 30<I_s/FeO>60 and mature I_s/FeO>60 [9]. *Note: The green circles represent Hi-Ti Mare soils, and the gold color Highland soil represents the mature soil used in Fig. 1a.*

spectra from RELAB as well as experiments conducted by [4,5,6,7]. We find that PC1 is directly correlated with slope, thus an increase in slope results in an increase in PC1. PC2 appears to be related to curvature variations in the data [13]. PC1 (slope) space is most sensitive to soil maturity.

The fresh LHA and Apollo 68416 samples are distinct from the Apollo soils in PC1 space and suggest that even the most immature lunar soils have experienced some degree of weathering. The progression of our samples in PC space indicates that our laser irradiation experiments slowly matures each of the samples used in this study, and even after 40 minutes of irradiation, the samples only begin to transition from the immature to submature region of PC space.

While laser irradiation experiments on SCO by [4,5] result in a greater range in PC1 space, the PC2 variations appear to evolve away from the region of the lunar soils. The ion bombardment experiments on SCO by [7] show a similar progression in PC space as our data, however, experiments by [6] also diverge from lunar soils in PC2 space.

Conclusions: PCA allows us to characterize the level of spectral maturation of our irradiated samples relative to lunar soils, which span a wide range of I_s/FeO (i.e. maturity). As of yet it appears that our laser irradiation experiments require additional irradiation time (~40-60 minutes) in order to achieve a spectral maturity consistent with I_s/FeO values of greater than 60 (mature). Nonetheless, our experiments mature samples along similar PC evolutionary tracks as lunar soils. Future work will include measuring I_s/FeO of laser irradiated soils in order to compare the actual maturity index with the samples' spectral maturity.

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Acknowledgements: This work was funded by NASA's *Solar System Exploration Research Virtual Institute* VOlatiles Regolith Thermal Investigations Consortium for Exploration & Science grant to APL and J.J. Gillis-Davis.