EVALUATING SPACE WEATHERING AND SURFACE EXPOSURE TIMESCALES FOR GRAINS FROM APOLLO 17 CORE SAMPLE 73002. J. A. McFadden[1], M. S. Thompson[1], L. P. Keller[2], R. Christoffersen[3], R. V. Morris[4], C. Shearer[5], and the ANGSA Science Team[6] [1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907, (mcfadde8@purdue.edu) [2]ARES, Code XI3, NASA/JSC, Houston, TX 77058 [3]Jacobs, NASA Johnson Space Center, Mail Code XI, Houston, TX 77058 [4]NASA-JSC, Houston, TX, USA [5]Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131 [6]ANGSA Science Team list at https://www.lpi.usra.edu/ ANGSA /teams/. (cshearer@unm.edu).

Introduction: Space weathering causes the surface soils of airless bodies like the Moon to be morphologically, microstructurally, and chemically altered due to micrometeoroid bombardment and solar wind exposure [1]. These processes produce a multitude of microstructural and chemical changes to individual soil grains that accumulate over time with continued exposure on the surface. One type of change is the formation of altered rims on regolith grains, due to various combinations of direct ion damage from the solar wind and local condensation of impact-generated silicate vapors. Also present are solar flare tracks (SFT), which are nanoscale lineations within grain interiors formed by heavy, high energy ions (predominantly Fe group nuclei) originating from solar flares and similar energetic particle events penetrating millimeters within the surface [2]. Recent work has determined that the width of solar wind-damaged rims on anorthite and olivine, and their respective SFT densities are correlated with each other and with grain surface exposure ages [3].

Core sample 73002, recently released under the Apollo Next Generation Sample Analysis (ANGSA) Program, has provided an opportunity to study material collected from the light mantle formation explored in the Taurus-Littrow Valley by Apollo 17. The formation is thought to have been deposited via an avalanche originating from the neighboring South Massif [4]. Preliminary spectral profiles and ferromagnetic resonance measurements of bulk soils sampled at cm-intervals from 73002 indicate that the upper 9.5 cm of regolith have maturity indices consistent with longer durations of surface processing than samples deeper in the core. [5,6]. Here we present the first observations of microstructural and chemical variations in grains in the 73002 core sample made at the sub-micron scale by transmission electron microscopy (TEM)

Methods: Bulk samples of regolith from the first eight intervals and every following fourth interval down the core (dissection Pass 2) were delivered to Purdue University as <45 μm size fractions. The first three intervals, representing the top 1.5 centimeters of regolith, were individually dry sieved into <20 μm size fractions, and prepared by ultramicrotomy for analysis in the scanning transmission electron microscope (STEM). Bright field (BF) and dark field (DF) STEM images of solar flare tracks and space-weathered rims were acquired on a JEOL 2500SE TEM, equipped with a 60 mm^2 ultrathin window silicon drift energy dispersive X-ray (EDX) spectrometer at NASA Johnson Space Center. Nanoscale compositional variations in grains were mapped by X-ray energy-dispersive (EDS) compositional spectrum imaging. SFT densities and amorphous rim thicknesses were measured on BF and DF images.

Results: The majority of grains studied by TEM showed significant evidence of space weathering. BF and DF STEM images show splash-melt and vapor deposited rims on outermost grain margins with embedded Fe-bearing nanoparticles ranging in size up to ~10 nm in diameter (Fig. 1). Images also show solar-wind damaged rims below the vapor deposits, and SFT present in grain interiors. The rim thicknesses and SFT densities were determined using the methods of [3] for six grains from Interval 1,five grains from Interval 2 and four grains from Interval 3. With the exception of two olivine grains in Interval 1, all of the grains were ~An_{90} anorthite.

A track production rate of $4.4 \pm 0.4 \times 10^4$ tracks cm^{-2} yr^{-1} was calculated in [3] for surface exposed regolith grains and used to estimate the surface exposure times of the grains in this study. Exposure times are in the 1 - 5 MY range, with a low value of 9 x 10^5 years in Interval 1 and a maximum of 4 x 10^6 years in Interval 2 [Fig. 2]. The track densities and solar wind damaged rim thickness for individual grains show no significant variation with interval depth.

SFT densities were compared to amorphous or nanocrystalline rim thicknesses of their respective grains.

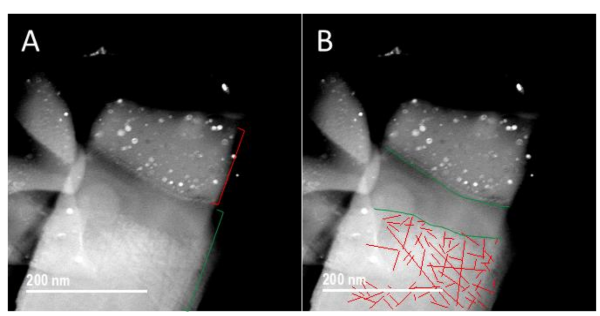

Figure 1: DF STEM images of A) a lunar anorthite rim with the red bracket identifying splash melt containing metallic Fe nanoparticles and the green bracket denoting the grain interior; B) the amorphous rim is bounded in green and SFTs traced in red.

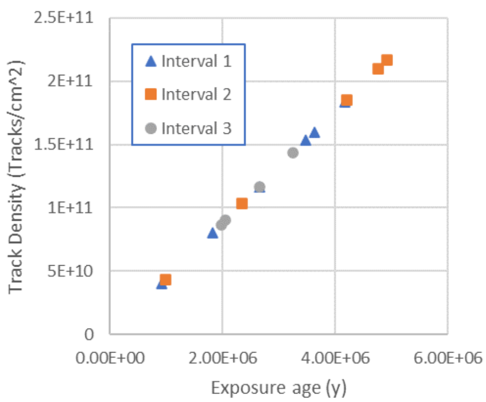

Figure 2: A) Distribution of SFT density with calculated exposure ages.

Fig. 3 shows that rim thickness and SFT density is strongly correlated for both olivine and anorthite grains.

The minimum and maximum rim thickness for anorthite were 24 nm and 66 nm, respectively. In contrast, for olivine the minimum was 64 nm and maximum was 112 nm. As expected, olivine rim thickness increases much faster over the same track production timescale compared to anorthite [3].

Discussion: The <20 µm size fraction of the top 1.5 cm of 73002 bulk soil composition is primarily anorthite, exhibiting very few mafic minerals. A grain population dominated by plagioclase is advantageous for our work as anorthite is the most well constrained mineral for analyzing solar flare tracks and amorphous rims. Our results for olivine, although limited at this point, provides an opportunity to further contrast the relative effects of solar wind and solar flare exposure on both mineral types.

The lack of measurable interval-to-interval track density distributions in the top 1.5 centimeters of 73002 implies that the soil has experiencing effective regolith reworking at the uppermost surface, which is within the bounds of space weathered soil depth concluded by [5,6] and modern regolith mixing models [7]. The models, however, consider impacts as the sole means of regolith mixing, while this core has been collected from an area which has undergone regolith overturn via avalanche. Vertical regolith mixing subsequent to avalanche emplacement may be representative of the intervals discussed in this paper. Lateral mixing may be better represented deeper within the core. Analysis of deeper intervals will be required to determine if lateral mixing mechanisms should be considered.

A maximum surface exposure age determined via SFT density is approximately 5 million years. This is consistent with the lower estimate of surface exposure ages of the light mantle determined in previous studies, which can range from 10s to over 100 Ma [4]. The limited number of analyzed grains restrict the implications that can be made regarding the history of the light mantle deposit. Additional analysis will be performed for an additional 12 intervals in 73002 and the lower portion of the core (sample 73001) which is yet to be released.

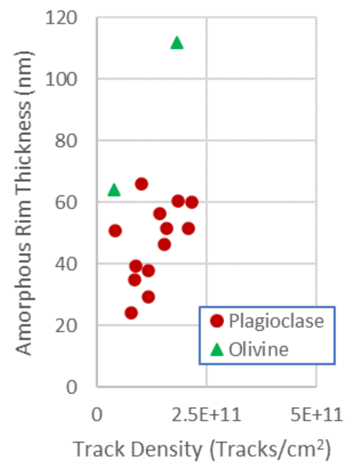

Figure 3: Amorphous rim thickness and respective solar flare track densities.

Spectral and FMR analysis performed by [5,6] concluded that the reworking zone of 73002 extends to 9.5 to 14 cm in depth, well beyond the depth of this study. With this in mind, we currently have samples from the first 8 intervals embedded and analysis of SFT densities is progressing. In addition, an interval by interval modal analysis of grain mineralogy will be developed to better understand the compositional diversity of grains in the <20 µm size fraction compared to the bulk soil.

Conclusions: SFT densities and amorphous or nano-crystalline rim widths were measured in space weathered <20 µm sized anorthite and olivine grains within the first 1.5 cm of Apollo core sample 73002. These values correspond to surface exposure ages ranging from approximately 1 to 5 million years. SFT density variability with respect to grain depth suggests that these intervals are well mixed in accordance with previous spectral observations and regolith mixing models. Additional grains will be analyzed to develop more in depth conclusions regarding the nature of regolith mixing and possible discontinuities within the geologic context of the 73002 core.

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