NANOMETER-SCALE CHEMICAL MAPPING OF SPACE WEATHERED LUNAR SOIL: A NEW VIEW.

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Introduction: The term "space weathering" refers to the cumulative effects of several processes operating at the surface of any solar system body not protected by a thick atmosphere. These processes include cosmic and solar ray irradiation, solar wind implantation and sputtering, as well as micrometeorite bombardment [e.g. 1 and references therein]. In lunar soils the most voluminous weathering products are agglutinates, glass welded aggregates created via micrometeorite bombardment. In addition, space weathering produces thin (60-200nm) amorphous rims surrounding individual grains in mature soils [2]. Although less voluminous than agglutinates, amorphous rims are surface-correlated, and thus play a larger role in altering the spectral properties of soils [3].

Weathered rims are created by both depositional and erosional processes. Material is deposited by impact-generated melts and vapors as well as through sputtering. Erosional processes also include sputtering, as well as irradiation. Rims are often characterized by inclusions of nanophase iron ($npFe^0$). These nanometer-scale inclusions of metallic iron are also observed in agglutinitic glass. The abundance and distribution of $npFe^0$ is the primary cause of spectral alteration of lunar soils [4].

The basic processes and products underlying space weathering and the optical changes associated with the phenomenon are becoming better understood, but there are still many open questions about the rates and relative importance of various processes and the compositional dependence of the various components of the weathering process. New instrumentation and techniques allow us to examine these weathering products with unprecedented detail, providing fresh insights and an improved understanding of space weathering processes.

Methods: For these analyses, we used the recently installed JEOL 2500SE 200 keV field-emission scanning-transmission electron microscope (FE-STEM) at JSC. The FE-STEM is equipped with a large-area, thin window energy-dispersive X-ray (EDX) spectrometer to obtain spectrum images of grain rims in ultramicrotome thin sections (~50 nm thick) of Apollo 11 soil 10084 (sub-20 μm sieve fraction). Each pixel of a spectrum image contains a full EDX spectrum, enabling the determination of quantitative element abundances on the scale of individual pixels. Spectrum images of the lunar grains were acquired with a 4 nm incident probe whose dwell time was minimized to avoid beam damage and element diffusion during mapping. Successive image layers of each rim were acquired and combined in order to achieve suitable counting statistics for major elements (e.g. Mg, Al, Si, Ca, Ti, and Fe) in each pixel.

Discussion: Sample 10084 is a very mature soil rich in agglutinitic glass with most grains displaying evidence for space weathering effects. Maps were acquired from grains of plagioclase, cristobalite, olivine, pyroxene, and ilmenite, as well as glass. Depositional rims on silicate grains, including both melt and vapor deposited material are chemically distinct from their host grains. Spectrum images of these rims often show complex, compositionally distinct layering on the nanometer-scale (e.g. Figure 1). The rim in Figure 1 records the deposition of multiple layers of melt glass over the host grain. Complexity on this scale is common in the soil.

Distinct differences were observed between the rims on oxides and those on silicates. Previous work [2, 5, 6] has shown that ilmenite and other oxides exhibit complex chemical and structural changes in response to solar wind radiation. Sputtering and radiation results in the reduction of some iron in the outer layers of the mineral producing $npFe^0$ in addition to the $npFe^0$ that condensed from the vapor phase (Fig. 2). The spectrum images of ilmenite rims show that the Fe-depleted, Ti-rich surface layers produced by irradiation are common, as are surface accumulation of deposited components (e.g. amorphous silicate material). Ilmenite rims are often thinner than those on silicates. These differences may be related to different residence times based on observed solar flare track densities. Ion-mixing of the deposited rims with the irradiated rims in ilmenite complicates their interpretation.

Conclusions: Quantitative X-ray mapping with a new generation FE-STEM reveals incredible complexity within lunar weathering products. Weathering products are found to be heterogeneous at the nanometer-scale, implying multiple processes and a complex history involving multiple events. In addition, the production of weathering products is found to be dependent, in part, on the composition of the grain substrate.

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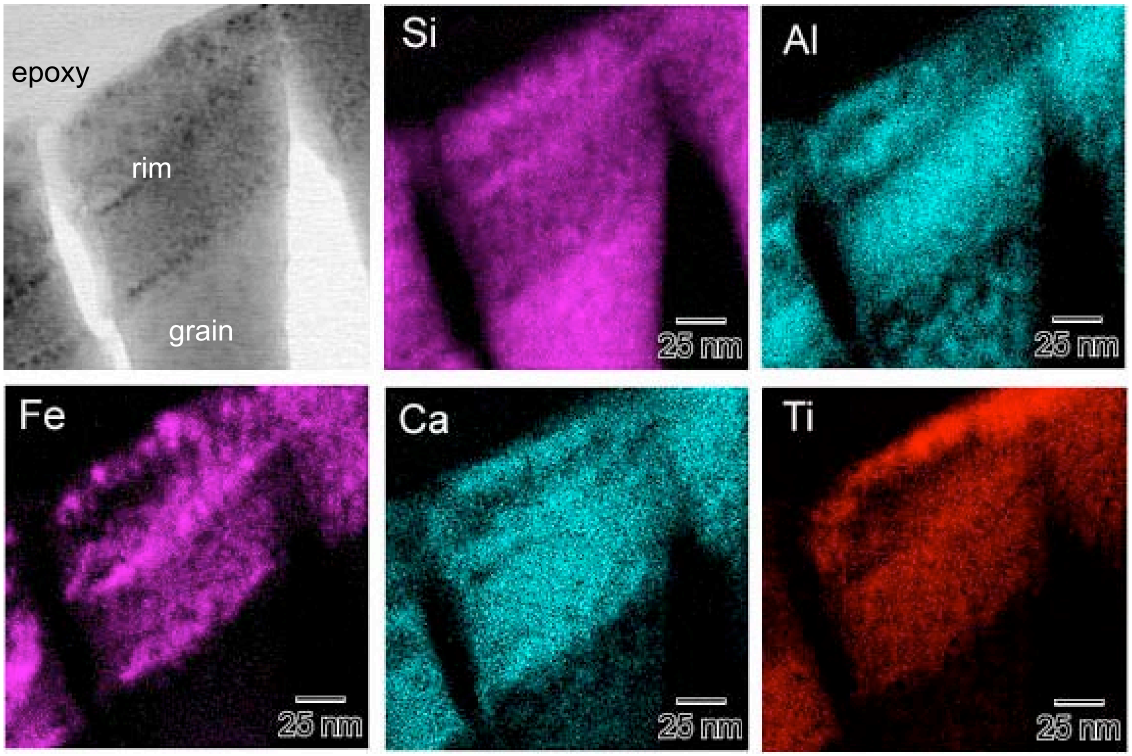

Figure 1. Multiple layers of glass deposition are evident in the elemental composition of this complex rim on a silicate grain.

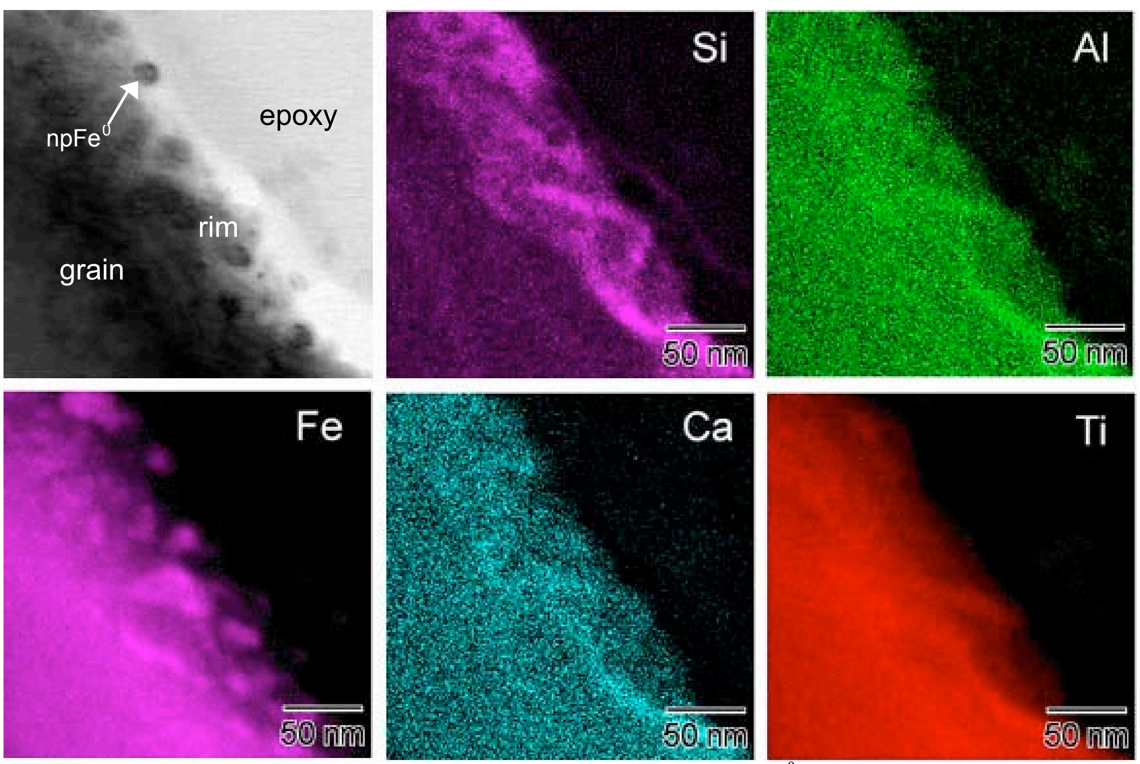

Figure 2. This is a typical rimmed ilmenite grain. The rim contains npFe^0 blebs and is enriched in Ti. In addition, the rim has incorporated Si and other foreign components.