NANOSCALE ANALYSIS OF SPACE-WEATHERING FEATURES IN SOILS FROM ITOKAWA

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Introduction: Space weathering alters the spectral properties of airless body surface materials by reddening and darkening their spectra and attenuating characteristic absorption bands, making it challenging to characterize them remotely [1,2]. It also causes a discrepency between laboratory analysis of meteorites and remotely sensed spectra from asteroids, making it difficult to associate meteorites with their parent bodies. The mechanisms driving space weathering include micrometeorite impacts and the interaction of surface materials with solar energetic ions, particularly the solar wind. These processes continuously alter the microchemical and structural characteristics of exposed grains on airless bodies. The change of these properties is caused predominantly by the vapor deposition of reduced Fe and FeS nanoparticles (npFe^0 and npFeS respectively) onto the rims of surface grains [3].

Sample-based analysis of space weathering has traditionally been limited to lunar soils and select asteroidal and lunar regolith breccias [3-5]. With the return of samples from the Hayabusa mission to asteroid Itokawa [6], for the first time we are able to compare space-weathering features on returned surface soils from a known asteroidal body. Analysis of these samples will contribute to a more comprehensive model for how space weathering varies across the inner solar system. Here we report detailed microchemical and microstructural analysis of surface grains from Itokawa.

Samples and Methods: In this study we analyzed Itokawa samples RA-QD02-0042-01, -02, and -03. Each of these samples is an ultra-microtomed transmission electron microscope (TEM) section prepared by the Hayabusa mission curation team. These samples are sections of one particle that originally measured 96.2 µm. A selection of the slices in these samples were previously analyzed and shown to exhibit evidence of space weathering [7-9].

We analyzed the microtome slices using: a 200 keV JEOL 2010F TEM at Arizona State University, a 200 keV JEOL 2500SE field-emission S/TEM at NASA JSC, and a 200 keV FEI OSIRIS ChemiSTEM at FEI headquarters. The assemblages were imaged in conventional bright-field (BF) and both bright-field and dark-field (DF) scanning TEM (STEM) modes. Selected area electron diffraction (SAED) was used to identify grain mineralogy. Their compositions were measured using thin window Si(Li) detectors on the 2010F and the 2500SE, and a quad-annular SDD detector on the ChemiSTEM.

Results: Over 40 individual sections of this assemblage were analyzed from the three allocated samples. The assemblage is primarily composed of low-Ca orthopyroxene with embedded Fe-S and Fe-Ni-S grains. There are also smaller, peripheral regions of plagioclase, olivine, Fe-Ni metal, and other Fe-Ni sulfides.

We see several features indicating that these grains have been subjected to space-weathering processes. The most significant feature is a microstructurally and compositionally complex rim on the orthopyroxene and plagioclase particles. High-resolution TEM (HRTEM) imaging shows a discontinuous zone of partial amorphization on the outer rim of the orthopyroxene that extends between 10 to 60 nm into the grain interior. In this zone, localized nanocrystalline domains are interspersed with amorphous material. In contrast, a completely amorphous rim of uniform thickness (20 nm) is found on the exterior of the plagioclase grain (Fig. 1).

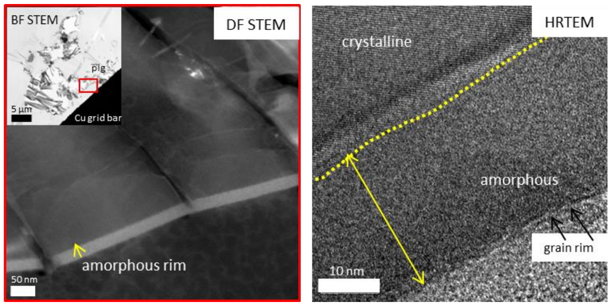

Figure 1: *Left: DF STEM image of the amorphous rim on the plagioclase grain (inset image shows location of the rim). Right: HRTEM image showing uniform thickness of the rim and complete amorphization.*

High-angle annular dark field (HAADF), HRTEM, and EDS-spectrum imaging reveal dual-layer rim features displaying local chemical and structural heterogeneity on regions of the orthopyroxene grain exterior. The outer layer is predominantly nanocrystalline, uniform in thickness (2 to 5 nm), and is enriched in Fe and Mg and depleted in Si relative to the bulk orthopyroxene interior (Fig. 2). The interior layer is also uniform in thickness (2 to 5 nm), but exhibits an enrichment in Si and depletion in Fe and Mg relative to the grain interior. This underlying layer is also amorphous (Fig. 3).

In addition to altered grain rims, we have observed nanophase Fe particles (npFe^0), melt islands, and vesiculated textures. HAADF imaging and EDS-spectrum imaging show a high concentration of uniformly dis-

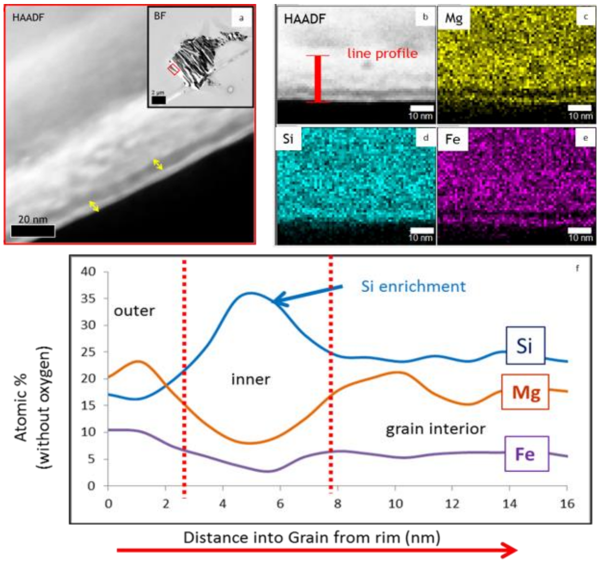

Figure 2: *a) HAADF image of the dual layer rim, indicated by yellow arrows on the exterior of the orthopyroxene grain. Note the layers are uniform in thickness and extend along the rim consistently. Inset shows the rim location on the assemblage. b) Higher magnification HAADF image. c-e) EDS spectral images of Mg, Si and Fe (1 nm probe). Dual layer rim is visible and corresponds to HAADF image. f) Compositional profile (excluding oxygen) of the rim along the line shown in b). Zone labelled 'outer' represents the outermost layer, enriched in Fe and Mg and depleted in Si relative to the bulk grain. 'Inner' refers to interior layer, enriched in Si.*

tributed npFe^0 particles, 2-3 nm in size, in localized regions of the orthopyroxene rim, occurring up to 60 nm from the grain surface. BF, HRTEM and EDS-spectrum imaging also reveal amorphous melt 'islands' on the surface of the orthopyroxene grain as well as vesicles. The islands are enriched in Fe, Mg, and S relative to the underlying grain. Both well and poorly developed vesicles (10 to 20 nm in size) occur within the outer rim of the grains up to 30 nm below the surface in a partially amorphous matrix. We attempted to find but were ultimately unable to observe any distinct solar flare tracks in these assemblages.

Discussion: Our results show grains from the surface of Itokawa have experienced a complex processing history. Interaction with solar-wind ions (H^+ and He^+) generated zones of total and partial amorphization and vesiculated textures on the rims of these grains. The theoretically predicted depths of penetration for these particles [8] is consistent with the thicknesses of these amorphous zones. The discrepancy between the depth and degree of amorphization in pyroxene and plagioclase could suggest that these minerals, though currently part of one complete assemblage, were not exposed at the surface of Itokawa for the same duration of time. Alternatively, the chemical and structural differences between these minerals may result from a non-uniform response to radiation damage.

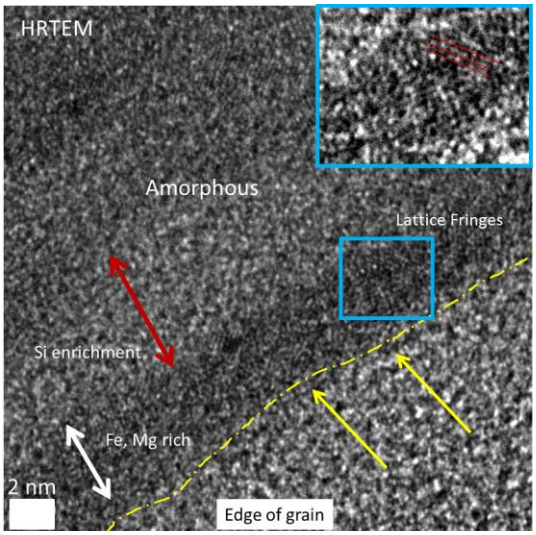

Figure 3: *HRTEM image showing chemically heterogeneous dual-layer rim. Outer zone (Fe, Mg rich) is nanocrystalline (inset). Underlying Si-rich zone is mostly amorphous.*

Forthcoming theoretical calculations and experiments could help to provide an upper limit for the exposure time of these grains and provide insight into mineral response to solar wind ion irradiation.

The data we report here suggest that micrometorite impacts also play a role in space weathering on the surface of Itokawa. The amorphous melt islands, exhibiting distinct chemical compositions from their underlying 'host' grains, suggest formation through the melting/vaporization of adjacent mineral grains in an impact event on the surface and the subsequent redeposition of this material.

The TEM data suggest that a combination of vapor redeposition from both radiation processing and micrometeorite impacts contributed to the formation of the dual-layer, chemically and structurally heterogeneous zone on the rim of the pyroxene grain. The npFe^0 particle concentration is most similar to immature lunar soils and suggests contributions from space-weathering mechanisms occurring over a short exposure time, relative to timescales for more mature lunar soils. We hypothesize that such a short exposure time is due to high frequency stirring events on the Itokawa surface.

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