Space weathering of sulfides and silicate minerals from asteroid Itokawa

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Space weathering refers to the progressive spectral, microstructural, and chemical alterations of mineral grains on the surfaces of airless planetary bodies [1]. These changes are produced by high-velocity micrometeoroid impacts and solar wind irradiation, causing vesiculation, melt and vapor deposits, sputtering, ion implantation, and amorphization on regolith grains. Spectrally, space weathering produces multiples alterations in the visible near-infrared (VNIR) wavelengths, including reddening, darkening, and attenuated absorption bands [1]. The spectral anomalies have been attributed to the presence of Fe nanoparticles (npFe) that are mainly composed of metallic iron ($npFe^0$). Analyses on individual lunar grains show that the spectral alterations in the VNIR depend on the particle size, where npFe with diameters < 5 nm produce reddening, whereas particles >10nm produce darkening [2]. In 2010, the Japan Aerospace Exploration Agency (JAXA) Hayabusa mission successfully collected 1534 regolith particles from the surface of S-type asteroid Itokawa [3]. Prior to sample return, S-type asteroids were hypothesized to be the parent bodies of ordinary chondrites; however, the spectral characteristics of the meteorites in our collections differed from these asteroids. Geochemical analyses in Itokawa particles indicated a composition similar to LL4-LL6 chondrites [3], corroborating the link between ordinary chondrites and S-type asteroids and demonstrating the importance of space weathering studies for accurate characterization of asteroidal surfaces.

Previous studies have identified space weathering features in Itokawa regolith particles, including disordered rims, chemically distinct layers, whisker-like structures, sulfur depleted rims, and Fe^0 and FeS nanoparticles [4,5,6,7,8]. Most space weathering studies have concentrated on understanding the response of silicate minerals to interplanetary space [4,9,10] as these phases are the most common in lunar samples and Itokawa particles. However, our understanding of the behavior of other minerals under space weathering conditions is still in a very early stage. Among these understudied minerals are sulfides which are present in the sample collection of asteroid Itokawa [11] and are relevant minerals in carbonaceous chondrites [12], thought to be meteoritic counterparts of asteroids Bennu, Ryugu, and Psyche [13,14,15].

To compare the responses of silicates and sulfides under space weathering conditions, we performed coordinated analyses of the RC-MD01-0025 Itokawa grain previously identified to contain olivine, low-Ca pyroxene, and Fe-Ni- sulfides. We embedded the particle in low-viscosity epoxy and prepared electron transparent thin sections with an approximate thickness of 50 nm using a Leica EM UC7 ultramicrotome. To identify microstructural and chemical properties associated to space weathering in silicate and Fe-Ni- sulfide grains in the Itokawa particle, we used a FEI Talos 200 KeV transmission electron microscope (TEM) coupled with a Super –X silicon drift detector (SDD) energy-dispersive X-ray spectrometer (EDS). The sample preparation of the Itokawa particle and the electron microscopy analyses of the ultramicrotomed samples were performed at Purdue University.

Bright-field (BF) TEM imaging shows the presence of a ~50 nm mottled rim in an olivine grain (Fig. 1a). Chemically, EDS maps show the rim presents three layers (Fig. 1b,c). Layer 1 (L1) thickness is ~30 nm and shows similar O, Mg, Fe, and Si concentrations as the bulk grain. Layer 2 (L2) has a thickness of 5-10 nm and presents depletion of Mg, Fe, and enrichment of Si compared to L1. Layer 3 (L3) has a thickness of 5-10 nm and is Si depleted compared to L1 and L2; it is enriched in Fe and Mg compared to L2 but depleted in these elements compared to L1. High resolution (HR) TEM images show an amorphous region in the rim's outer 5-10 nm with some nanocrystalline regions. The nanocrystalline domains present d-spacing values of 0.20 nm that correspond to $npFe^0$. Metallic iron nanoparticles were previously identified in silicates and Fe-sulfides in Itokawa regolith particles [4,5]. The identification of chemically distinct layers in returned samples [4,6,7] and in H^+ irradiation experiments on olivine [16] suggests this multilayer rim might correspond to a combination of sputtering, redeposition, and ion irradiation damage processes.

High resolution (HR) TEM imaging of the Fe-Ni- sulfide grain shows d-spacing values of 0.28 nm similar to (222) pentlandite and the presence of a ~5-10 nm rim that presents nanocrystallinity (Fig. 2a). EDS mapping shows that the rim is depleted in Ni and S but enriched in Fe compared to the bulk mineral (Fig. 2b,c). Previous studies in Itokawa samples have identified sulfur-depleted rims Fe-sulfides [5,17], and the origin of these rims is attributed to solar wind damage. The depletion in S and Ni and the enrichment of Fe of the rim suggest it might have formed in a complex process of sputtering and redeposition. The microstructural and chemical characteristics in the olivine and pentlandite grains further indicate that solar wind irradiation is the main contributor to the space weathering of both mineral phases. Future work will include the TEM and EDS analyses of the low-Ca pyroxene grains present in the RC-MD01-0025 regolith particle. In addition to TEM and EDS, we will perform electron energy-loss spectroscopy (EELS) to compare the oxidation state of Fe between the mineral grains and the space weathered rims. Understanding how different mineral phases respond to space weathering conditions using returned samples is crucial to accurately interpret remote sensing observations of the surfaces of airless bodies and adequately characterize the regolith samples collected from asteroids Ryugu and Bennu.

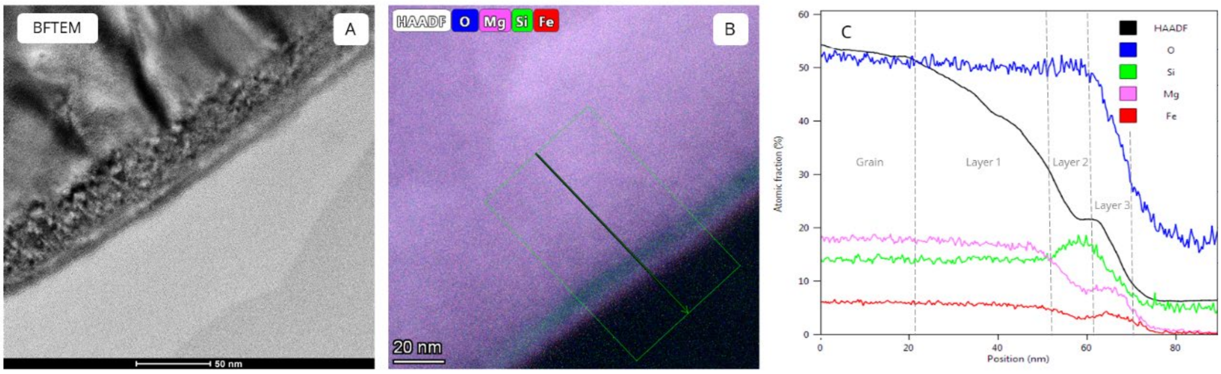

Figure 1. Space weathered rim on olivine grain. a) Bright field (BF) TEM image shown the ~50 nm mottled rim on olivine. b) High-angle annular dark field image overlain with EDS maps (O, Mg, Si, Fe). c) EDS line scan showing the chemical layering of the rim.

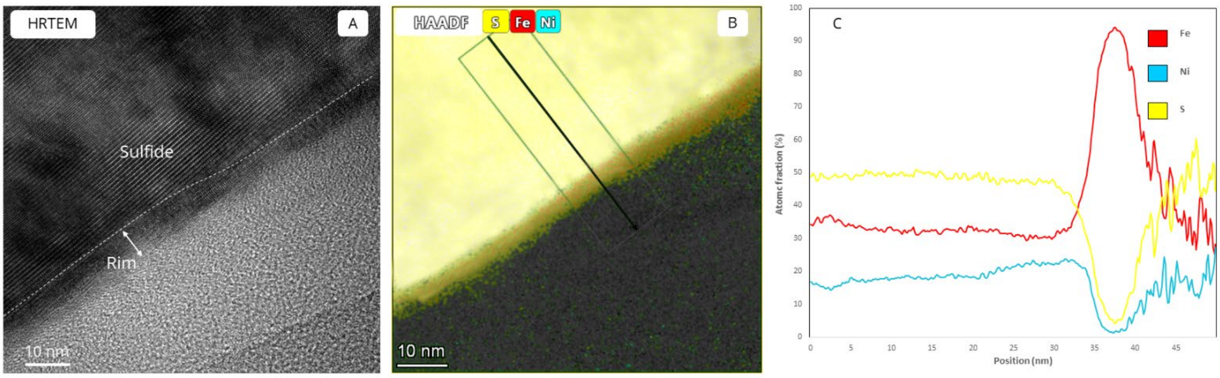

Figure 2. Space weathered rim on Fe-Ni- sulfide grain. a) High-resolution (HR) TEM showing the presence of a 5-10 nanocrystalline rim. b) High-angle annular dark field (HAADF) image overlain with EDS maps of S, Fe, and Ni. c) EDS line scan showing the Ni and S depletion on rim compared to the bulk mineral.

References

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