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STEM of Three Itokawa Grains: Space Weathering and Presence of Cubanite

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The particles from asteroid Itokawa along with data collected by the Hayabusa spacecraft tell of a young surface, frequently stirred up and refreshed, on a rubble-pile asteroid composed of equilibrated and unequilibrated LL4-6 ordinary chondrite material [1-3]. Although the majority of examined particles show low degrees of exposure to the space environment, the Itokawa particles do exhibit a number of classic space weathering features known from lunar space weathering studies, including amorphous rims, vesicular rims, and presence of nanophase metallic iron inclusions ($npFe^0$) [3,4]. They also possess some features not seen in lunar samples, including Fe-sulfide nanoparticles in thin surface layers [3,4], that highlight the differences in composition and processes occurring the two bodies. Each newly studied particle adds to the story of space weathering on Itokawa or reveals something new about its exposure history [5-8].

The three grains examined for this study, RA-QD02-0114, RB-CV-0038, and RB-QD04-0045, are complex multiphase grains, each 40-60 µm across. Each grain was mounted in epoxy such that most of the grain was available for imaging then coated by 60-80 nm of evaporated carbon. SEM images and FIB samples were obtained with an FEI Helios G3 equipped with an Oxford 150 mm^2 SDD energy dispersive X-ray spectrometer (EDS). After imaging, protective straps of C or Pt were deposited on regions of interest, and multiple sections suitable for STEM analysis were extracted from each particle using standard techniques. STEM analysis was performed with the Nion UltraSTEM200-X at NRL. The microscope is equipped with a Gatan Enfinium ER spectrometer for electron energy loss spectroscopy (EELS) and a windowless, 0.7 sr Bruker SDD-EDS detector. Data were collected at 200 kV.

All three grains are predominantly composed of the silicate phases olivine, high-Ca pyroxene (HPx), low-Ca pyroxene (LPx), and plagioclase. Two of the grains (0038 and 0045) contain the iron sulfide pyrrhotite, and minor merrillite (Ca-phosphate) and chromite were also noted. The compositions of the silicate phases all fall within the ranges expected for ordinary chondrites and are consistent with equilibrated LL material. However, in addition to these expected phases, a ~2 µm Cu-Fe-sulfide grain is present with the pyrrhotite at interface with the olivine in particle RB-CV-0038 (Fig. 1). The composition of the Cu-Fe-sulfide is close to $CuFe_2S_3$, consistent with cubanite. Cu metal is relatively common in ordinary chondrites [9], but cubanite has only been identified in CI chondrites and Comet 81P/Wild2 samples [10,11]. The combination of pyrrhotite and cubanite together indicates low temperature (< ~210°C) hydrothermal alteration [10] and would not be present in material exposed to the thermal alteration experienced by the equilibrated LL5-6 grains [2]. The cubanite has an open crack with oxidized magnetite edges that is decorated by Cu metal nanoparticles, indicating oxidizing conditions during alteration of the grain. Both the cubanite and pyrrhotite lack Ni. The formation and processing conditions suggested by these phases means it is likely the cubanite and pyrrhotite in the grain are exogenous to the Itokawa parent body although the olivine in the grain is compositionally the same as that in other Itokawa grains.

The space weathering features observed include thin, damaged (but not amorphous) rims in olivine, LPx and HPx, vesicles in HPx (Fig. 2a), 1-3 nm $npFe^0$ in olivine and LPx rims (Fig. 2b), a single layer of $npFe^0$ on the surface of plagioclase (Fig. 2c), and depletion of S relative to Fe at the surface of the pyrrhotite. All of these features are again consistent with relatively young exposure ages. Additionally, the surface of the olivine in 0045 is fractured but shows no other rim features (Fig. 2d), and several of the phases in multiple grains have thin (~10 nm) oxidized rims, with iron oxide nanoparticles present on the pyrrhotite in some regions.

High resolution examination of particles from Itokawa continues to reveal new details of its space weathering exposure history. All of the particles examined here have low degrees of space weathering, and basically all observed features can be attributed to irradiation by the solar wind. There are variations between particles and phases within each particle, with HPx rims containing a higher abundance of vesicles than neighboring phases while 1-3 nm $npFe^0$ are most prevalent in olivine rims. Oxidized rim material is present on multiple grains and phases but varies in extent. RB-CV-0038 contains cubanite that is likely exogenous.

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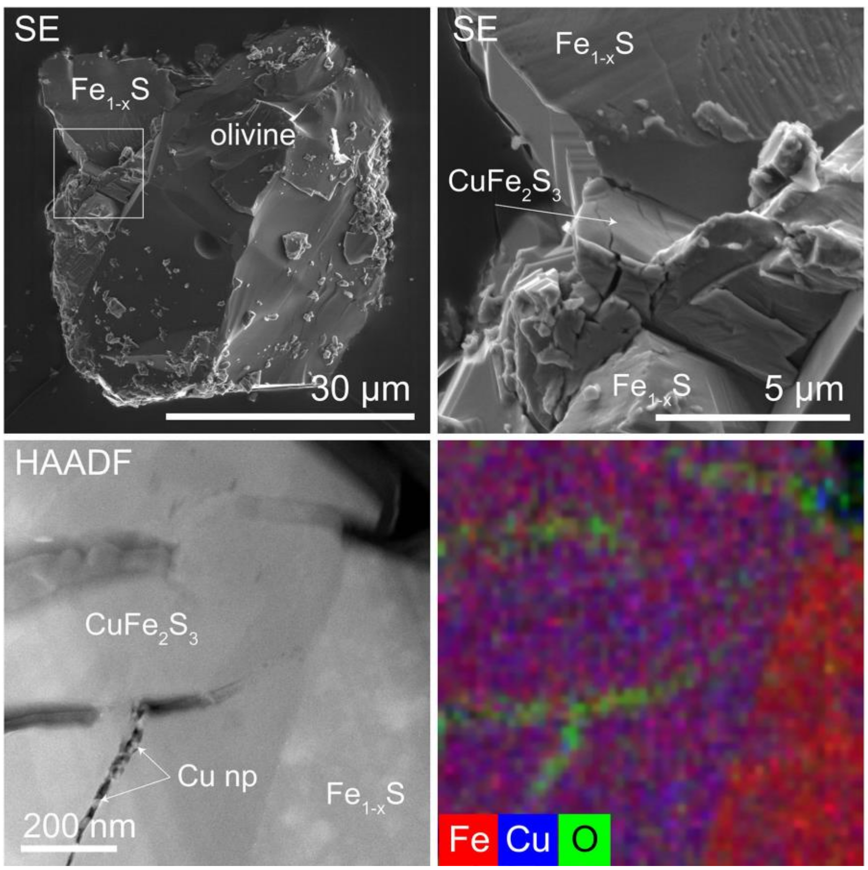

Figure 1. A cubanite grain was identified in RB-CV-0038. It has a crack decorated with Cu metal nanoparticles and magnetite rims.

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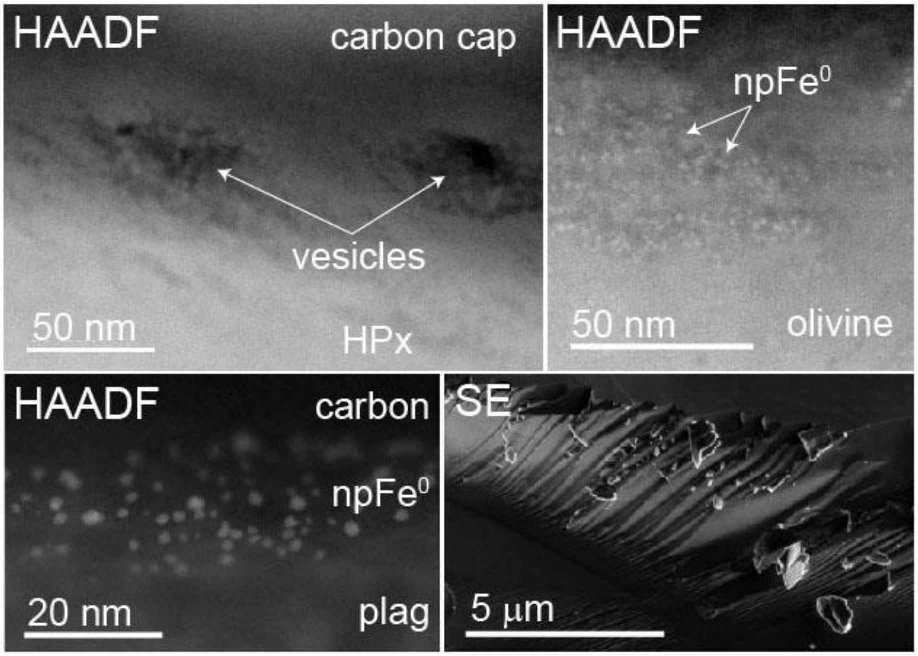

Figure 2. Images from Itokawa particles showing (a) vesicles in HPx, (b) npFe0 in olivine, (c) npFe0 are present at the surface of a plagioclase grain, and (d) fractured olivine surface decorated with adhered particles.

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