Introduction: The fine-grained matrices of carbonaceous chondrites have long been considered a proxy for the degree of secondary alteration within their asteroid parent bodies. With the return of samples from asteroids Itokawa and Ryugu, their fine-grained matrix is being similarly evaluated as indicative of parent body alteration. Some anhydrous chondritic interplanetary dust particles (IDPs) and Antarctic micrometeorites (AMMs) are indisputably the least altered meteoritic materials, presumably because they were preserved from small, frozen cometary parent bodies at large heliocentric distances. These least altered IDPs and AMMs contain glass embedded with metal and sulfides, or GEMS [1]. Since these IDPs and AMMs are likely examples of nebula dust accreted by asteroids, evaluations of asteroid alteration degree (via meteorites and returned samples) necessarily starts with IDPs and AMMs. Compositions and crystallography are well documented, and yet there are few one-to-one comparisons, to date, of IDPs and AMMs with fine-grained matrix in chondritic meteorites and returned samples at the requisite nano-scale. We previously described analyses of FIB-extracted and microtomed Ryugu samples [2,3]. We found that compositions of GEMS in IDPs overlap those of texturally similar regions in highly porous Ryugu grains, but nanoscale mineralogy differs. Here we describe analyses on additional FIB-prepared samples of the least altered Ryugu lithology.

Samples and Methods: We were allocated two FIB sections, C0002-P5_FIB001 and FIB002, by JAXA Curation. We characterized these at the Molecular Foundry, Lawrence Berkeley National Lab at 300 kV using a low-base TitanX “ChemiSTEM” with four windowless X-ray silicon drift detectors (~0.7 sr, Bruker); and a high-base 80-300 keV STEM instrument with a monochromator, one chromatic and two spherical aberration correctors, and a Continuum electron energy-loss spectrometer with a K3 direct electron camera (Gatan-Ametek Inc.) enabling single electron detection for imaging and spectroscopy. In addition to imaging, we applied X-ray energy-dispersive and (monochromated) electron energy-loss spectrum images (EDS and EELS maps), in conjunction with scanning nanodiffraction or 4D-STEM to recover pixel-by-pixel diffraction and crystal structures information.

Results: We selected regions of Ryugu matrix that most closely resemble anhydrous IDP matrices, specifically regions with both (organic) carbon and “GEMS-like” objects. Figure 1 shows an example GEMS-like object consisting of Fe, Ni and S-rich inclusions in silicate Mg-Fe matrix and surrounded by diffuse carbonaceous material. Close inspection of the O, Mg and Si maps shows that, in contrast to bona fide GEMS in anhydrous IDPs, the GEMS-like matrix is a poorly crystallized fibrous layer silicate. Two compositionally distinct sulfides are observed, Ni-rich (upper left and right in Fig. 1 Ni map) and Ni-poor, consistent with pyrrhotite, surrounding the GEMS-like object (center). However, S and Ni maps (Fig. 2) show that Ni-poor inclusions are likely altered pentlandite, rather than unaltered pyrrhotite, with localized S depletions and residual Ni hotspots evident.

Figure 1: Darkfield (HAADF) image of Ryugu GEMS-like object and corresponding EDS spectrum images showing distribution of C, O, Mg, Al, Si, S, Fe and Ni.

Figure 2: Higher magnification S and Ni spectrum images of the “GEMS-like” object in Fig. 1. The white arrow indicates an altered sulfide with a remnant high-S core. Ni has diffused throughout the layer silicate matrix.

HOW PRIMITIVE IS THE FINE-GRAINED MATRIX OF RYUGU? H. A. Ishii1, J. P. Bradley1, K. C. Bustillo2, C. Song2, and J. Ciston1. 1Hawai’i Institute of Geophysics and Planetology, University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA. 2National Center for Electron Microscopy, Molecular Foundry, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA. (hope.ishii@hawaii.edu).
Structural (crystallographic) properties were evaluated using 4D STEM. (See [4] for an overview and application to Ryugu samples.) Pixel-by-pixel (7×7 nm) diffraction patterns were recorded on a two-dimensional grid over the selected field of view (Fig. 3). Diffuse scattering in C0002-P5_FIB001 is due primarily to carbon and, to a lesser extent, poorly-ordered layer silicate matrix (Fig. 3c). Strong Bragg scattering is due to well-crystallized sulfide inclusions (Figs. 3b & 3d).

Iron oxidation states and spatial distributions in the C0002-P5_FIB001 sample were determined using EELS (Fig. 4). Two Fe oxidations states, Fe²⁺ and Fe³⁺, were detected using MLS fitting with reference spectra from Fe metal and oxides. The layer silicate matrix contains Fe²⁺ and Fe³⁺, and the sulfides are Fe²⁺. Notably, metallic Fe⁰ (or Ni⁰) were not detected by EELS or 4D STEM, and Fe and Ni are coincident with S in EDS maps.

**Discussion:** Overall, we find that the GEMS-like objects and matrix in the FIB sections of least altered Ryugu lithology are oxidized, consistent with aqueous alteration. Inclusions are predominantly pentlandite and, although both pentlandite and pyrrhotite have been identified in Ryugu samples, sulfides with pyrrhotite compositions in these GEMS-like objects we studied are consistent with (aqueously) altered pentlandite. Metal, a characteristic component of GEMS, is conspicuously absent. The matrix within GEMS-like objects as well as the surrounding matrix consist of poorly crystallized fibrous layer silicate. We conclude that the GEMS-like objects in the Ryugu FIB sections we studied are not consistent with *bona fide* GEMS as observed in IDPs and AMMs.

We have considered the possibility that the GEMS-like objects in Ryugu may once have been GEMS that have since been aqueously altered; however, the sulfides in the GEMS-like objects are consistent with aqueously altered pentlandite suggesting, instead, that these objects may represent the remnants of alteration of, perhaps, larger primary pentlandite grains that have since experienced additional aqueous processing. Other regions with GEMS-like objects in Ryugu also contain carbonates and phosphates, indicative of considerable aqueous processing [2,3]. Thus, it is unlikely the GEMS-like objects in Ryugu represent heavily altered *bona fide* GEMS.

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