MICROSTRUCTURE OF SULFIDE-ASSEMBLAGES IN A RENAZZO TYPE-II CHONDRULE AS REVEALED BY TRANSMISSION ELECTRON MICROSCOPY. D. L. Schrader[1], T. J. Zega[2], D. S. Lauretta[1], and H. C. Connolly Jr.[1,3,4] [1]Univ. of Arizona, Lunar and Planetary Laboratory (LPL), Tucson, AZ 85721, USA, (schrader@lpl.arizona.edu), [2]Materials Science and Technology Division, Naval Research Laboratory, Code 6366, 4555 Overlook Ave. SW., Washington DC, 20375, [3]Dept. Physical Sciences, Kingsborough Community College of CUNY, 2001 Oriental Blvd., Brooklyn N.Y. 100235, USA and Dept. Earth and Environmental Sci., The Graduate Center of CUNY, [4]Dept. Earth and Planetary Sciences, AMNH Central Park West, New York, N.Y. 110024, USA.

Introduction: Sulfides are ubiquitous within type-II chondrules and the matrix of CR chondrites [1,2,3]. Metals and sulfides are highly susceptible to alteration and therefore they can further our understanding of nebular and parent-body processes recorded in the CR chondrites. Our previous efforts have focused on textural and compositional analysis of sulfide-assemblages within type-II chondrules from the CR2 chondrites MAC 87320, EET 92011, and Renazzo using electron microprobe analysis (EMPA) [3]. Since many of the sulfide-bearing assemblages are too fine-grained for individual mineral analysis using EMPA, we report a combined focused ion beam scanning electron microscopy (FIB-SEM) and transmission electron microscopy (TEM) analysis of their microstructure.

Analytical Procedure: We used an FEI Nova 600 FIB-SEM at the Naval Research Laboratory to extract specific areas and thin them to electron transparency. We used milling and extraction procedures similar to those previously described [4], except that sections were welded to Cu half-grids. We extracted three 10-µm long FIB sections for TEM analysis from one type-II chondrule within Renazzo (section USNM 1123-1). We analyzed the FIB sections with a 200 keV JEOL 2200FS TEM equipped with an energy-dispersive X-ray spectrometer (EDS) and bright- and dark-field scanning TEM (STEM) detectors.

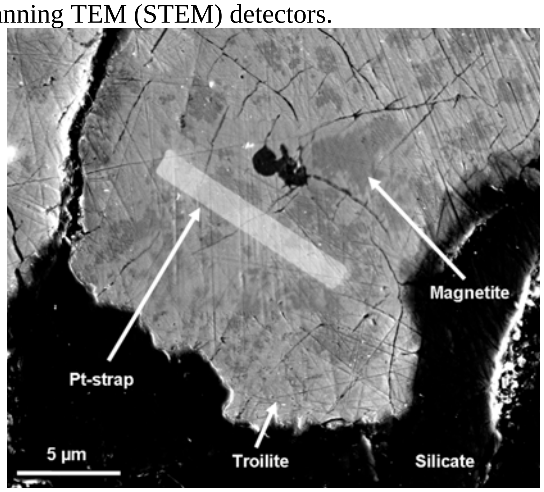

Figure 1. BSE image showing Pt-strap superimposed over a sulfide assemblage in Ch11, ROI-A. EMPA suggests dark patches are likely magnetite, while lighter areas are troilite.

Results: We extracted samples from three regions of interest (ROI) from Renazzo Chondrule 11 (Fig. 1-4; see [3] for detailed petrography). ROI-A and C are from fine-grained (<5 µm) areas in which EMPA suggest magnetite, troilite, and possibly tochilinite are intimately mixed (Fig. 1). ROI-B transects a pentlandite grain and the fine-grained mixture.

ROI-A: This region contains subhedral grains composed of Fe, O, and Cr (Fig. 2). This grain is crystalline and selected-area electron-diffraction (SAED) measurements and EDS spectra are consistent with Cr-bearing magnetite. Diffraction contrast in the bright-field image reveals a larger assemblage (~1 µm wide) composed of closely orientated magnetite grains that are surrounded by pyrrhotite (Fig. 2). The assemblage contains parallel fractures that are associated with currently uncharacterized lenses that the HAADF imaging indicates have higher average Z.

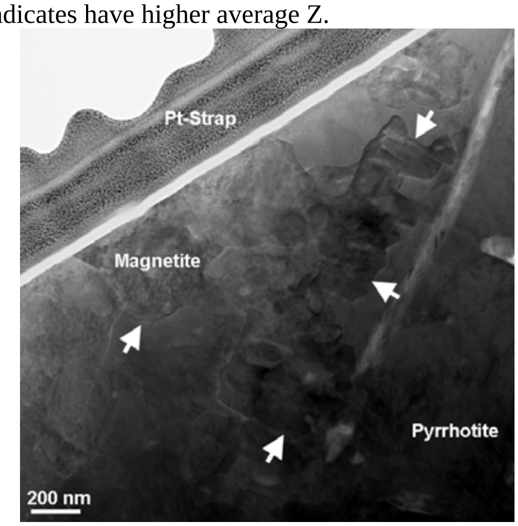

Figure 2. Bright-field TEM image of part of the FIB section from ROI-A. Magnetite occurs surrounded by pyrrhotite. The boundary of the magnetite assemblage is marked by white arrows.

ROI-B: Pentlandite dominates the majority of the section (Fig. 3). It varies in composition and morphology. A large crack separates the pentlandite grain nearest to the surface from that on the bottom. Bright-field imaging of the pentlandite at the bottom of the section shows a detailed microstructure. There are dark-contrast features that appear linear and extend across the section and others that occur in between at varied angles. HAADF imaging indicates that some of these features have higher contrast than the bulk pentlandite, suggesting higher average Z. EDS shows that the lower pentlandite grain has a higher Ni content than that near the surface.

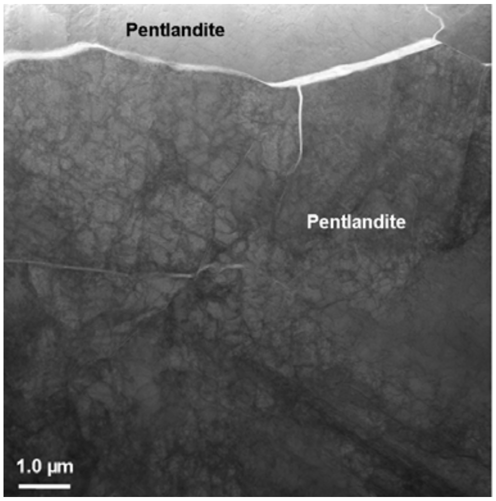

Figure 3. Bright-field STEM image of part of the FIB section from ROI-B. The pentlandite near the surface (top) shows uniform contrast, whereas that on the bottom is heterogeneous and reveals the detailed structure.

ROI-C: Pyrrhotite is the most abundant phase observed (Fig. 4), and has a hexagonal structure. We acquired SAED patterns from five different areas of the FIB section. Three of these indexed to the pyrrhotite [302] zone axis; the other two are closely oriented to [302] (within a few degrees). Therefore, the abundant polycrystalline grains of pyrrhotite are nearly uniformly oriented. Pyrrhotite crystal boundaries are parallel to fractures and bright lenses. Tochilinite is tentatively identified from two separate SAED patterns of a small grain, ~0.2 µm across.

Discussion: EMPA suggested that the fine-grained sulfide-assemblage consists of a mixture of magnetite, troilite, and possibly tochilinite, with pentlandite along the sulfide's edge. In comparison, the TEM data indicate the presence of pentlandite with at least two different Ni contents, that magnetite is present as sub-µm to µm-sized grains within pyrrhotite, and that pyrrhotite is an abundant phase in ROI-C. It is likely that pyrrhotite is abundant in the sulfide-assemblage, with ~µm-sized magnetite grains interspersed.

Sulfide formation in the early solar nebula was experimentally investigated by [5]. They found that the reaction of an H_2S/H_2 gas mixture with meteoritic metal produced a surface layer consisting of uniformly oriented layers of a monosulfide solid solution with pentlandite inclusions. The abundant pyrrhotite in ROI-C, which occurs as parallel crystals with the same or very close orientation, is consistent with crystallographically controlled growth. We hypothesize that the formation of these Renazzo sulfides occurred via gas-solid reaction in the nebula.

The microstructure in ROI-B is intriguing. The pentlandite nearest to the surface is a single crystal, and the data suggest it is compositionally uniform. In comparison, that on the bottom has a complex microstructure consisting of linear and interconnected features that appear to have higher Ni contents. Higher Ni content in pentlandite within hydrous IDPs and comet Wild 2 particles has been correlated to higher degrees of aqueous alteration [6]. This complex microstructure, which correlates with higher Ni content, may have resulted from varied degrees of aqueous alteration on the parent body.

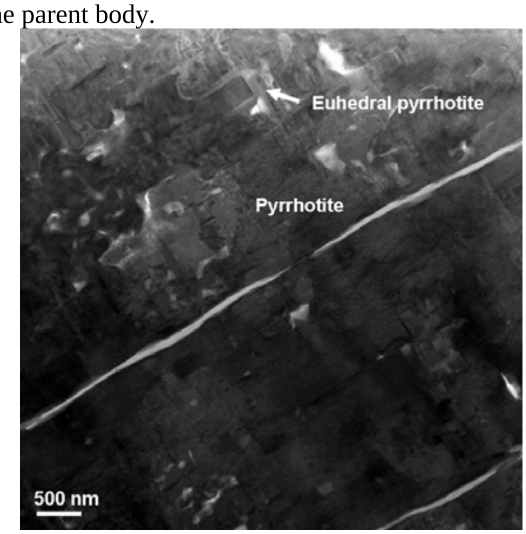

Figure 4. Bright-field STEM image of part of the FIB section from ROI-C. Euhedral pyrrhotite grains occur parallel to one another.

The sulfide-assemblages in this Renazzo chondrule have a complex microstructure that likely reflects a complex history. They are fine grained, intimately mixed, and show evidence for both gas-solid reactions in the solar nebula and variable degrees of aqueous alteration on the parent body. Additional work will provide further insight in the growth mechanics of the sulfide and the small-scale alteration.

References: [1] Connolly et al. (2003) LPSC XXXIV, #1770. [2] Connolly et al. (2007) LPSC XXXVIII, #1571. [3] Schrader et al. (2008) *GCA*, **72**, 6124. [4] Zega et al. (2007) *MAPS*, **42**, 1373. [5] Lauretta et al. [1997] *Science*, **277**, 358. [6] Zolensky et al (2006) *Science*, **314**, 1735.

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