A COORDINATED ANALYTICAL INVESTIGATION OF SULFIDE MINERALS IN TYPE 1 CHONDrites AS ANALOGS TO BENNU AND RYUGU.

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Introduction: Fe-sulfide minerals form over a wide range of thermodynamic conditions [1]. Detailed information on their structure and composition can provide information on secondary processing in asteroid parent bodies. Here we report on the compositions and structures of pyrrhotite [(Fe, Ni)₁₋₃S] and pentlandite [(Fe, Ni, Co)₉₋₁₂S₈] in the Orgueil (CI1.0) and Kolang (CM1 clast) chondrites. These meteorites are useful analogs to samples returned from asteroids Bennu and Ryugu, which show evidence for extensive aqueous alteration [2-4].

Methods: Petrographic thin sections of Orgueil (USNM 388) and Kolang (ASU 2147) were allocated from the Smithsonian Institution and the Arizona State University collections, respectively. The samples were mapped for S, Fe, Ni, Si, Ca, Mg, and P compositions using the Cameca SX-100 electron microprobe (EMPA) in the Kuiper-Arizona Laboratory for Astromaterials Analysis (K-ALFAA). Maps and quantitative analyses were acquired using a 15 kV, 20 nA beam. In addition, high-resolution X-ray maps were acquired for select regions of interest (ROI) on the Hitachi S-4800 scanning electron microscope (SEM). Chosen ROIs were cross sectioned, extracted, and thinned to electron transparency (≤100 nm) using a ThermoFisher Helios NanoLab 660 G focused-ion-beam scanning electron microscope (FIB-SEM) with methods previously described [e.g., 5]. FIB sections were analyzed for crystal chemistry and structure using the 200 keV Hitachi HF5000 scanning transmission electron microscope (S/TEM) equipped with a 3rd-order spherical aberration corrector for S/TEM mode, bright field (BF)- and dark field (DF)- S/TEM detectors, and an Oxford Instruments X-MaxN 100 TLE EDS system with dual 100 mm² windowless silicon-drift detectors (Ω = 2.0 sr). We report on three FIB sections from Orgueil and two from Kolang.

Results & Discussion: We observe abundant pyrrhotite grains, but no pentlandite within the Orgueil thin section. Quantitative EMPA on pyrrhotite indicates an average Ni content of 1.05 wt%. Orgueil pyrrhotites exhibit both subhedral and euhedral lath-shaped morphologies. Grain boundaries of lath-shaped pyrrhotites show post-formation alteration, as evidenced by varied degrees of embayment. Subhedral pyrrhotite grains contain silicate inclusions. TEM shows that pyrrhotites in Orgueil are consistent with 4C structures. Pyrrhotite grains contain abundant stacking faults parallel to their grain boundaries that may be related to growth of the crystal. More analysis is needed to determine if the stacking faults are connected to rapidly evolving thermodynamic parameters (T, P, pH) during growth.

In comparison, we observe abundant pyrrhotite grains and pentlandite assemblages in the polished section of Kolang. Pyrrhotite grains contain an average of 0.8 wt% Ni with primarily euhedral lath-shaped morphologies. The pentlandite assemblages occur as fine grains (~100’s nm) intergrown with phyllosilicates. The fine-grained pentlandite assemblages display similarities to the pentlandite-serpentinite grains found in [6]. Pyrrhotite-pentlandite intergrowths (PPI) also occur in Kolang. In cross section, the PPI assemblage contains lenticular-shaped grains of pentlandite that occur parallel to one another, twinned pyrrhotite, and abundant vesicles within and along the edges of the pentlandite grains. [6] suggests that fine-grained pentlandite and phyllosilicate assemblages form as an alteration product of PPI grains but they did not identify PPI grains in their study of CM1 chondrites. The presence of both intact PPI grains and fine-grained pentlandite assemblages in Kolang suggests that it experienced less extensive, or more heterogenous, alteration than those identified in [6].

Overall, the sulfide mineralogy of Orgueil and Kolang is consistent with previous observations of type 1 chondrites [6-8]. Some workers have identified minor pentlandite in Orgueil using TEM [7], whereas others (including us) do not [8], suggesting that the Orgueil parent body experienced highly heterogenous and localized chemistry that differentiates it from other CI chondrites. Future work on Orgueil, Kolang, Alais, and Tarda will help illuminate the range of thermodynamic conditions experienced by the aqueously altered chondrites.