MICROSTRUCTURAL ANALYSIS OF A SULFIDE GRAIN IN THE MATRIX OF THE SUTTER'S MILL CM-LIKE CARBONACEOUS CHONDRITE

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Introduction: Sulfide materials occur in meteorites, interplanetary dust particles, cometary samples, and asteroidal materials [e.g., 1–4]. They can form through gas-solid reactions, melt solidification, and as products of aqueous and thermal alteration [e.g., 5–11], and their structure and crystal chemistry can be sensitive to the conditions under which they formed or last equilibrated. Here we report on the analysis of a sulfide grain identified in the matrix of the Sutter's Mill CM-like carbonaceous chondrite. This work is part of a broader effort to determine the microstructures and origins of sulfide grains in meteorites and use such information as context for inferring the origins of sulfides in other planetary materials [10,11] including those already returned from asteroid Itokawa and Ryugu and those to be returned by OSIRIS-REx [12,13].

Sample and Methods: A petrographic thin section was obtained from Sutter's Mill stone 8 (SM8). We performed optical microscopy and electron microprobe analysis (EMPA) on SM8 to identify sulfide grains for microstructural analysis. We identified numerous sulfide-bearing opaque assemblages and selected two pyrrhotite-pentlandite intergrowths for detailed analysis using transmission electron microscopy (TEM). Electron-transparent sections were created using the Thermo Fisher (formerly FEI) Helios G^3 focused-ion-beam scanning-electron microscope (FIB-SEM) at the Lunar and Planetary Laboratory (LPL) with methods previously described [14]. Each FIB section was examined for its structure and composition using the 200 keV Hitachi HF5000 scanning transmission electron microscope (S/TEM) located at LPL. The HF5000 is equipped with a cold field-emission gun, a 3rd-order spherical-aberration corrector for STEM mode, bright field (BF)- and dark-field (DF)-STEM detectors and an Oxford Instruments X-Max N 100 TLE EDS system with dual 100 mm^2 windowless silicon-drift detectors (Ω = 2.0 sr).

Results and Discussion: Opaque Assemblage (OA) 3 occurs in the matrix of the Sutter's Mill chondrite. It has an anhedral morphology and measures approximately 44 μm × 56 μm in orthogonal dimensions. EMPA reveals anhedral grains consistent with pyrrhotite, pentlandite, and possible magnetite. A C capping layer, measuring ~6.5 μm wide, was deposited onto the surface of OA3 transecting a polyphasic region containing a mixture of the sulfide and oxide materials. We extracted a cross section of this area and thinned it to electron transparency (< 100 nm) using previously described methods [14]. Scanning TEM (STEM)-based bright-field (BF) and high-angle annular-dark-field (HAADF) images show that the FIB section of OA3 is polyphasic. EDS mapping reveals that the majority of the section is composed of Ni-poor sulfide interspersed with Ni-rich sulfide and an Fe-oxide material. Selected-area electron-diffraction (SAED) patterns from each of these distinct regions reveal all are crystalline, and confirm phases of pentlandite, pyrrhotite, and magnetite. The SAED pattern acquired from pyrrhotite is complex, containing a primary set of reflections that can be indexed to one of the polytypes, and a minor set that is aperiodic about the forward-scattered beam, suggesting the presence of a superlattice.

The microprobe analyses of the sulfides in this sample of Sutter's Mill reveal that it contains Fe-depleted pyrrhotite with at.% Fe/S ratios that are similar to those in the Migehi CM2 chondrite [11]. A separate study of the ferroan olivine compostions of chondrules in the same thin section of SM8 showed it has not been heated [15]. Combined, these data suggest that SM8 did not experience significant heating but likely experienced significant aqueous alteration on its parent body which resulted in Fe-depleted pyrrhotite [11]. That the magnetite crosscuts the sulfide suggests it could have formed by secondary processing on the parent body of Sutter's Mill. We hypothesize that the pyrrhotite could have been altered during hydrothermal processing, leading to the formation of magnetite. S/TEM analyses of additional FIB sections, which we plan to do, should help test this hypothesis.

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