

ALTERED PRIMARY IRON SULFIDES IN CR AND CM CARBONACEOUS CHONDRITES: FORMATION BY DISSOLUTION AND PSEUDOMORPHIC REPLACEMENT

S. A. Singerling and A. J. Brearley. Department of Earth and Planetary Sciences, MSC03-2040, 1 University of New Mexico, Albuquerque, NM 87131, USA. Email: ssingerling@unm.edu.

Introduction: One of the major goals of the study of primitive meteorites involves distinguishing primary solar nebular features from those resulting from secondary processes on asteroidal parent bodies. Iron sulfides are postulated to have formed in both nebular and asteroidal environments [2-6] and therefore may provide constraints on processes both before and after accretion of asteroidal parent bodies.

Previous studies of iron sulfides in carbonaceous chondrites argued for a secondary origin for pyrrhotite (Fe_{1-x}S) and pentlandite ($(\text{Fe,Ni})_9\text{S}_8$), postulating that they formed from the aqueous alteration of troilite (FeS) and/or Fe,Ni-metal in a parent body setting [1-4]. Recent work has shown, however, that pyrrhotite and pentlandite may also be primary phases formed from sulfidization [5] or crystallization [6-8]. Our previous work [9,10] involved reevaluating the sulfide mineralogy of the CR and CM carbonaceous chondrites and determined that primary sulfides, formed by both processes, are present in both groups. This study expands on our investigations [11] of the effects of aqueous alteration on primary iron sulfides in the more heavily altered CR and CM carbonaceous chondrites.

Methods: The meteorites studied for this work include: CR2s Queen Alexandra Range 99177, Elephant Moraine 92042, Meteorite Hills 00426, and Renazzo and CM2s Queen Alexandra Range 97990, Murchison, Murray, and Mighei. For microscopic-scale imaging of the textures and preparation of FIB sections for analysis by TEM, we used a FEI Quanta 3D Dualbeam[®] FEGSEM/FIB at UNM. The major and minor element compositions of the sulfides were obtained using a JEOL 8200 EPMA at the Institute of Meteoritics, UNM. For obtaining submicron-scale images of textures, EDS analyses, and SAED patterns, we used a JEOL 2010F STEM at UNM.

Results: We have identified three distinct groups of altered primary sulfide grains (Fig. 1). In all cases, the proportion of these grains increases with an increase in the degree of aqueous alteration for the bulk meteorite. Additionally, the dis-

tribution of these grains is heterogeneous in any given sample, and the different grain types can coexist within the same sample.

- 1) porous-pitted pyrrhotite-pentlandite (4P) grains (CM chondrites, type IIA chondrules and matrix).
- 2) altered pyrrhotite-pentlandite composite (COMP alt) grains (CR and CM chondrites, type IIA chondrules and matrix).
- 3) altered sulfide-rimmed metal (SRM alt) grains (CR chondrites, type IA and IIA chondrules).

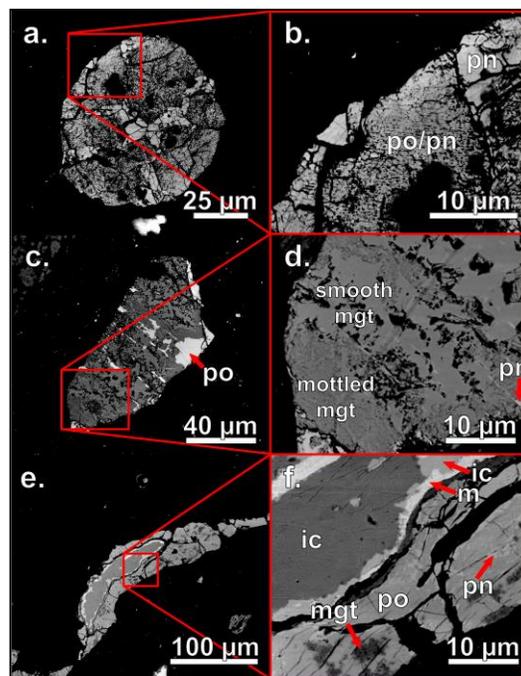


Figure 1. BSE images of altered primary sulfides. (a-b) 4P grain from CM Mighei, (c-d) COMP alt grain from CM Murray, and (e-f) SRM alt grain from CR Renazzo. po = pyrrhotite, pn = pentlandite, mgt = magnetite, m = Fe,Ni-metal, ic = iron carbide (cohenite)

The 4P grains consist of pyrrhotite with pentlandite exsolution or a homogeneous texture lacking exsolution. In all cases, the pyrrhotite contains extensive porosity that appears to be crystallographically controlled, either extending parallel or perpendicular to pentlandite lamellae. The homogeneous 4P grains have compositions intermediate between pyrrhotite and pentlandite which appear to be real (according to TEM EDS X-ray maps)

and not simply mixed analyses due to EPMA beam overlap.

The COMP alt grains are characterized by containing pyrrhotite with pentlandite exsolution where the pyrrhotite shows alteration to magnetite. The extent of alteration varies from micron-sized patches to complete replacement of pyrrhotite. The magnetite textures were found to differ between the CR and CM chondrites with CM COMP alt grains showing “smooth” and “mottled” (Fig. 1d) and CR COMP alt grains only showing “mottled” textured magnetites. In both cases, the magnetite does show porosity; it is the size and frequency of the pores which distinguish the two different textures. Additionally, COMP alt grains were observed in all CMs studied but only observed in the most altered CR studied, Renazzo. There does not appear to be a strong crystallographic orientation relationship between the pyrrhotite and magnetite. At the reaction fronts, the pyrrhotite contains flame-like textures which protrude into the pyrrhotite from the pyrrhotite-magnetite boundary. These textures resemble the troilite-pyrrhotite exsolution textures described in the TIL 91722 CM2 chondrite [6].

The SRM alt grains consist of Fe,Ni-metal (kamacite) cores rimmed by pyrrhotite that often contains pentlandite exsolution textures. In these grains, the pyrrhotite shows alteration to magnetite, while the metal shows alteration to magnetite and/or cohenite. The boundary between the metal and the magnetite is very sharp at the submicron scale. The complex textures found at the reaction fronts of the COMP alt grains are absent in the SRM alt grains. However, fractures oriented perpendicular to the metal-magnetite boundary were observed in magnetite in the SRM alt grains.

Discussion: It is clear from the exsolution textures, which only form by solid-state processes at moderate temperatures (<610°C, [12]), that all these different kinds of grains were initially primary sulfides. We can also assume that these grains are not the result of terrestrial alteration for two reasons: (1) the expected iron oxide formed by terrestrial alteration ought to be maghemite or goethite rather than magnetite [13-15], and (2) there is a positive correlation between the degree of alteration of the bulk meteorite and the modal abundance of altered primary grains.

The 4P grains were originally composite pyrrhotite-pentlandite (COMP) grains formed by crystallization of sulfide melts during the chondrule-forming event(s). These grains only occur in CM chondrites, both in type IIA chondrules and as isolated grains in the matrix. Subsequent to formation, these grains experienced dissolution, as evidenced by the porosity of the grains, but do not appear to have been pseudomorphically replaced by a secondary phase during aqueous alteration.

The COMP alt grains were also originally COMP grains formed by crystallization of sulfide melts within chondrules. However, these grains subsequently experienced pseudomorphic replacement of their pyrrhotite rather than just dissolution. Volume calculations for the reaction of pyrrhotite to magnetite confirm a molar volume deficit, consistent with the porosity of the magnetite.

The SRM alt grains were originally sulfide-rimmed metal (SRM) grains which formed by sulfidization and subsequently experienced pseudomorphic replacement. Volume calculations for the reaction of metal to magnetite or cohenite (Fe_3C) confirm molar excess reactions, consistent with the lack of porosity of these phases.

For all three altered primary grains, slight differences in environmental conditions (T , $f\text{O}_2$, a_s) could result in dissolution or pseudomorphic replacement. These grains clearly demonstrate that pyrrhotite and pentlandite are not stable under some parent body conditions, in contrast to the view that they are secondary in origin. Microchemical environments [16] or brecciation could explain why these different alteration conditions could coexist within the same sample.

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