

Iron-Nickel Sulfide Compositional Ranges in CM Chondrites: No Simple Plan

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Introduction

Iron-nickel sulfides are found in most or all solar system environments, and are probably the only minerals found in all extraterrestrial materials on hand. Despite this ubiquity, they have only just begun the attention they deserve. The most common Fe-Ni sulfides in chondrites are troilite (FeS), pyrrhotite (Fe_{1-x}S) and pentlandite (Fe,Ni)₉S₈. Troilite is believed to have resulted from sulfidation of metal (Fe-Ni) grains in an H₂S-containing environment. Pyrrhotite is produced when friable troilite grains, which are exfoliated from the metal nucleus, are submitted to continued sulfidation [1]. Some asteroids are known to have experienced aqueous alteration, forming products including new generations of sulfides (pyrrhotite and pentlandite). Pentlandite in particular is known to form during such alteration [1]. However, experimental work by Lauretta has indicated that pentlandite may also have been formed during the initial sulfidation process [2], due to the faster diffusion rate of nickel into the forming sulfide, as compared to iron. Finally, there is considerable evidence [1,3&4] for a family of phases intermediate between pyrrhotite and pentlandite, following the trend of the high temperature monosulfide solid solution [5], something not encountered in terrestrial rocks.

Each sulfide has its own particular stability conditions, which have been determined for most phases. The long-term objective of our research is to characterize sulfides in chondritic materials in order to better establish the conditions under which they formed, and the subsequent processes they experienced. Ultimately, it will be possible to infer whether the sulfides in the chondrites were formed in the solar nebula or on asteroids, and if formed on the asteroids, deduce how much alteration has occurred there. Here we explore the relationships between the finest grain size portions of carbonaceous chondrites, these being matrix and chondrule rims; fine-grained materials are the most sensitive to their environment. This abstract is one of a series reporting results for chondrites, earlier work reported results for a much more limited set of CMs, as well as for CVs [6-7] and CIs [8].

Experimental Procedure

Sulfides from ten CM chondrites were analyzed during the course of this study. These CMs were chosen because they completely span the aqueous

alteration range exhibited for these meteorites, from relatively unaltered Kivesvaara (CM2) to completely altered EET83334 (CM1) [9]. Sulfides were analyzed using a Cameca Camebax electron microprobe, as well as a JEOL 200FX TEM equipped with a Link EDX detector. The analyses were calibrated using natural mineral standards, and analytical results are accurate to within 1% and 5% relative for, respectively, the probe and TEM.

Results

The sulfides analyzed were randomly selected from different areas of thin and microtomed sections. Their morphologies ranged from rounded, oval, spherical, rectangular to anhedral, and their sizes extended from 50 microns down to approximately 0.1 micron. The sulfide compositions are plotted in simple diagrams indicating only the Ni atom% composition (Figure 1), to better permit comparison of many meteorites in this abstract. In order to verify that the intermediate-composition sulfides did not merely represent inadvertent analyses of two separate phases at once, we analyzed the sulfides in Mighei, and Nogoya by TEM as well as by microprobe. Although it is simple to observe intergrowths of pyrrhotite and pentlandite in the microprobe by BSE imaging, it is practically impossible to miss it in bright- and dark-field images in the TEM. The resultant analysis sets were essentially identical, indicating that the analyses we present are for real, separate phases.

We made many analyses of sulfides in chondrule rims as well as matrix for the chondrites Nogoya, Mighei, Kivesvaara, ALH83100 and EET83334. For each chondrite the compositional range of the matrix and chondrule rim sulfides were identical. This contrasts to the data for matrix and chondrule rims in CV3 chondrites Efremovka, Vigarano and Mokoia, which were found by us earlier to be significantly different [6-7].

Kivesvaara, probably the least altered CM2 chondrite known (based upon high bulk Fe matrix composition [9]) contains only stoichiometric pentlandite and pyrrhotite. Mighei and Sayama also contain predominately these two phases. Pollen is unique in containing only pentlandite (as far as we could tell).

As noted above, most of the CMs contain sulfides that are either more Ni-rich than typical pyrrhotites, or too Ni-deficient to be proper

pentlandites - the so-called intermediate compositions. It is possible that a solid solution not observed in terrestrial sulfides exists within this area of the diagram, as mentioned above. Apparently, the Ni content of the Fe-Ni sulfide is related to the degree of nonstoichiometry of the monosulfide solid solution (A. El Goresy, personal communication, 1998). The crystal structures of these phases are being determined in collaboration with K. Ohsumi (Photon Factory, Tsukuba). In the present work we see that two CM chondrites showing intermediate degrees of aqueous alteration (Bells, Nogoya) have sulfides with a complete Ni-Fe solid solution. The other CMs show only hints of this. The most completely aqueously-altered CMs (MET01073 and EET83334) contain only stoichiometric pentlandite and the Ni-rich "pyrrhotite"-like intermediate phase.

Because pentlandite is commonly (though not exclusively) an alteration product during aqueous alteration, its presence in all CM chondrites is consistent with their degree of aqueous alteration relative to other primitive chondritic materials. Assuming this view, the predominant presence of Ni-poor sulfides in reduced lithology of the Vigarano CV3 chondrite [6&7], seems to indicate that this meteorite is the least altered of those we have analyzed to date. Experimental work by Lauretta et al. [2] to the effect that pentlandite can be produced by gas-solid reactions deserves consideration here as well. However, in our study of chondritic interplanetary dust particles (IDPs), pyrrhotite, pentlandite and other Ni-rich sulfides were only located in aqueously altered IDPs; in anhydrous IDPs only troilite was found [1].

Conclusions

There is no simple progression in the compositional variation of CM chondrites as a function of aqueous alteration. However, we do observe some general trends. The least-altered CMs contain pyrrhotite with the least Ni, and the most-altered CMs contain the most Ni-rich pyrrhotite. Pentlandite is present in all CMs, regardless of degree of aqueous alteration - of course even the least-altered CM chondrite (Kivesvaara) has still witnessed more aqueous alteration than most chondritic materials. CM chondrites having intermediate levels of aqueous alteration can contain Ni-Fe sulfides showing complete solid solution. It is still a mystery how these intermediate sulfides are stable at low temperatures. Chondrule rim sulfides have the same compositions as matrix sulfides, suggesting similar alteration conditions at least. Due to the occurrence of alteration processes, inferred

from the Ni-rich composition of the sulfides, we suggest that the majority of primary sulfides in CMs were modified during hydrous reactions. Thus only a few primary troilite grains remain in CM chondrite matrix and chondrule rims.

References

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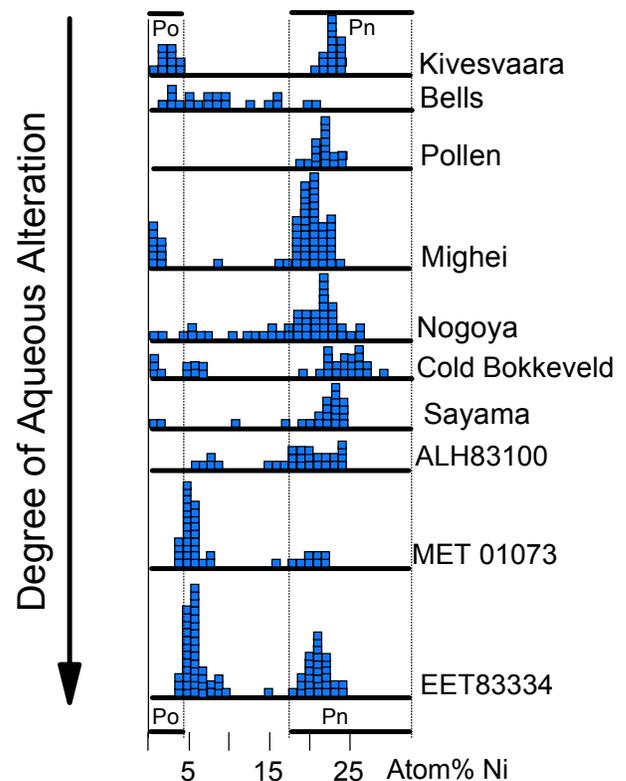


Figure 1 Compositional range of Fe-Ni sulfides in 10 CM chondrites, spanning the complete range of aqueous alteration from least altered (Kivesvaara) to most altered (EET83334). Analyses are plotted as atom % Ni. The fields of pyrrhotite (Po) and pentlandite (Pn) are indicated as horizontal bars and vertical dotted lines.