

SULFIDE MINERAL ASSEMBLAGES IN BORISKINO CM CHONDRITE; N.Z. Boctor¹, G. Kurat², C.M.O.D'Alexander³, and C.T. Prewitt¹, ¹Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd., NW, Washington, DC 20015; USA, ²Naturhistorisches Museum, Postfach 417, A-1014, Vienna, Austria, ³Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd., NW, Washington, DC 20015, USA.

Introduction: Phosphorus-bearing iron-nickel sulfides have been reported in CM chondrites and in CM clasts in howardites (1-7). The phosphorus-bearing sulfides in these meteorites are intriguing as they point to a chalcophile affinity of phosphorus, an element that in meteorites normally shows a lithophile or siderophile character. The P-bearing sulfides were considered to be of nebular origin by (3). (2), however, suggested that these sulfides could be of extrasolar origin, or at least they could preserve some trace element signature of non-solar nucleogenetic processes. In this investigation, we report on two distinct sulfide mineral assemblages in Boriskino CM chondrite and use mineralogical and experimental criteria to assess their origin.

Techniques: The sulfides were examined optically in reflected light, and their compositions were determined by Joel superprobe. The sulfide standards used were FeS₂, NiS, and CoS. Apatite was used as a standard for P, and synthetic pyroxene and orthoclase were used as standards for the other elements. Previous analyses of the sulfides showed low totals, so we quantitatively analyzed for oxygen using wave length dispersive techniques and an LDE1 crystal. The operating voltage was 15KV, and the current was 30ηA.

Mineralogy: Two different mineral assemblages were observed in Boriskino. The first assemblage consists of pyrrhotite, Ni-bearing monosulfide solid solution, pentlandite, and Ni-rich phosphorus-bearing sulfide. Pyrrhotite is commonly associated with olivine and pyroxene in round or oval forms surrounded by rims interpreted by (8) as accretionary dust. Occasionally, pyrrhotite forms mantles on pentlandite. Pentlandite is mostly a discrete phase and is rarely seen as exsolution in pyrrhotite. Porous aggregates of pyrrhotite and pentlandite are also present. Phosphorus-bearing sulfide occurs as discrete small grains 5 to 10μm in size.

The second mineral assemblage is very different from the first, and is confined to regions of carbonate precipitation and aqueous alteration. The minerals in this assemblage are mackinawite (FeS_{1-x}), magnetite, and residual grains of Fe-Ni metal with extremely variable Ni contents. Mackinawite occurs commonly as tabular crystals in association with carbonate or as ag-

gregates of small crystals in veins transecting the altered zones.

Mineral Chemistry. The chemical composition of the sulfide and oxide minerals are shown in Table 1. Pyrrhotite, Ni-rich monosulfide, and the P-bearing sulfide plot on the join FeS-NiS in the system Fe-Ni-S (Fig. 1). In the P-bearing sulfide, a positive correlation was observed between Ni and P (Fig. 2) and a negative correlation between O and S. Potassium concentrations in the P-bearing sulfide range between 0.25 and 1.0 wt. %, and P between 0.70 and 3.4 wt. %. Analyses of Na, Mg, Al, Ca, Si in the P-bearing sulfide simultaneously with O show no correlation; all these elements are present in trace amounts. Mackinawite is Co and Ni-poor (0.37 to 0.49 wt. % Ni and 0.02 to 0.055 wt. % Co). The Ni content of the metal varies between 4.5 and 67.0 wt. %.

Discussion: Although there is no evidence of sulfide-silicate liquid immiscibility in Boriskino, its sulfide assemblage appears to be primary and shows similarities to magmatic Fe-Ni sulfides. The bulk composition of the Boriskino sulfides, like that of most magmatic Fe-Ni sulfides, falls within the monosulfide solid solution field in the Fe-Ni-S system. Also, the pyrrhotite end member, like other magmatic Fe-Ni sulfides, exsolved pentlandite. Crystallization of pentlandite and its exsolution from the monosulfide solid solution occurs during subsolidus equilibration at temperatures below 610°C (9). Therefore, we consider the mineral assemblage consisting of pyrrhotite, Ni-rich monosulfide solid solution, and P-bearing sulfide a primary assemblage. (3) suggested that this assemblage formed by condensation in the solar nebula with the P-bearing sulfide condensing after formation of the CAIs. We concur that this assemblage may have formed in the nebula, but we propose an alternative hypothesis: sulfidation of Fe-Ni metal by the reaction $\text{FeNi}(\text{metal}) + \text{H}_2\text{S}(\text{g}) \rightarrow (\text{Fe,Ni})_{1-x}\text{S} + \text{H}_2$ (10). The phosphorus present in solid solution in metal could have been the source of P in the sulfide, and metal with a range of Ni concentrations may account for the variation in the Ni content of the different sulfide phases. The paucity of metal in Boriskino suggests that the sulfidation reaction occurred at high sulfur fugacity. The incorporation of K in the P-sulfide suggests that

this element like P tends to show a chalcophile tendency at low oxygen fugacities. The presence of O in the P-sulfide raises the possibility that it is an oxy or hydroxy sulfide. However, the possibility that the O is contributed by submicroscopic inclusions of tochilinite or magnetite cannot be excluded.

The second mineral assemblage consisting of mackinawite, magnetite, and metal, "a disequilibrium assemblage" is secondary. Mackinawite has been synthesized under hydrothermal conditions at temperatures below 180°C (11). Mackinawite in the alteration zones probably precipitated at low temperature from S-bearing aqueous fluids. The low Ni content of mackinawite and the high Ni content of metal grains that were pervasively altered to magnetite attest to the low mobility of Ni relative to Fe in aqueous fluids. This is in agreement with the experimental results of (12). The low temperature of formation of mackinawite and its association with carbonate precipitation and aqueous alteration suggest that the secondary mineral assemblage formed on the parent body of the CM chondrites.

References: [1] Nazarov et al. (2001) LPI XXXII, 1769. [2] Nazarov et al. (2000) LPI XXXI, 1662. [3] Nazarov et al. (1998) *Geochemistry International*, 36, 415. [4] Nazarov et al. (1997) LPI XXVIII, 1003. [5] Nazarov et al. (1996) LPI XXVII, 939. [6] Nazarov et al. (1993) LPI XXIV, 1053. [7] Bunch et al. (1979) *Geochim. Cosmochim. Acta*, 43, 1727. [8] Metzler et al. (1992) *Geochim. Cosmochim. Acta*, 56, 2873. [9] Kullerud (1963) *Can. Mineralogist*, 7, 353. [10] Lauretta et al. (1996) *Proc. NIPR Symp. on Antarctic meteorites*, 9, 79. [11] Uda (1967) *Zeit Anorganische und Allgemeine Chemie*, 350, 105. [12] Saulwood and Popp (1984) *Geochim. Cosmochim. Acta*, 48, 2713.

Table 1. Microprobe analyses of the sulfide minerals and metal

	1	2	3	4	5	6
Ni	29.9	0.56	7.7	25.0	0.45	4.6
Fe	33.9	60.5	55.4	35.6	64.7	94.9
Co	1.9	0.11	0.19	0.79	0.04	0.35
Cr	0.04	0.03	0.03	0.08	0.02	0.34
K	0.09	0.02	0.03	0.95	—	—
S	33.5	39.0	36.5	31.9	36.1	—
P	—	—	—	1.2	—	0.36
O	—	—	—	2.7	—	—
Total	99.3	100.2	99.9	98.2	101.3	100.6

1-pentlandite, 2-pyrrhotite, 3-Fe-Ni monosulfide, 4-P-bearing Fe-Ni sulfide, 5-mackinawite, 6-metal

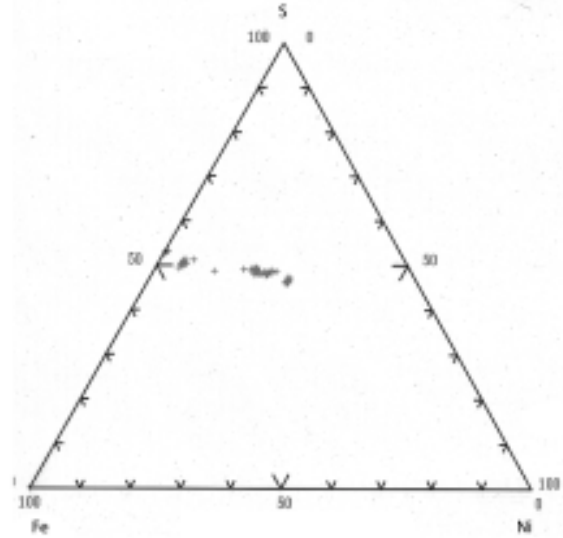


Figure 1. Composition of the Fe-Ni sulfides.

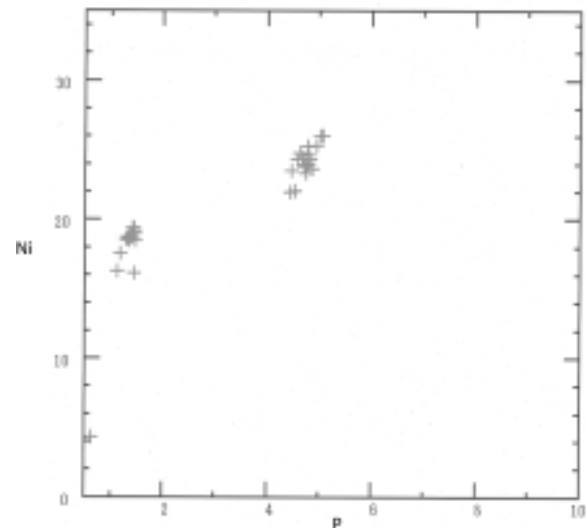


Figure 2. Plot of Ni at. % vs. P at. %.