EXSOLUTION TEXTURES IN PYRRHOTITE AND ALTERATION OF PYRRHOTITE AND PENTLANDITE IN THE CM2 CARBONACEOUS CHONDRITES CRESCENT, MIGHEI AND ALH81002
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Introduction. Carbonaceous chondrites are composed of the earliest materials produced during the formation of the solar system. They contain materials, such as chondrules and CAIs that formed in the solar nebula, but have, in many chondrites, been modified by processes that occurred after accretion of asteroids, such as aqueous alteration and thermal metamorphism. The CM2 chondrites, in particular, show significant evidence of aqueous alteration that has formed a variety of secondary phases [1-4]. It is well-established that different CM2 chondrites appear to have experienced various stages of aqueous alteration [1-4]. Understanding the response of primary minerals to this progressive aqueous alteration is an important step to developing a full geochemical understanding of the alteration processes involved. In this context, the role of sulfide minerals [5-9] is of particular importance, because a major alteration phase in CM chondrites is the oxysulfide tochilinite whose origin is not fully understood.

Our studies of the very weakly altered CM2 chondrite TIL 91722 [8,9] show that it contains a significant proportion of sulfide grains which are clearly of primary origin, not secondary as is commonly assumed. Composite grains of sulfide consisting of pyrrhotite (*po* - $Fe_{(1-x)}S$) and pentlandite (*pn* - $Fe,Ni)_9S$ occur in TIL 91722 with complex exsolution textures indicative of solid state reactions during primary nebular cooling [8,9]. The textures include the submicroscopic exsolution of troilite (*tr* - FeS) from *po*, which has not been observed previously in any chondritic sulfide and can only have occurred at temperatures below 130ºC [10]. In this study, we have set out to address several additional questions regarding the origin of these sulfide grains. First, we wish to establish if such primary sulfides also occur in other CM chondrites. Second, we want to establish the primary origin of these sulfides. In TIL 91722 [8,9], all the grains we found are relatively large (>50 µm) and embedded within the matrix with no relationship to other components in the chondrite. However, we speculated that they may have originated in type IIA chondrites. Finally, we wish to understand if the primary sulfides are stable during progressive alteration of CM chondrites.

Here, we document textures of sulfides in three additional CM2 chondrites (Crescent, Mighei, ALH81002). Crescent exhibits a similar degree of aqueous alteration to TIL 91722, whereas Mighei and ALH 81002 show progressively higher degrees of alteration as measured by their abundances of unaltered primary silicates [4]. We find that there are systematic differences between the sulfides in these three chondrites that are correlated with increasing degree of aqueous alteration. In addition, we have established a definitive relationship between these *po*-*pn* grains and type IIA chondrules.

Techniques. One polished thin section of each chondrite was studied using BSE imaging with a FEI Quanta 3D FEGSEM instrument operating at an accelerating voltage of 30kV and a beam current of 2.2 nA. The location of individual sulfide grains was carried out using mineralogical modal abundance maps for the full thin sections of each meteorite [4]. This technique allowed extremely rapid location of essentially all sulfides larger than 5 µm in size within each thin section. For this study, a physical basis for selection was those grains with diameters >50µm.

Results. We studied 21 grains in Crescent with sizes ranging from 20 to >100 µm, 25 grains in Mighei with ranging from 50 to >150 µm and 4 grains in ALH81002 that are ~10-20 µm in size.

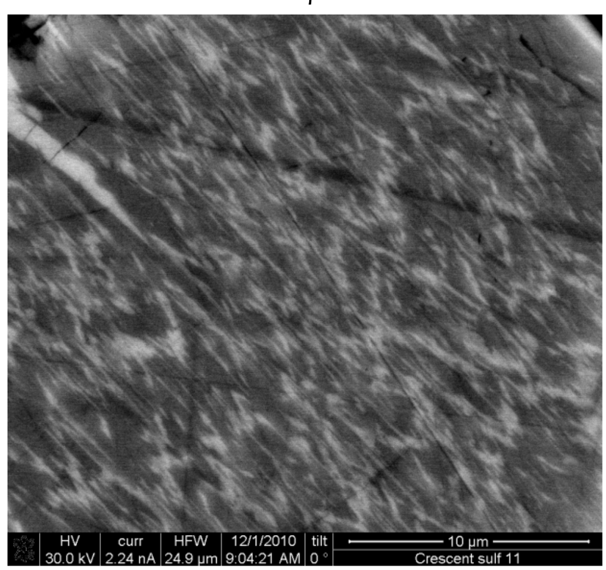

Figure 1 BSE image of chevron-like exsolution texture within a grain of pyrrhotite in Crescent. The exsolved phase is a Ni-bearing sulfide, probably pentlandite.

Crescent: In Crescent, we observed several composite *po*-*pn* grains with textures similar to those in TIL 91722. Many of these grains occur isolated within the matrix, but several occur clearly within type IIA chondrules. These grains consist dominantly of *po* with larger grains of *pn* distributed around the periphery of the grains. Like TIL 91722, the *po* contains very finegrained blebs or lamellae of Ni-bearing sulfides. In addition, we found two *po* grains with an unusual che-

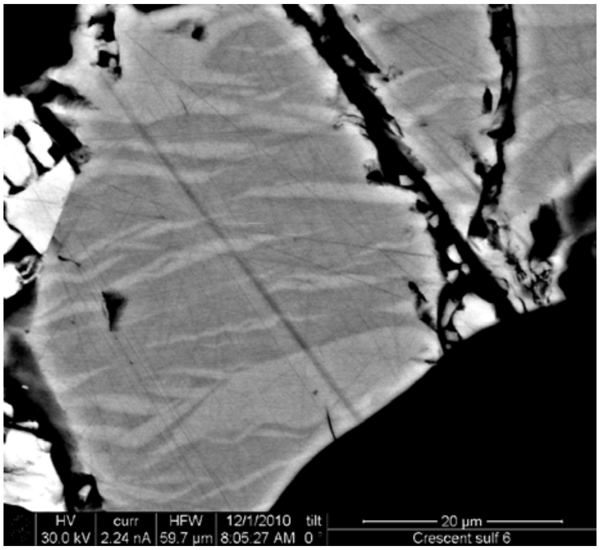

Figure 2. BSE image of a remarkable coarse flame texture resulting from low temperature exsolution of troilite (bright) from pyrrhotite (dark) from Crescent.

vron-like exsolution texture (Figure 1). Several of the *po* grains in Crescent also show a subtle fine-scale flame texture, like that found in TIL 91722, which is the result of very low temperature *po-tr* exsolution, occurring in late stages of cooling [8]. Unlike TIL 91722, the scale of this exsolution is highly variable from grain to grain. Indeed, one grain shows a remarkably coarse flame texture with lamellae of *tr* several microns in width (Figure 2). None of the sulfide grains show evidence of alteration: grain boundaries with the matrix are sharp and well-defined.

Mighei: Composite *po-pn* grains like those in TIL 91722 and Crescent occur as both isolated grains and within type IIA chondrules. The largest grains (>50 µm) are isolated grains. Fine-scale exsolution of *pn* within *po* occurs as both blebs and lamellae. None of the grains we studied show evidence of the fine-scale flame-like *tr-po* exsolution observed in Crescent or TIL 91722. Further, unlike grains in TIL 91722 and Crescent, 7 of the sulfide grains in Mighei show clear evidence of alteration. Alteration takes the form of distinct elongate embayments at the edges of the crystals (Figure 3). In some cases, for smaller grains, the replacement is extensive. The details of this alteration are described in [11].

ALH 81002: No grains were located in ALH81002 with the *po-pn* textures found in Crescent or Mighei. Coarse-grained sulfides are extremely rare in this meteorite. In type IIA chondrules, several highly altered relicts of larger *po-pn* grains were found. These altered grains consist of several highly corroded sulfide relicts < 10µm in size. The dominant residual phase in these aggregates is *pn*, little or no *po* remains.

Discussion. Composite sulfides in Crescent and Mighei have microstructures that are consistent with those found in sulfide grains in TIL 91722, indicating that they are primary sulfides that record a complex cooling history as discussed by [8,9]. However, the variation of the textures observed in Crescent, particularly the chevron-like texture in some grains, is significantly larger than that observed in TIL 91722, suggesting that the thermal history of these grains was somewhat different from those in TIL 91722. We have also, for the first time, demonstrated that these primary *po-pn* sulfides are unstable and undergo replacement that is correlated with progressive aqueous alteration. Grains in Mighei exhibit the earliest stages of replacement, but have been completely obliterated in

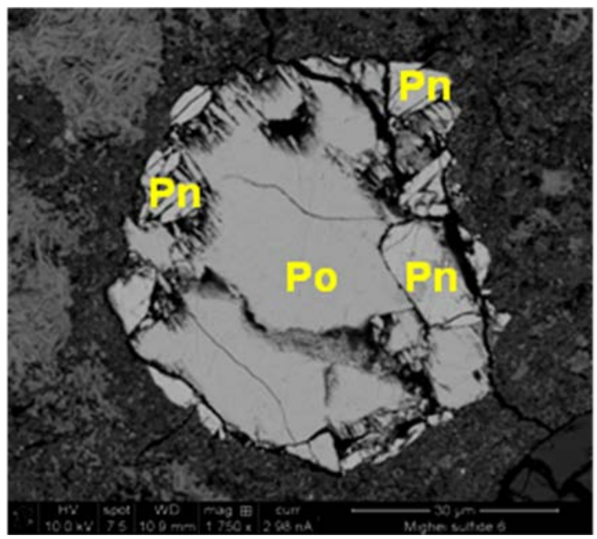

Figure 3. BSE image of a composite *po-pn* grain in Mighei. The brighter grains around the periphery of the grain are *pn*. The grain shows evidence of significant alteration as indicated by the crystallographically-oriented embayments at many locations around the periphery of the grain. .

ALH 81002. Finally, we have established a clear link between these composite grains and their formation in type IIA chondrules.

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