MICROSTRUCTURAL INVESTIGATION OF THE CRYSTALLINE COMPONENT OF MATRIX IN THE PRISTINE CR CHONDRITE MET 00426: IMPLICATIONS FOR DIVERSITY IN NEBULAR DUST

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Introduction: Understanding the constituents of fine-grained nebular dust prior to asteroidal accretion is a significant challenge in meteoritics. A key to this puzzle lies in the fine-grained matrices of carbonaceous chondrites, which are composed of a significant proportion of nebular dust. However, in most carbonaceous chondrites much of this material has been altered by secondary processes such as thermal metamorphism and aqueous alteration. Nevertheless, in the most pristine chondrites (very low petrologic type 3's) the matrix appears to preserve at least some record of the primary characteristics of nebular dust. These matrices consist of a complex assemblage of unequilibrated materials including silicates, sulfides, oxides, carbonaceous grains and isotopically anomalous presolar grains [1,2,3,4,5]. These unique components provide insight into processes that occurred in the solar nebula.

Type 3.00 chondrites are composed of material unchanged by metamorphic processes on their parent asteroids. A notable feature of these pristine chondrites is that their matrices consist of a significant component of amorphous silicate material, in addition to crystalline silicates [1,2,3,4,5]. However, the proportion of crystalline silicates varies considerably among the few chondrite groups for which we have type 3.0-3.1 chondrites [6]. In particular, studies of type 3.00 CR chondrites (e.g. [4]) indicate that the abundance of crystalline silicate phases is anomalously low. Nevertheless, recent studies of multiple regions of matrices of one CR 3.00 chondrite (MET 00426) prepared by focused ion beam (FIB) techniques show that crystalline components are present, providing the opportunity to find and study these matrix grains in detail.

MET 00426 is one of the most pristine chondrites ever described [4], with one of the highest abundances of presolar silicates ever reported [7]. In this study, we have characterized the crystalline phases in MET 00426 matrix in order to understand their origins and the constraints they provide on nebular processes. Such grains provide insights into whether the fine-grained crystalline silicate component of different chondrites have common sources and whether they may also be related to phases in IDPs and STARDUST cometary particles. This work investigates those silicates as part of an ongoing effort to characterize the origin and alteration history of nano-scale crystalline components in pristine CR chondrite matrices.

Experimental: Multiple electron-transparent FIB sections of MET 00426 matrix were extracted for this work. The results from TEM studies of two sections are reported here (FIB sections 2 and 4). Areas of matrix were selected using BSE imaging on the FEI Quanta 3D Field Emission Gun SEM/FIB. Analyzed regions were chosen to be as homogeneous-looking as possible in BSE images and free from visible isolated phases with grain sizes >1 µm. Weathering products were also avoided. The selected areas were extracted using FIB milling techniques. Microstructural studies were carried out using the JEOL 2010 high resolution transmission electron microscope (HRTEM) and the JEOL 2010F FASTEM field emission gun scanning transmission electron microscope (STEM/TEM).

Results: Low magnification dark field STEM imaging shows that both FIB sections of MET 00426 matrix consist of extremely fine-grained material (<50 nm in size). Although the two sections contain similar mineral assemblages that occur in domains or clusters, each section shows unique textural characteristics indicating that the matrix is heterogeneous in character, consistent with previous descriptions [4]. Both sections are composed primarly of amorphous grains of ferromagnesian silicates <200nm in diameter. In addition, nanophase Fe and Fe,Ni sulfides (<200nm) are commonly present, distributed heterogeneously throughout both sections.

Crystalline Silicates. In addition to the amorphous silicates, each section contains five or six crystalline or nanocrystalline olivine grains, varying in size from <100 to 400 nm in diameter. Most of these grains have a subrounded shape. None of these silicates show evidence of replacement by hydrous phases and all have well-defined boundaries with the amorphous silicate material. Interestingly, the crystalline phases appear most commonly in clusters in both sections, though isolated instances also occur. In addition to olivine, a few isolated crystalline pyroxenes occur distributed heterogeneously through both sections. These pyroxenes tend to be of enstatitic composition.

FIB Section 2. A unique, distinct fine-grained olivine-Fe-sulfide-carbonate aggregate with a well-defined boundary with the adjacent matrix was found in this sample (outlined in figure 1 below). This object is ~1µm in diameter. The aggregate is composed of subrounded to rounded grains (<200 nm) of olivine, several larger grains (<500 nm) of well crystallized Fe-Mg carbonates ranging in composition from Sd52 to Sd62 and a few small Fe-Ni sulfides (<200 nm) that appear to be slightly faceted. Olivine compositions in the aggregate are Fo_{70-75} with variable Cr_2O_3 contents (0.13 to 2.35 wt%). Olivines in this aggregate also contain variable amounts of MnO (0.50-0.63 wt%).

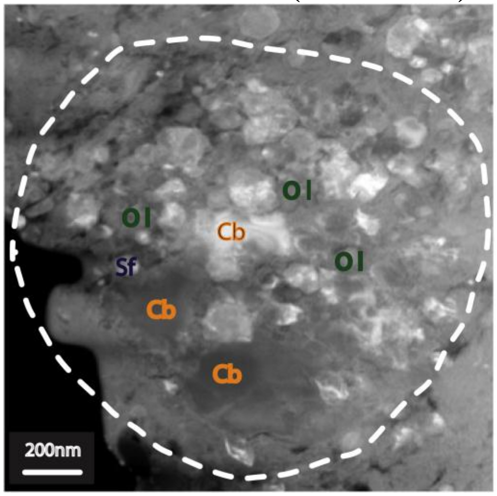

Figure 1: Dark Field STEM image of the crystalline olivine(Ol)-carbonate(Cb)-sulfide(Sf) aggregate (outlined in dashed white line) in FIB Section 2.

FIB Section 4. This section, like FIB Section 2, also has a unique silicate cluster (Figure 2). This object is composed entirely of olivine crystals (>300-400 nm in diameter). The olivines are faceted, exhibit 120º triple junctions between grains and are dislocation free. The cluster is ~600 nm in its longest dimension. The olivines in this aggregate are significantly more Mg-rich (Fo_{93-96}) than those of the object in FIB Section 2. These olivines also contain detectable Cr_2O_3 (0.11 – 0.75 wt%) and MnO (0.09 – 0.13 wt%).

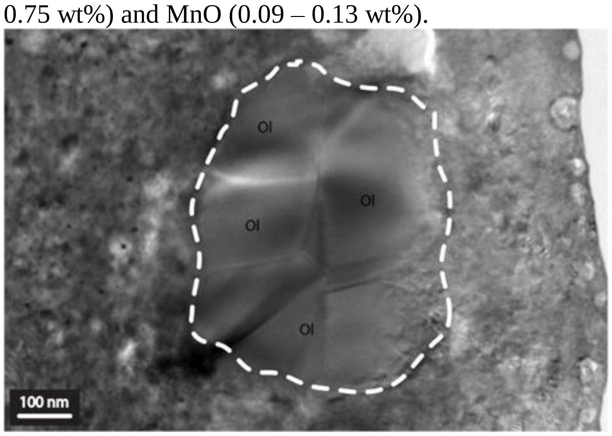

Figure 2: Bright Field TEM image of the crystalline olivine (Ol) aggregate (outlined in dashed white line) in FIB Section 4.

Discussion: *FIB Section 2: crystalline aggregate.* This aggregate has distinct characteristics from the adjacent matrix and has evidently experienced a different formational and thermal history from the typical matrix material in MET 00426. The grains in this aggregate are two or three times larger than grains of the surrounding matrix. The coarser grain size, sub-round to faceted shapes and crystallinity of grains indicate that this object has undergone greater degrees of thermal annealing than typical matrix material. However, this annealing was not extensive. Chromium is highly mobile in olivine during thermal processing [8] but individual olivine grains in this aggregate retain high Cr contents. Additionally, the subrounded texture of the olivines negate the possibility of extended high temperature annealing, as these grains (as well as sulfides) would have coarsened into larger grains at high temperatures.

The object also contains the first carbonates ever discovered in MET 00426 and these carbonates are clearly only associated with the aggregate in this FIB section. The origin of this carbonate is currently unclear. However, compositionally, the grain is very unusual being a siderite-magnesite solid solution, unlike any known carbonate in a carbonaceous chondrite. However, magnesian siderite has been reported previously in an IDP [9]. The first carbonates produced by aqueous alteration in carbonaceous chondrites are invariably Ca-carbonates, not Mg-Fe carbonates, indicating that this carbonate is not the product of in situ aqueous alteration (either terrestrial or preterrestrial). Furthermore, the carbonates are contained entirely within the aggregate and do not occur elsewhere within the FIB section. These observations raise the possibility that this grain is a primary grain that formed in the nebula or possibly in an extrasolar environment [9] prior to incorporation into the CR parent body.

FIB Section 4. This section, though extracted less than 200 µm from FIB Section 2 contains a crystalline-olivine aggregate that has been annealed at much higher temperatures. The large crystal diameter, mineralogy, crystallinity, and triple junctions of olivines in this aggregate point to thermal annealing.

Objects such as these give important insights into the diversity of materials present in the nebula and hence help to constrain the range of processes that were involved in producing the components of nebular dust.

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