Metamorphism of Low Petrologic Type Ordinary and Carbonaceous Chondrites: Further Insights from The Behavior of Chromium in Ferroan Olivine from Aberration Corrected Scanning Transmission Electron Microscopy

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The metamorphic sequences observed in the ordinary and CO chondrites provide important insights into the behavior of chondritic materials during asteroidal thermal heating. Several criteria have been identified which provide very useful ways of identifying the petrologic type of a particular chondrite, developing on the concepts original proposed by Van Schmus and Wood (1967). Of particular note has been our improved understanding of the remarkable changes that occur in very low petrologic type 3 chondrites (<type 3.2), including the response of metallic phases (Kimura at al. 2008) to heating and the behavior of Cr in ferroan olivine as proposed by Grossman and Brearley (2005). The subtle, but measurable changes occurring in metals and Cr in ferroan olivine are extremely powerful ways of determining the very earliest stages of parent body thermal metamorphism in type 3 chondritic meteorites. The change in Cr content in ferroan olivines in type II chondrules has been widely adopted as a method for classifying low petrologic type chondrites, due to its comparative simplicity and application to both unequilibrated ordinary (UOC) and CO3 chondrites.

The exact mechanisms involved in the redistribution of Cr during low degrees of thermal metamorphism are not completely understood. although Grossman and Brearley (2005) showed evidence that submicron Cr-rich phases were exsolving within olivine as petrologic type increased.

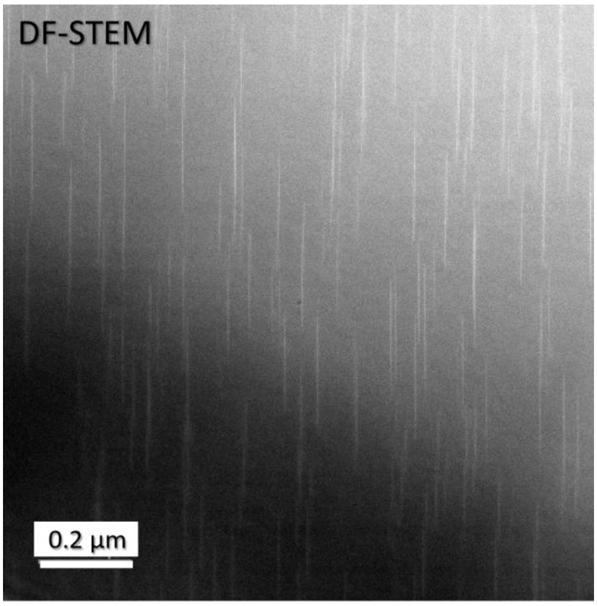

Figure 1. Dark-field STEM image of ferroan olivine from a chondrule in QUE 97008 showing myriad, crystallographically oriented lamellae with high Z contrast.

In an effort to understand the behavior of Cr in ferroan olivine, we have started to examine the micro- and nanostructures of low petrologic type 3 ordinary and CO chondrites using aberration corrected scanning transmission electron microscopy. Here we report observations from the L3.05 UOC, QUE 97008 and the CO3.2 chondrite Kainsaz. Additional studies are in progress on the CO3.02 chondrite ALHA77307. In this study, we have undertaken a micro and nanostructural study to investigate the behavior of Cr in olivine during the very earliest stages of thermal metamorphism. We wish to understand the detailed mechanisms of how Cr undergoes progressive removal from olivine and determine if there are different stages in the process that ultimately lead to a reduction in the Cr content of ferroan olivine as olivine becomes more equilibrated with increasing petrologic type.

Methods: Thin FIB specimens of ferroan olivine were prepared from type IIA chondrules from QUE 97008 and Kainsaz using an FEI Helios NanoLab 650 Dualbeam® FEGSEM/FIB for TEM analysis. TEM imaging was carried out on a JEOL NEOARM 200CF aberration corrected TEM/STEM instrument at the University of New Mexico, using a variety of different imaging techniques, STEM X-ray mapping and STEM EELS spectral imaging.

Observations: In QUE 97008 high-angle annular dark-field STEM imaging of ferroan olivine shows that the olivine contains myriad, crystallographically oriented lamellae distributed quite homogeneously throughout the FIB section (Figs. 1 and 2). The lamellae have higher Z contrast than the surrounding olivine. The lamellae are always discontinuous, <0.25 in length, and have a wavelength typically <50 nm. However, lamellae often seem to be paired close to the region where they terminate and are much closer together in these regions, sometimes < 10 nm apart. Atomic resolution DF-STEM imaging (Fig. 2) viewed down the *a* axis of the olivine show that the lamellae are consistently ~0.375 nm in width and are coherently intergrown with the olivine. STEM EDS line profiles across the lamellae show that Cr is significantly enriched in the lamellae and appears to be inversely correlated with Mg. None of the other detectable elements, O, Si, or Fe show any significant change at the lamellae. Detailed analysis of the atomic positions and intensities of the individual atoms in atomic resolution STEM images, show that the Cr-enriched lamellae have exactly the same structure as the adjacent olivine.

In Kainsaz, with a higher degree of thermal metamorphism, more extensive redistribution of Cr has occurred. Unlike, QUE 97008, Cr-rich veins, typically a micron or less wide are detectable with individual olivine grains. These veins often completely crosscut the olivine grain. STEM imaging and EDS analysis shows that the veins are polycrystalline in nature and are compositionally zoned. The core of the veins contains essentially pure chromite whereas the edges of the veins consist of chromite that contains elevated concentration of V (up to 6 wt% V_2O_5). The grain size in the veins also varies systematically with coarse-grained chromite in the middle of the veins and much finer grained V-rich chromite on their edges. In addition, adjacent to many veins the olivine contains linear high Z features that appear to be about 1 unit cell in thickness and resemble the features observed in olivine in QUE 97008. These features have not yet been examined by aberration corrected STEM, because they were not in the appropriate orientation for imaging within the FIB sections studied. Additional FIB sections are currently in preparation of these olivine grains.

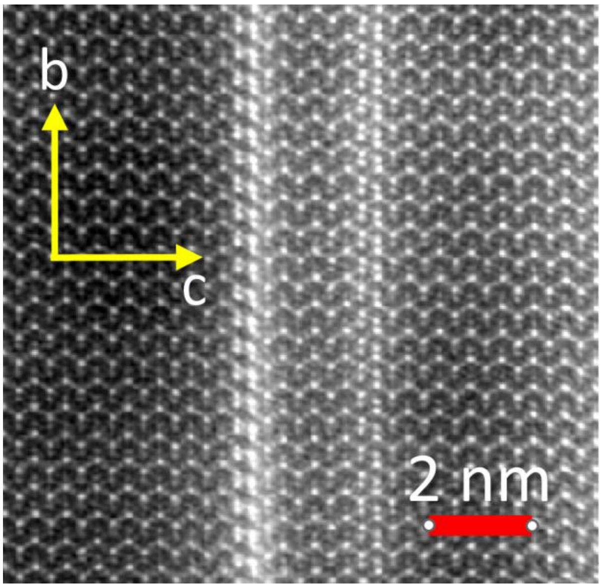

Figure 2. Atomic resolution HAADF STEM image of olivine viewed down the *a* axis, showing two coherently intergrown lamellae with high Z-contrast intergrown with the olivine. The atomic columns in the olivine and within the lamellae are clearly resolved.

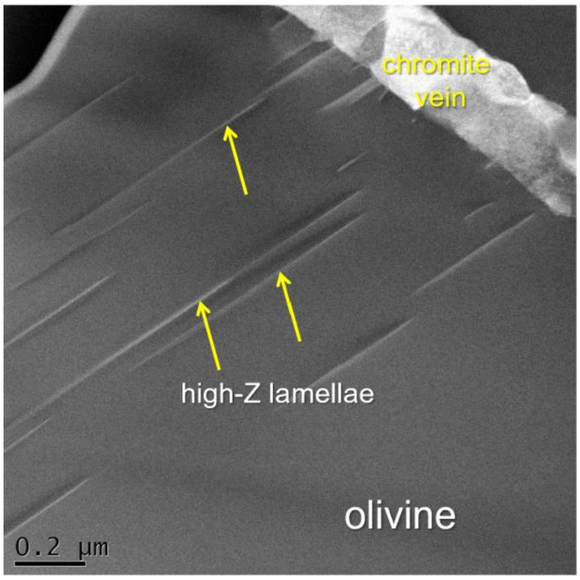

Figure 3. HAADF STEM image of ferroan olivine from Kainsaz showing a chromite vein in the upper right of the image and crystallographically oriented planar lamellae with the olivine very similar to those shown in QUE 97008 in Figure 1.

Discussion: These new TEM observations demonstrate the complex behavior of Cr in ferroan olivine during thermal metamorphism. In QUE 97008, we observe what appears to be the very earliest stages of exsolution of Cr from olivine during metamorphism. Rather than exsolving as an oxide phase, which might be expected, these new data indicate that Cr is actually forming unit cell thick lamellae of Cr-rich olivine. This phenomenon has not been observed before in either meteoritic or terrestrial olivines. Similar lamellae appear to be present in the significantly more metamorphosed CO3 chondrite, Kainsaz, but are much less common. However, the exact identify of the lamellae in Kainsaz still remains to be determined. In Kainsaz, much more extensive mobility of Cr is observed, with the development of chromite-rich veins cross-cutting olivine. It is therefore not clear why such delicate lamellae are still preserved within the olivine. Surprisingly, the results from Kainsaz demonstrate that V exhibits significant mobility, like Cr, at comparatively low degrees of metamorphism. Further studies are currently ongoing on more weakly metamorphosed chondrites such as ALH A77307 (CO3.02) to establish if similar nanostructures are present and determine the very lowest metamorphic conditions chondrites that affect the distribution of Cr in olivine.

References

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