THE BEHAVIOR OF CHROMIUM IN FERROAN OLIVINE DURING THE EARLIEST STAGES OF METAMORPHISM IN THE TYPE L3.05 ORDINARY CHONDRITE, QUEEN ALEXANDRA RANGE 97008: INSIGHTS FROM ABERRATION CORRECTED SCANNING TRANSMISSION ELECTRON MICROSCOPY A. J. Brearley[1] [1]Dept. Earth and Planetary Sci., Univ. of New Mexico, Albuquerque, NM 87131, USA (brearley@unm.edu)

Introduction: The very earliest stages of parent body thermal metamorphism in type 3 chondritic meteorites are indicated by a number of subtle, yet detectable chemical and textural changes [1]. These changes have become extremely useful for assessing the degree of metamorphic equilibration experienced by individual meteorites. Among these measurable changes, the behavior of Cr in ferroan olivines in type II chondrules has been shown by [1] to be an especially useful sensitive recorder of the very lowest grades of metamorphism. This approach has become a widely used technique to classify low petrologic type chondrites, because it is simple to apply and seems to provide a robust and relatively unambiguous and consistent petrologic designation for <3.2 type chondrites including the unequilibrated ordinary (UOC) and CO3 chondrites.

Although the Cr in olivine technique has been widely applied, there are several aspects of the behavior of Cr during the early stages of metamorphism that are not fully understood. In our recent work, we have investigated the oxidation state of Cr in olivine during low grade metamorphism in CO and UOCs [2,3]. However, the actual mechanisms by which Cr is lost from the olivine are still unknown. For example, [1] showed evidence that submicron Cr-rich phases were exsolving within olivine as petrologic type increased, but the details of this process have not been studied.

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: We have studied olivine in a type IIA chondrule from the QUE 97008, a L3 unequilibrated ordinary chondrite that was classified by [1] as petrologic type 3.05. This meteorite was selected because it retains the high Cr contents (~0.5 wt% Cr_2O_3) in ferroan olivine typical of very low petrologic type 3 chondrites, but shows more variability in Cr content than the most unequilibrated ordinary chondrite, Semarkona. Further, based on FEGSEM studies of olivine [1], it shows no detectable exsolution of a Cr-rich phase within olivine, that is apparent in olivine in slightly more metamorphosed type 3 chondrites such as MET 96503 (type 3.1) [1]. The chondrule was originally prepared for TEM studies using conventional argon ion beam milling almost 15 years ago. The same TEM sample was used to prepare focused ion beam foils. FIB foils were extracted 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.

Results: Three FIB sections were prepared from the core regions of two different type IIA chondrule olivines. Two were taken at different orientations in the same olivine and the third FIB section was extracted from a different olivine grain.

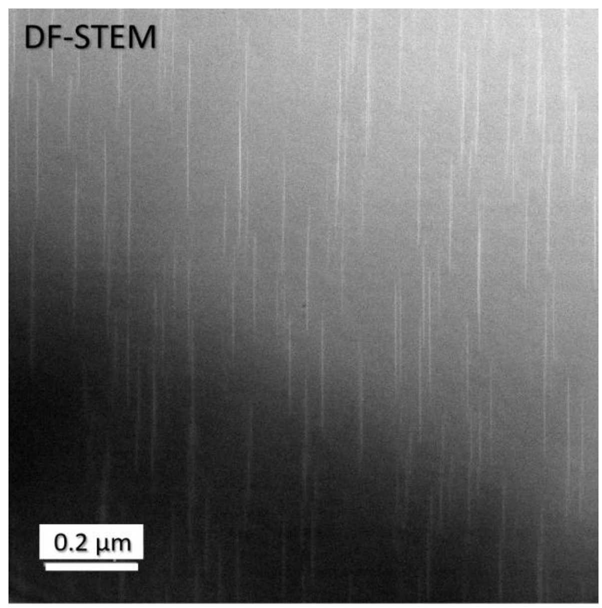

Figure 1. Dark-field STEM image of ferroan olivine from a chondrule in QUE 97008 showing myriad, crystallographically oriented lamellae with high Z

High-angle annular dark-field STEM imaging 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

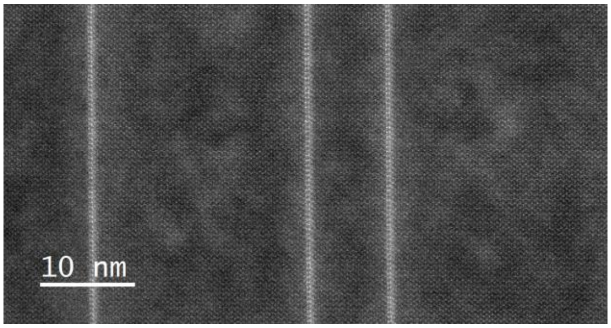

Figure 2. High Resolution Dark-field STEM image of three crystallographically oriented lamellae of a high Z phase within olivine.

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. 3) 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. Figure 3 shows an example of two lamellae adjacent to each other within the olivine. The atomic number contrast in the lamellae on the left is higher, probably due to the fact that the atom columns extend all the way through the

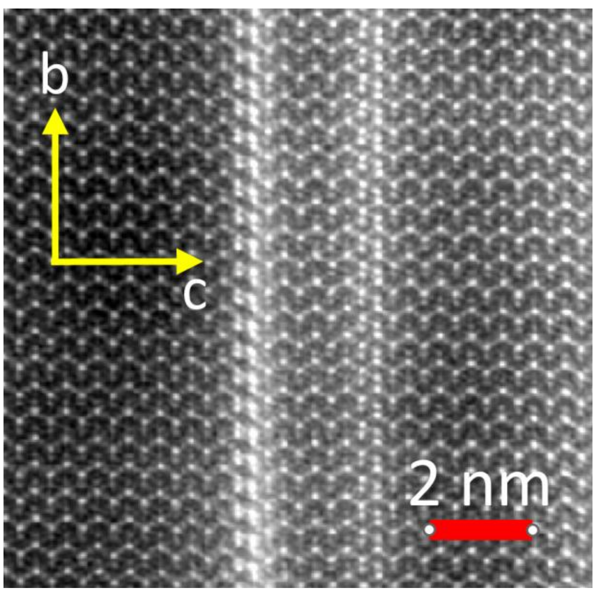

Figure 2. Atomic resolution HAADF STEM image of olivine viewed down the *a* axis, showing two coherently intergrown lamellae with high Z-contrast intergrown with the olivine. The atomic columns in the olivine and within the lamellae are clearly resolved.

FIB foil whereas the columns on the right are in a lamellae that is close to terminating and may not extend through the full width of the foil.

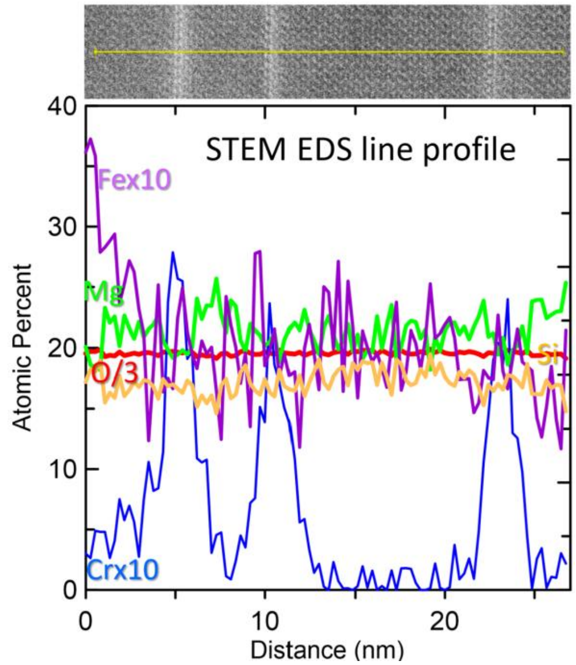

Figure 4. STEM EDS line profile across three lamellae intergrown with the olivine shown in the DF STEM image at the top of the image. The only elements which show significant variation at the lamellae are Cr and Mg.

STEM EDS line profiles across the lamellae (Fig. 4) 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.

Discussion. These observations show the very earliest stages of exsolution of Cr from olivine during metamorphism occurs into unit cell thick lamellae of a coherently intergrown Cr-rich phase. The most likely candidate expected for exsolution would be an oxide phase such as chromite. However, the available STEM EDS data are not consistent with chromite. There is no evidence of a decrease in Si or an increase in Fe in the lamellae which would be expected for an oxide phase such as chromite. The data are most consistent with a Cr-rich silicate phase that also contains Mg and Fe, whose identity remains to be established.

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References: References: [1] Grossman J. N and Brearley A. J. (2005) *M&PS 40*, 87-122. [2] Simon S. B. et al. (2018) *81st Ann. Met. Soc. Mtg.*, Abstract #6173. [3] Simon S. B. et al. (2018) LPI Contribution No. 2067, i.d. 6173.