MATRIX OLIVINES IN THE METAMORPHOSED CK CHONDRITE NWA 1628: POSSIBLE AFFINITIES TO OLIVINES IN THE MATRICES OF OXIDIZED CV3 CHONDRITES AND DARK INCLUSIONS Adrian J. Brearley, Department of Earth and Planetary Sciences, MSC03-2040, University of New Mexico, Albuquerque, NM 87131, USA. brearley@unm.edu

Introduction: The metamorphosed CK chondrites frequently contain evidence of shock darkening of silicates, a feature which has been documented by several authors [1,2]. This darkening is the result of shock mobilization of sulfides and their injection into silicate minerals forming micron to submicron inclusions. Several studies have observed matrix olivines in CK chondrites which appear to be the result of shock darkening. In particular, [2] made persuasive arguments that some olivine grains in the matrix of the Kobe CK4 fall formed by crystallization from shock-produced melts. In these grains, the olivines are vesiculated and contain and inclusion assemblage of magnetite, pentlandite and rare pyroxene and chlorapatite. In this study we have examined the inclusion assemblage in matrix olivines in the metamorphosed CK chondrite, NWA1628, a meteorite which has previously received little attention. This CK chondrite is notable because it contains abundant matrix olivines which are morphologically similar to those in the matrices of Allende-like oxidized CV chondrites, and CV dark inclusions.

We have carried out a petrographic study of NWA 1628 using scanning electron microscopy and electron microprobe analysis. In addition, selected regions of several matrix olivines were extracted using the focused ion (FIB) beam lift out technique and were studied by transmission electron microscopy.

Petrography. NWA 1628 was classified as a CK chondrite of unspecified petrologic type and shock stage S3-6 [3]. Our new observations confirm that it is a metamorphosed CK chondrite, probably of high petrologic type 3. However, although NWA 1628 has clearly been shocked, the shock level indicated by our sample appears to be lower than S3. Chondrule silicates do not show evidence of darkening and there is little evidence of undulose extinction. Matrix in NWA 1628 constitutes about 60 model % of the meteorite, the remainder being mainly porphyritic Mg-rich chondrules. Chondrule olivines and low-Ca pyroxenes show extensive evidence of metamorphic equilibration. Olivines are highly zoned ranging from Fo_{100} to Fo_{63} on their rims, whereas low-Ca pyroxene has developed patchy zoning along contraction cracks and cleavage planes. Opaque nodules in chondrules have been entirely replaced by magnetite and an unidentified Mg, Si-rich phase. Mesostasis is fully recrystallized and commonly consists of augite, albitic feldspar and sometimes anorthite. One fine-grained anorthite-rich CAI also occurs in the thin section studied.

Matrix mineralogy Matrix consists dominantly of equilibrated fayalitic olivine (Fa_{37}) ranging in morphology from anhedral to elongate with grain sizes that range from <2 microns to 100 microns. The matrix texture is variable from one region to another consisting of densely packed anhedral olivines in some regions to more porous aggregates of platelike olivine grains in others. Ca-rich pyroxene $En_{41}Fs_{10}Wo_{49}$, albitic plagioclase ($An_{37}Ab_{62}Or_{1}$-to $An_{17}Ab_{82}Or_{1}$) and sulfides also occur in the matrix. High resolution FESEM imaging of the olivine grains shows that the y have a dusty appearance and \contain myriad inclusions which range from a few microns down to ~ 100 nm in size (Figure 1). Two distinct types of inclusion

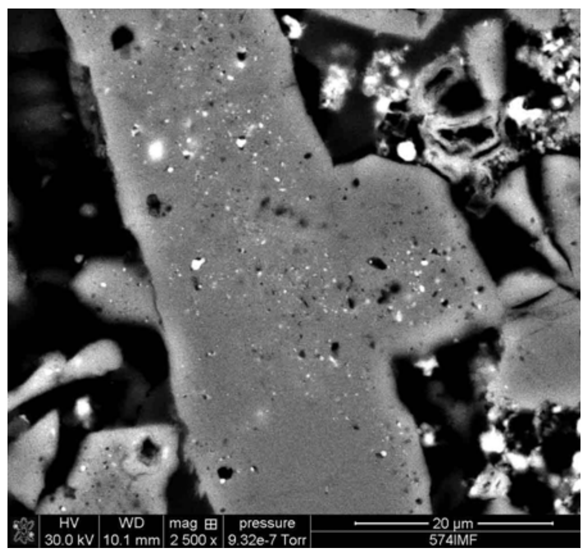

Figure 1. FESEM image of elongate olivine grain in the matrix of NWA 1628, showing heterogeneous distribution of inclusions. The dark inclusions appear to be vesicles and the high Z inclusions are dominantly FeNi sulfides.

are present, one with high Z contrast in BSE images, which dominantly sulfide grains and low Z inclusions, which appear to be voids or vesicles. Large sulfide grains are comparatively rare, but high densities of very small sulfides are extremely abundant in many grains. The distribution of inclusions appears to be somewhat heterogeneous even within individual grains. Some olivine grains have localized regions which appear to be free of any kind of inclusions, whereas most grains have significant abundances of inclusions. There is clearly no correlation of olivine morphology with the occurrence of inclusions. Essentially all olivine grains appear to be inclusion bearing.

FIB-prepared TEM sections were studied using high resolution TEM and analytical electron microscopy in order to characterize the microstructures of the olivine grains in more detail. The grains examined so far do contain dislocations, but the dislocation density is relatively low. The inclusion assemblage inside in the olivines ranges in size from micron size down to a few nanometers and is remarkable in terms of its diversity. As indicated by FESEM observations, the high Z phase is sulfide. AEM data and electron diffraction studies show that this sulfide is dominantly pentlandite with highly variable Ni contents. It is also possible that Ni-bearing pyrrhotite is present, but this requires confirmation. These grains have no apparent crystallographic relationship with the olivine, i.e. are randomly oriented. The sulfide grains usually occur partially filling voids in the olivine (Figure 2). Their grain size, shape and distribution is highly variable. The smallest grains are < 5 nm, but can range up to 300 nm. The largest grains tend to be rounded whereas smaller grains show well-developed facets.

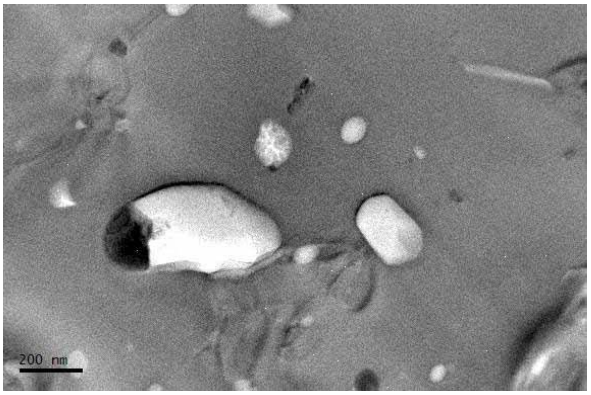

Figure 2. Low magnification TEM image of voids in matrix olivine from NWA1628. Many of the voids are associated with sulfide crystals. Dislocations are present locally in the olivine.

The largest inclusions found so far are magnetite grains, that are comparatively rare. One example observed by TEM is actually a dense aggregate of irregular-shaped grains with highly curved grain boundaries, indicating that it is far from textural equilibrium.

Preliminary data suggest that rare phyllosilicate minerals are associated with the voids in the olivine. One of the most remarkable inclusion phases found so far is a 350 nm long inclusion, probably a platelet in three dimensions with a 1 nm basal spacing. The AEM data for this phase is consistent with a high Ti potassic mica that is most likely an Mg-Fe biotite. In addition, preliminary high resolution TEM data and AEM data also indicate that some voids contain ~100 nm grains of a phase with a 1.4 nm basal spacing which compositionally appears to be an aluminous chlorite.

Discussion. The morphologies and microstructures of olivines in NWA 1628 bear some interesting resemblances to olivines in the matrices of Allende-like oxidized CV3 chondrites and dark inclusions (DIs). Morphological, platy, elongate olivines that are typical of CV3 matrices are common in NWA matrix, although the grain size is much coarser in NWA. It is notable that NWA does appear to be more highly metamorphosed than Allende. Ollvines in Allende and Allende DIs contain both abundant voids and sulfide grains, typically pentlandite and pyrrhotite, with similar morphologies and grain sizes to those in NWA olivines [4]. Pentlandite is the most common sulfide in NWA olivines, but pyrrhotite seems to be less common. Allende olivines are characterized by abundant graphitic inclusion [4], which we have not yet observed in NWA olivines. However, we have not studied these olivines in detail yet using energy filtered TEM, so the presence of carbonaceous inclusions in NWA cannot be ruled out.

It has been suggested that fluid assisted metamorphism played a role in the formation of olivines in the oxidized CV3 chondrites [e.g. 5], although this hypothesis remains controversial. We infer from the characteristics of matrix olivines in NWA 1628 that fluids may also have played a role in the growth of olivines in this meteorite. This conclusions is supported by the presence of inclusions of hydrous phases in the NWA olivines. Further studies are needed to fully determine the distribution and abundances of these phases, but the initial data indicate that they represent phyllosilicates that are stable at relatively high temperatures, consistent with formation during fluid-limited metamorphism. Our data suggest that although shock darkening clearly played a role in the formation of inclusions in olivines in some CK chondrites, other processes may have also contributed to the complex inclusion assemblages in CK matrix olivines.

References [1] Rubin, A.E. (1992) *GCA* **56**, 1705. [2] Tomeoka, K et al. (2001) *MAPS* **36,** 1535 [] Russsell et al. (2005) *MAPS* **40**, A201. [4] Brearley, A.J. (1999) *Science* **285**, 1380. [5] Krot, A.N. et al.. (2004) *Antarct. Meteorit. Res.*, **17**, 153.

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