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CARBIDES IN ORDINARY CHONDRITES REVISITED

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Introduction: Iron-nickel carbide minerals cohenite $(Fe,Ni)_3C$ and haxonite $(Fe,Ni)_{23}C_6$ have been observed previously in type 3 ordinary chondrites [1,2,3] with suggested formation via low-temperature aqueous alteration [3]. More recently, a carbide mineral has been observed in ordinary chondrites containing higher type (>type 3) material [4,5]. Here we report the results of a combined EMP, SEM, EBSD, and TEM study on 26 H- and L-chondrites.

Observations going into study based on preliminary data from 2 genomict breccias (NWA 5964 and Buck Mountain Wash) [4,5]:

- Carbide associated with whole rock shock melt, but never found inside shock melt
- Carbide not associated with a particular shock stage
- Carbide only found in genomict breccias containing both type 3 material and whole rock shock melt
- Carbide possibly cohenite based on preliminary data.

Samples and optical mapping:

- Range of samples - 26 ordinary chondrites, including genomict and monomict breccias, variably metamorphosed and variably shocked chondrites, samples with extensive shock melt that are not genomict breccias, L-melt rocks, shock-recrystallized chondrite
- Optical mapping of all occurrences in a thin section, optical photomicrographs of all occurrences

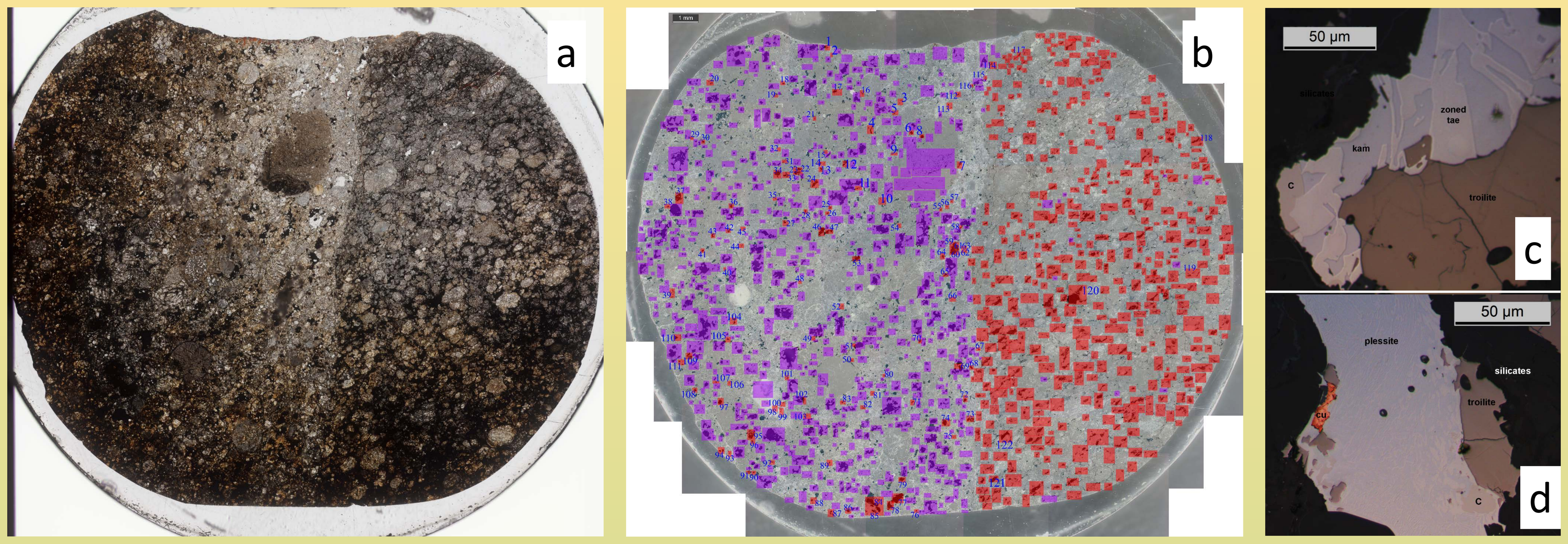

Figure 1. Thin section scan (a) and map on inverted reflected light mosaic showing carbide locations (b) in Buck Mountain Wash (H3-6). Metal regions in (b) are colored red if containing a carbide, and purple if lacking a carbide. The right hand side of the section is shock-blackened type 3 material; that on the left is a mixed lithology that is dominantly equilibrated, and yet has over 100 occurrences of a carbide. Fig.1 (c) and (d) are reflected light images that show carbide locations 75 and 23 from NWA 5954 (L3-6)--c=carbide, cu=copper, kam=kamacite, tae=taenite. (c) Carbide at edge of zoned taenite grain. (d) Carbide between troilite and plessite in a grain that also contains copper.

Confirm the presence of carbide:

- EMP analyses – limited number of analyses
- SEM line scans – many analyses

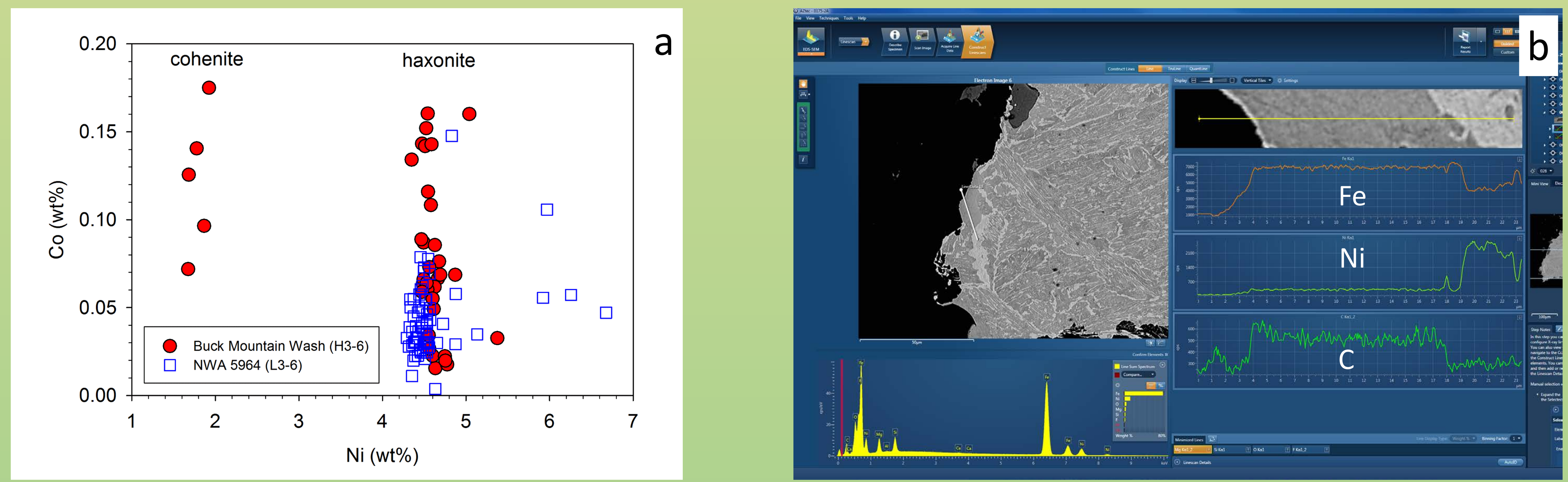

Figure 2. (a) Ni and Co contents in carbide grains in Buck Mountain Wash and NWA 5964 (EMP data). The data clearly indicate the presence of two carbides, and are consistent with cohenite and haxonite. (b) Line scans obtained with an SEM confirmed the presence of elevated carbon in grains identified optically as carbides, in this case haxonite.

References: [1] Taylor G. J. et al. (1981) *LPS XXII,* 1076-1078. [2] Scott E. R. D. et al. (1982) *Meteoritics 17*, 65-75. [3] Krot A. N. (1997) *GCA 61*, 219-237. [4] Hauver K. L. and Ruzicka A. M. (2011) *42nd LPS*, Abstract #2627. [5] Likkel L. et al. (2013) *Meteoritics & Planet. Sci., 48,* A188.

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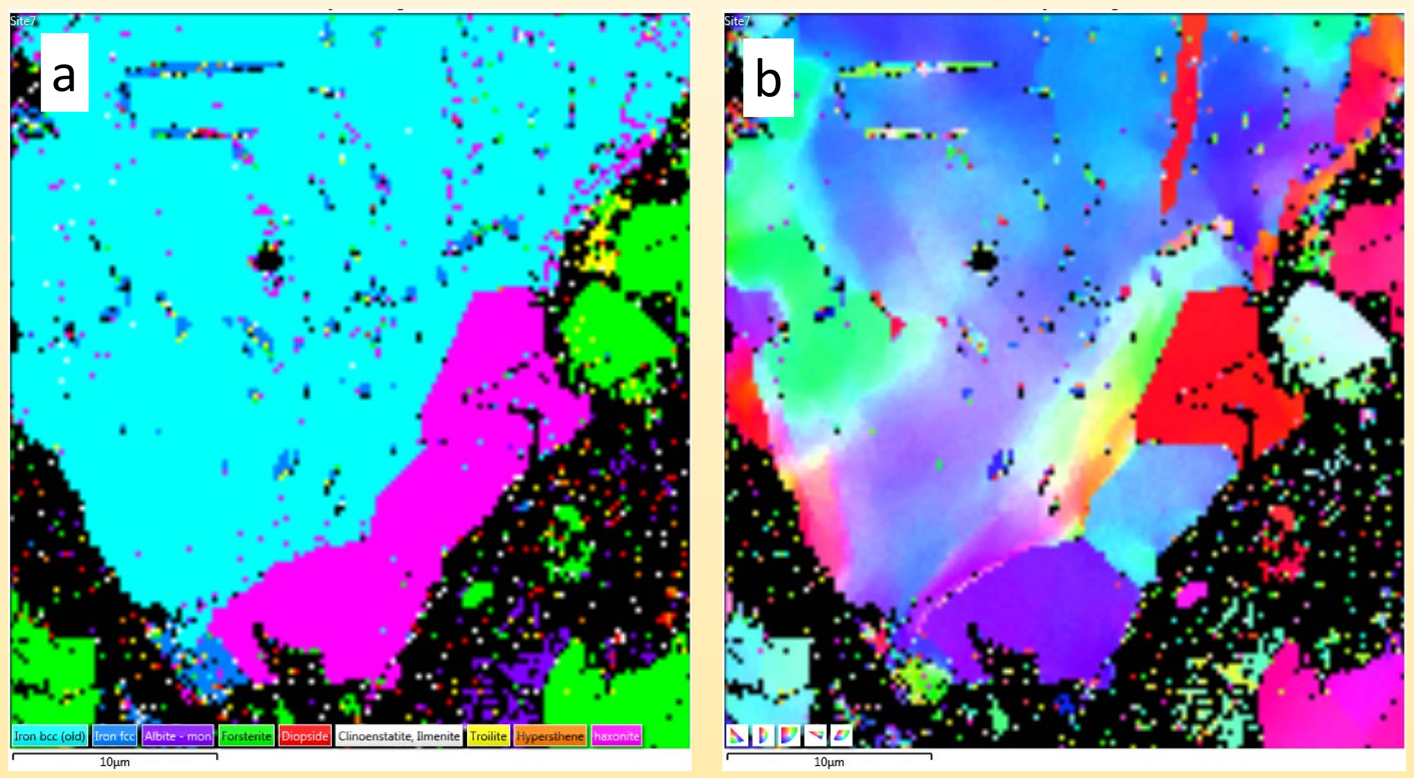
Confirm the identification of carbides as cohenite and haxonite

- EBSD data
- TEM data



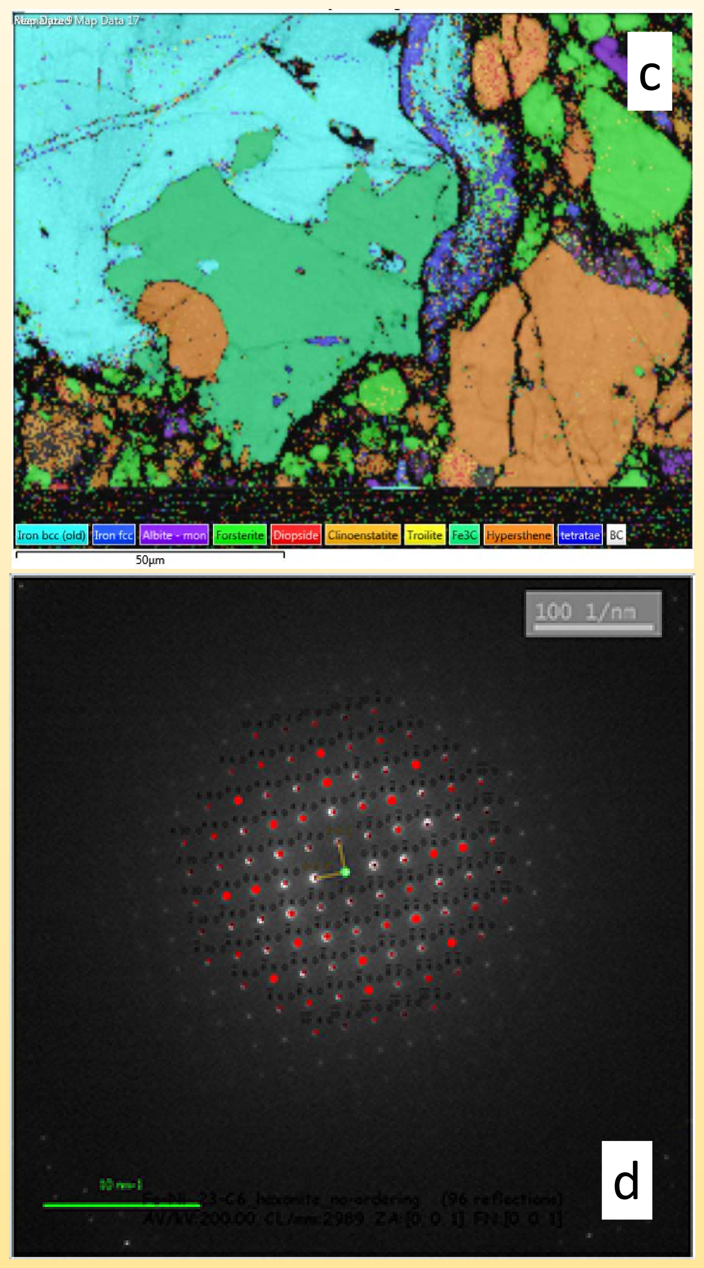
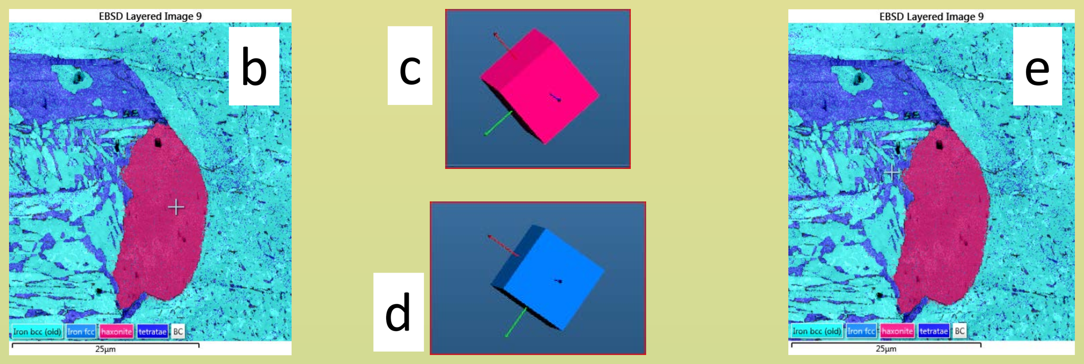


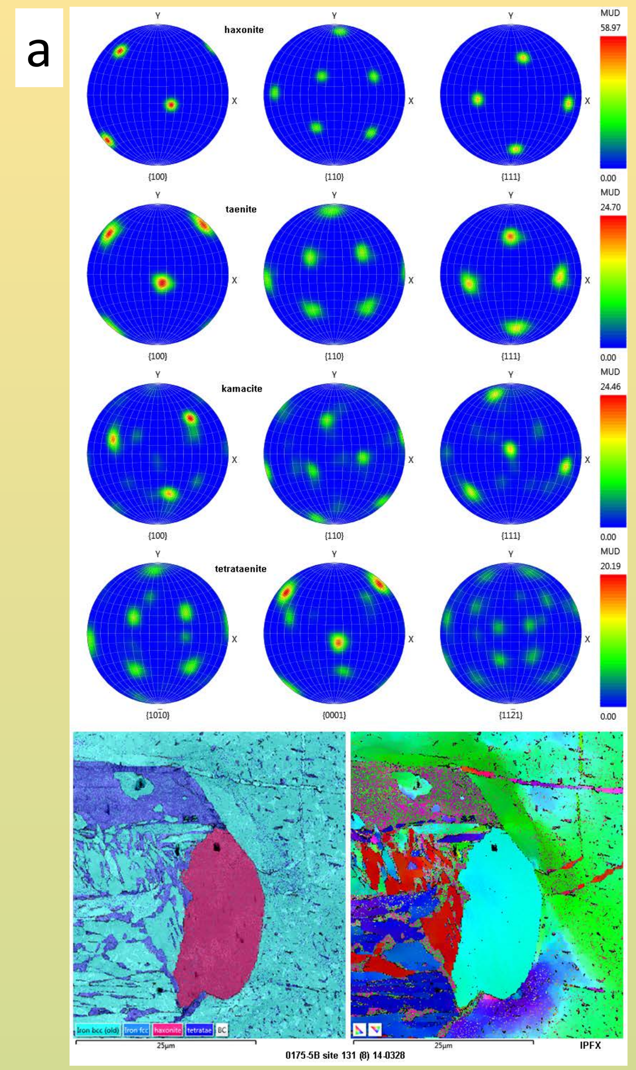
Figure 3. (a) EBSD crystal structure phase map (pink=haxonite, light blue = kamacite) and (b) corresponding IPFX orientation map, of three subhedral haxonite grains at the edge of a metal grain in NWA 5964. Smooth color variations in the IPFX map indicate strain, which is concentrated in kamacite near haxonite. (c) EBSD crystal structure phase map (light blue = kamacite, olive green = cohenite) of three cohenite grains at the edge of a metal grain in Buck Mountain Wash. (d) A model haxonite diffraction pattern (in red) overlaid on the [001] zone axis pattern for a carbide grain in NWA 5964.

Examine the relationship of carbide to other phases

- See relationship between haxonite and taenite – crystal orientations often similar with about 10° or less offset
- Often see kamacite strained against edge of carbide

Figure 4. (a) Phase map and IPFX orientation map near the center of a metal grain in NWA 5964 and the accompanying pole figures for haxonite, taenite, kamacite, and tetrataenite, showing similarity of the haxonite and taenite crystal orientations, and strain in the metal adjacent to haxonite . (b) and (c) show the crystal orientation at a point marked with a "+" in the phase map; (d) and (e) show the same date for taenite. The two structures are similar with a small rotation.





Results:

- EBSD data are unambiguous regarding the presence of cohenite, but allowed for the possibility that haxonite was actually Fe_4C. A single haxonite/Fe_4C grain was examined with both EBSD and TEM. Haxonite was the only match with the sample data.
- Only haxonite was found in 7 L genomict breccias and one other chondrite NWA 10454 (L5/6). Both cohenite and haxonite were observed in Buck Mountain Wash (an H genomict breccia).
- No carbides were found in any of the other 18 chondrites studied, none of which were genomict breccias.
- EBSD data suggest preferred orientation relationships between haxonite and the various co-existing phases, especially taenite, consistent with growth from taenite.
- We observed elevated C in taenite compared to kamacite (consistent with a taenite precursor) and a common occurrence of carbides in breccias containing both significant melt and type 3 components.
- The common association of carbide with zoned taenite or tetrataenite suggests carbide formation at low temperature during slow cooling, implying burial in the parent body of warm materials.
- We suggest that carbides formed as separate phases in metal during cooling after shock reheating.