COHENITE IN NWA 5964 (L3-6 MELT BRECCIA): A POSSIBLE PRODUCT OF SHOCK-INDUCED CONTACT METAMORPHISM. K. L. Hauver[1] and A. M. Ruzicka[1], [1]Cascadia Meteorite Laboratory, Portland State University, Dept. of Geology. 1721 SW Broadway, Portland, OR 97201 U.S.A. (hauverk@pdx.edu , ruzickaa@pdx.edu).

Introduction: Cohenite [$(Fe,Ni)_3C$] in meteorites is best known from iron meteorites that contain between ~ 6-8 wt% Ni [1] but has also been reported in some weakly metamorphosed but hydrothermally altered ordinary chondrites [2], in weakly metamorphosed CO3 chondrites [3], and in enstatite chondrites such as Abee [4]. It is known to be a metastable phase but one that can form easily instead of slightly more stable graphite under some conditions [5-7]. Here we report the discovery of cohenite in NWA 5964, a complex, partially shock melted ordinary chondrite that contains a large (>27 × >17 mm) shock melt zone embedded in an L3-6 chondritic host [8] (Fig. 1). Cohenite is found intergrown with metal within the chondritic host (Fig. 2-3). We suggest that this cohenite formed by shock-reheating under conditions that can best be described as contact metamorphism.

Methods: Metal and sulfide were studied using optical microscopy and scanning electron micrsocopy using a JEOL JSM-25C SEM at Portland State University (PSU), and electron microprobe analysis was carried out using a CAMECA SX100 housed at Oregon State University via remote access from PSU using standard WDS operating conditions. Thin sections were carbon coated prior to analysis and cohenite was analyzed in two ways, including and excluding carbon. Fe, Ni, Co, P, S, and C were calibrated using metal, pyrite, apatite, and SiC standards Analyses with and without C gave results consistent to within ~1 wt% of measured and inferred C. Bulk compositions of assemblages were estimated from the area of phases in thin section and from measured and estimated phase compositions and phase densities.

Results and Discussion: The shock melt zone consists primarily of fine-grained zoned olivine set in glass and contains occasional large globules of metal-sulfide that have dendritic texture, characteristic of rapid crystallization from a melt [e.g., 9]. Immediately adjacent to the melt zone and apparently injected into the host from the shock melt is an irregularly shaped, especially large (11 x 8 mm) dendritic metal-sulfide (DMS) grain (Fig. 1). The spacing of the dendrites in the globules from the shock melt have been used to estimate a cooling rate of ~12˚C/sec using the technique of Scott [9]. This rapid cooling must reflect the quenching of the shock melt zone as it came into contact with colder materials including the chondritic host. The lack of cohenite in the shock melt is consistent with previous experiments [7] in which upon quenching of C-bearing metal, no cohenite, and only graphite, formed. Currently we have no direct evidence for the presence of graphite in the dendritic assemblages or elsewhere, but its presence may have been overlooked.

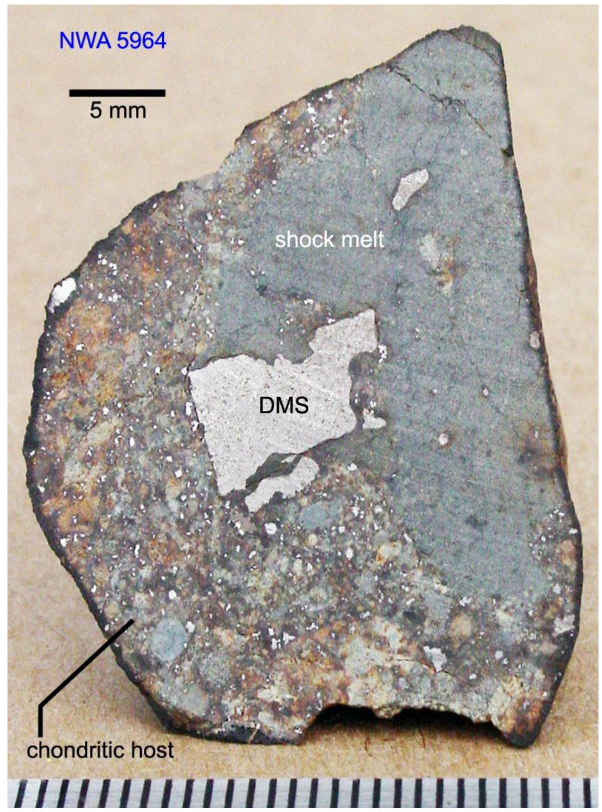


Fig.1. Image of NWA 5964 in a cut surface showing shock melt, chondritic host, and a large dendritic metal-sulfide assemblage (DMS). Cohenite occurs in metal particles within the host (bright spots).

Within the host, cohenite is typically located along the edges or within metal grains that contain a variety of metal phases and textures (Fig. 2, 3). Although cohenite is absent from both the large shock melt zone and from smaller igneous-textured and recystallized clasts, it is present in some metal assemblages immediately adjacent to these regions. Moreover, the host adjacent to the shock melt contains a high proportion of type 5-6 and little type 3-4 material. The observations are consistent with the possibility that the cohenite was produced by shock heating of metal caused by proximity to the shock melt.

Table 1 shows bulk compositions and mineral associations for three representative cohenite-bearing assemblages. There appear to be two populations of such assemblages. One population (#1 and #2 in Table 1, Fig. 2) has relatively low bulk C (<0.1 to 0.7 wt%) and has cohenite occurring on the rims of (mainly) kamacite as one or more small, usually rounded regions. The second population (#3 in Table 1, Fig. 3) has larger masses of cohenite within metal grains containing taenite and plessite. The bulk carbon content of these types of grains is estimated to be ~1.4-1.6 wt%.

Table 1. Bulk composition of 3 cohenite-bearing assemblages in NWA 5964 (wt%, normalized to exclude troilite). Coh=cohenite, K=kamacite, Tt=tetrataenite, Tae=taenite, Pl=plessite, Tr= troilite.

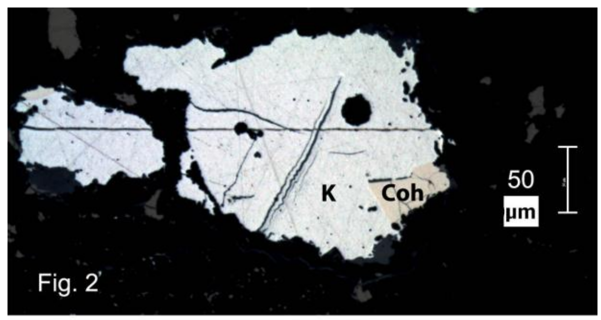
Assemblage	C	Fe	Ni	Phases
1	0.69	91.0	8.3	Coh, K, Tt
2 (Fig. 2)	0.59	91.8	7.6	Coh, K
3 (Fig. 3)	1.51	71.7	25.8	Coh, Pl, Tt, Tr

Cohenite in both types of assemblages has about the same composition (wt% mean and s.d., N=31): 7.0±1.1 C, 89.0±1.3 Fe, 5.1±1.0 Ni (total 99.9). The compositions of coexisting metals and their identity provide information on the closure temperature (Tc) of the assemblages as inferred from the Fe-Ni phase diagram [10]. Thus for #1 in Table 1, the Ni content in kamacite (~5.6 wt%) and the presence of tetrataenite imply Tc ~ 290-340°C. For #2, the Ni content in kamacite (~7.9 wt%) implies Tc ~425°C. For #3, the presence of tetrataenite implies Tc <400°C. All assemblages are consistent with the Fe-Ni-C phase diagram [8] extrapolating downwards in temperature from 500°C. In experiments, cohenite is produced only by relatively slow cooling from higher temperatures [7]. Thus, cohenite in NWA 5964 can be understood to be the quasi-stable C polymorph produced by relatively slow cooling of a C-bearing metal down to temperatures of ~290-425°C.

The source of the carbon is not directly apparent, but type 3 ordinary chondrites contain up to 1.0 wt% bulk C [11], and experiments show that synthetic cohenite can form through the reaction of a C-rich vapor with Fe metal alloy [12]. Shock heating can raise temperatures ~250-350°C at the transition between shock stage stages S4/S5, ~600-850°C for S5/S6, and ~1500-1750°C at the onset of whole-rock melting [13]. One might expect C-bearing vapors to be generated for such relatively intense shock events.

Conclusion: The presence of cohenite only in NWA 5964 (and in one other still-unclassified NWA shock melt breccia we have examined) suggests that the conditions involved in forming such shock melt breccias were favorable for producing cohenite. The cohenite apparenty formed in reheated chondrite 'wall rock' portions during contact metamorphism.

References: [1] Brett R. (1966) *GCA* **31**, 143–159. [2] Krot A.N. et al. (1997) *GCA* **61**, 219-237. [3] Shibata Y. (1996) *Proc. NIPR Symp. Antarct. Meteorites* **9**, 79-96. [4] Dawson K. R. et al. (1960) *GCA* **21** 127-144. [5] Massalski T.B. (1986) *Binary Alloy Phase Diagrams*. [6] Kubascheski O. (1982) *Iron-binary Phase Diagrams*. [7] Romig A. D. and Goldstein J. I. (1978) *Metall. Trans. A* **9A**, 1599–1609. [8] Weisberg M. et al. (2010) *MAPS* **4**5, 449-493. [9] Scott E. R. D. (1982) *GCA* **46**, 813–823. [10] Yang C.W. et al. (1996) J. Phase Equil. 17, 522-531. [11] Hayes J. M. (1967) *GCA* **31**, 1395-1440. [12] Zhang, J. et al. (2000) *Metall. Materials Trans. B* **31B**, 1139-1142. [13] Stoffler D. et al. (1991) *GCA* **55**, 3845-3857.



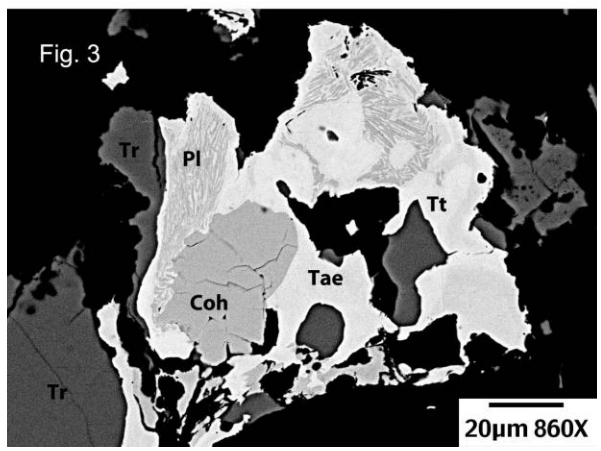


Fig. 2 (top image). Color image obtained in reflected light of a kamacite (K) – cohenite (Coh) assemblage with cohenite appearing as the creamy color phase at the right edge of the kamacite. Silicates appear black.

Fig. 3 (bottom image). BSE image of an assemblage containing cohenite (Coh), taenite (Tae), tetrataenite (Tt), plessite (Pl) and troilite (Tr). Silicates appear black.