Cohenite in NWA 5964 (L3-6 Melt Breccia): A Possible Product of Shock-Induced Contact Metamorphism

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1. Background

We report the discovery of cohenite in NWA 5964, an L3-6 partially shock melted ordinary chondrite. NWA 5964 contains a large (>27 x >17 mm) shock melt zone embedded in the chondritic host (Fig. 1). The chondritic host exhibits features indicative of shock stages S1 to S6. Cohenite is found intergrown with metal throughout the chondritic host (Fig. 2-4). Cohenite [(Fe,Ni)3C] is common in iron meteorites [1], and less frequently found in enstatite chondrites [2], hydrothermally altered ordinary chondrites [3], weakly metamorphosed CO3 chondrites [4]. Cohenite is a metastable phase, but its formation can be favored over the more stable graphite under specific, slow cooling conditions [5-7]. Ni contents in the metal grains reflect a closure temperature of less than 400˚C, also suggesting slow cooling conditions. We suggest the cohenite is formed as a result of heating caused by proximity to shock melt, in a process best described as shock-induced contact metamorphism.

Figure 1.

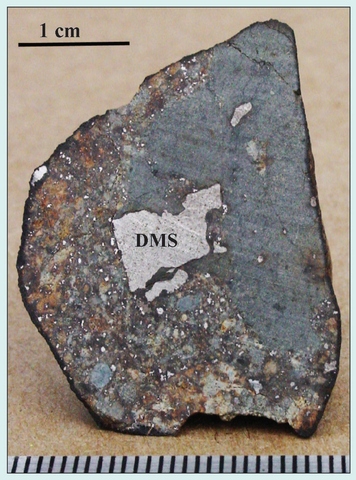
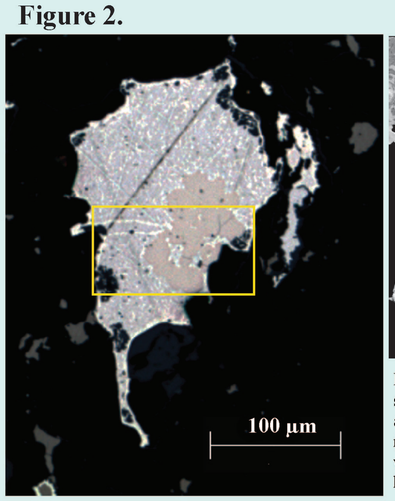


Figure 1. Image of NWA 5964 in a cut surface showing shock melt, chondritic host, and a large dendritic metal-sulfide assemblage (DMS). Cohenite occurs only in metal particles within the host (bright spots).

Figure 2.



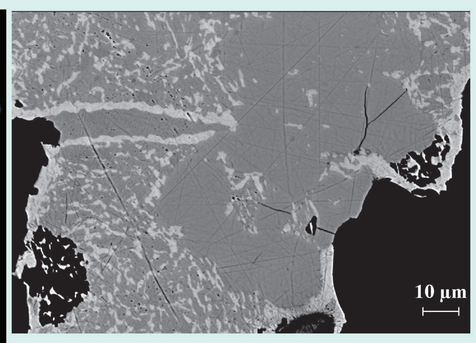


Figure 2. (Left) Reflected light image of cohenite +martensite assemblage. (above) Backscatttered electron (BSE) image showing a closer view of area in yellow box accenting the high Ni (bright regions), and low Ni (grey) intergrowths within martensite, as well as the cohenite (coh) which is difficult to distinguish from kamacite in BSE without the corresponding optical image.

2. Methods

Opaque minerals across 5 polished thin sections, representing areas within the chondritic host and shock melted regions of NWA 5964, were studied using reflected light optical microscopy. Scanning electron microscopy (SEM) was completed at Portland State University (PSU), and electron microprobe analysis (EMPA) was carried out via remote access from PSU to Oregon State University, using standard WDS operating conditions. Cohenite was analyzed with and without carbon being directly measured, and both techniques yielded consistent results to within ~1 wt% C. Bulk compositions of mineral assemblages were estimated from the areas of the phases in thin section, assuming average mineral compositions based on EMPA data and representative mineral densities [8] (Table 1).

Table 1.

Table 1. Average (± standard deviation) compositions of phases used to determine bulk assemblage compositions, based on N number of points.

Average Phase Compositions wt%

	Cohenite	Kamacite	Martensite[1]	Taenite[2]
C	6.50	0.00	0.00	0.00
Ni	4.50	5.23	12.47	40.76
Fe	89.00	92.86	86.67	58.22
S	0.00	0.00	0.00	0.00
Density	7.70	7.90	8.00	8.10

[1]'Martensite' here describes any fine-grained intergrowth of kamactie and Ni-rich metal (fine plessite).
[2]Average for all taenite and tetrataenite points as they are optically similar and counted together .

3. Assemblages and Textures

Cohenite is observed only in metal grains within the chondritic host (Fig. 2-4, 6), and not in the shock melt regions which consists of metal-sulfide dendrite structures (Fig. 5). The cohenite is usually present as small grains along the edges of metal particles (Fig. 4), and less commonly as larger masses of cohenite extending substantially into the metal particles from their edges (Fig. 2, 6), or along internal grain boundaries (Fig. 3). Cohenite (coh) is always intergrown with metal particles that can consist of kamacite, taenite, and/or martensite; tetrataenite has also been identified in some grains via EMPA.

Figure 3.

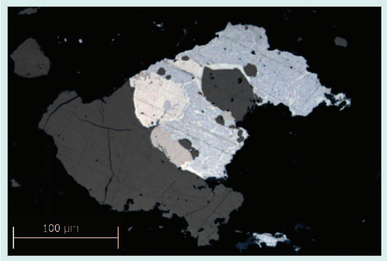


Figure 3. (right) Reflected light image of cohenite + kamacite + taenite assemblage. The cohenite in this case occurs along a kamacite-troilite grain boundary, rather than along the edge of the opaque assemblage.

Figure 4.

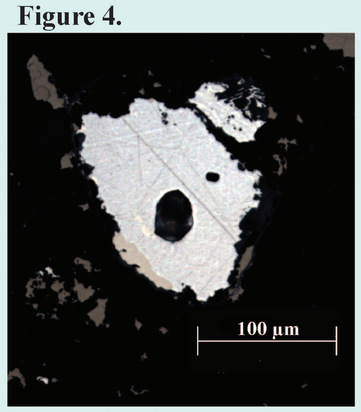


Figure 4. (above) Reflected light image of cohenite + kamacite + taenite assemblage. The relatively small cohenite grain along the edge of the metal particle is the most common setting in which cohenite is observed.

Figure 5.

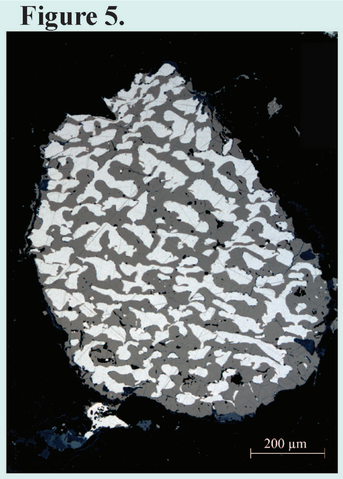
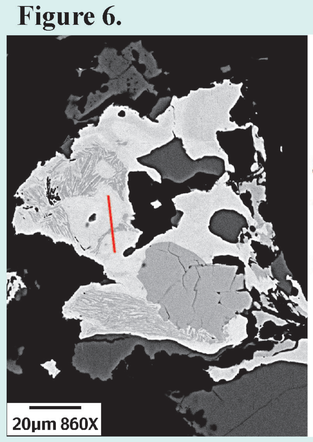


Figure 5. Reflected light image of metal-sulfide dendritic structures found within the shock melted region of NWA 5964. The spacings of the arms were measured and used to calculate an approximate cooling rate of 12 ˚C/sec using methods described by Scott [15].

4. Phase Compositions

The average cohenite composition is consistent with the mineral formula [(Fe, Ni)3C] as well as with metallurgy experiments [7] which consistently measured 6.67 wt% C for cohenite from a variety of cooling experiments. The spread in values for martensite composition is attributed to it being generalized to any fine intergrowth of kamacite and taenite. The spread in the taenite composition is a result of including taenite and tetrataenite, which is necessary as in reflected light the two phases could not be reliably distinguished.

Figure 6.



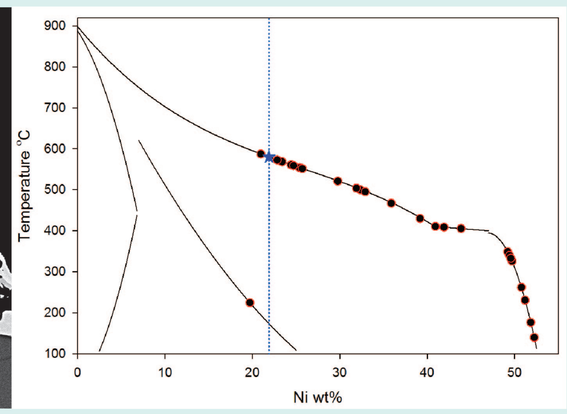


Figure 6. (Left) BSE image showing taenite (T) + tetrataenite (Tt) + martensite (M) + cohenite (coh) assemblage. EMPA data collected along the red line are plotted on the graph (right) with their corresponding closure temperatures [14]. The bulk metal composition is 21.8 wt% Ni, shown in blue. All analyzed grains within NWA 5964 fell within the closure temperature range seen in this grain (~600-125 °C).

5. Formation of cohenite from C-bearing vapor

We attribute the formation of cohenite to the reaction of C-bearing vapor with Fe-metal, a mechanism that has been experimentally duplicated when metal is heated to 400-800˚C and exposed to an atmosphere containing C [9-10]. The source of the carbon in NWA 5964 is not directly apparent, but type 3 ordinary chondrites can contain up to 1.0 wt% bulk C [11] and models predict C-bearing vapor will be produced by heating L chondrites above 300 ˚C [12]. Shock heating can raise temperatures up to 350°C at the transition between shock stage stages S4/S5, 850°C between shock stage stages S5/S6, and 1750°C at the onset of whole-rock melting [13]. Thus, one might expect C-bearing vapors to be generated for such relatively intense shock events.

6. Stability of cohenite upon cooling

The Ni content in the metal grains can be used to estimate a closure temperature for cohenite-bearing assemblages (Fig. 6), which for all assemblages in NWA 5964 ranges from ~600 - 125 ˚C. Figure 7 shows the bulk compositions of cohenite-bearing assemblages plotted on the phase diagram at 500 ˚C [7] the cohenite-bearing assemblages are consistent with the relatively high bulk C we determined. Cooling experiments in C-bearing systems show that cohenite can crystallize along with metals during slow cooling (25 ˚C/h), but graphite forms instead of cohenite during rapid cooling [7]. Thus, the presence of cohenite in the chondritic host areas can be explained as the result of slow cooling. The absence of cohenite in the shock melt areas can be explained as a result of rapid. Indeed, the dendritic metal-sulfide structures in the shock melt region represent a very fast cooling rate of 12˚C/sec at melt temperatures, inferred using the methods described by Scott [15]. Either cooling in the melt was so rapid as to favor graphite formation over cohenite, or C was expelled from the melt as a gas phase. We have searched for graphite but this search has been inconclusive.

Figure 7.

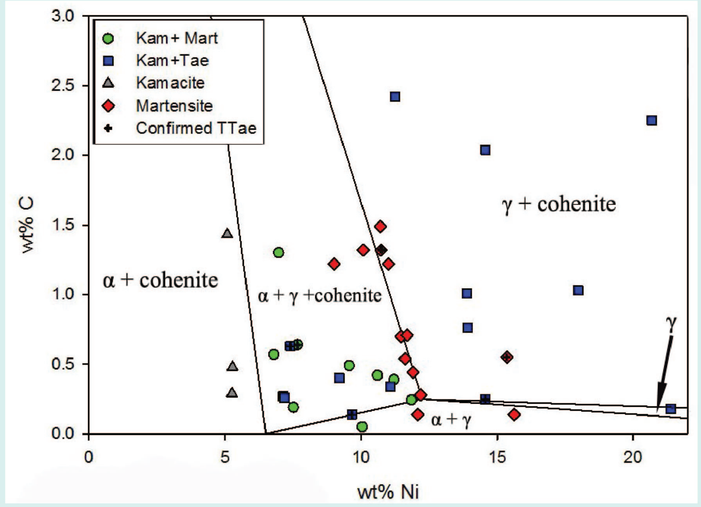


Figure 7. Bulk compositions are relatively consistent with expected assemblages for closure temperatures of 500 °C or below assuming that at lower temperatures the kamacite + taenite + cohenite stability field will expand relative to the taenite + cohenite stability field, that martensite will decompose to kamacite + Ni-rich metal, and that taenite will be replaced by tetrataenite.

7. Conclusion

Conditions involved in forming shock melt breccias were favorable for producing cohenite. The cohenite is limited to 'wall-rock' regions experiencing significant shock induced heating of 400˚C or greater, resulting in processes analogous to contact metamorphism. The existence of another shock melt breccia NWA 6580 (pending approval) with similar textures, compositions, and cohenite-bearing assemblages (Fig. 8) further support these conclusions.

Figure 8.

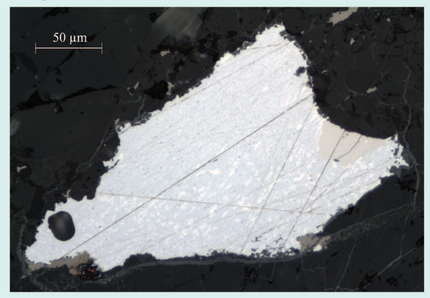


Figure 8. Kamacite + martensite+ cohenite assemablge from NWA 6580 (pending approval), also a partially shock melted L chondrite breccia.

9. Acknowledgements

This work was supported by public donations to the Cascadia Meteorite Laboratory as well as by an internal grant (Faculty Development Award) from Portland State University to Alex Ruzicka.

10. References

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