

**Magnetite in CK and CV Chondrites: Evidence for Two Parent Bodies?** T.L. Dunn<sup>1</sup> and J. Gross<sup>2,3</sup>  
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**Introduction:** The CK chondrites are a highly-oxidized group of carbonaceous chondrites characterized in part by the presence of nickel-rich olivine and Cr<sub>2</sub>O<sub>3</sub>-rich magnetite [1-3]. Similarities between the CK and the CV chondrites, such as oxygen isotopes, mineral compositions, and bulk rock compositions, led [4 & 5] to suggest that both groups are derived from the same parent asteroid. The CV and CK chondrites do have one significant difference however, and that is the degree of metamorphism that they have experienced.

All CV chondrites are classified as petrologic type 3 [6 & 7], while CK chondrites are the only carbonaceous chondrite group to exhibit the complete range of thermal metamorphism, from type 3 to type 6 [1]. Petrologic type is a measure of the degree of metamorphism in a sample, with type 3 being the least metamorphosed and type 6 being the most metamorphosed [8]. Because metamorphic effects are particularly prominent in petrologic type 3 material, meteorites of this grade can be further divided into petrologic subtypes (i.e. type 3.0 – 3.9) [9-11].

Most CK chondrites are equilibrated (types 4-6). However, twenty-two type 3 CK chondrites have been identified. Though the type 3 CV chondrites are thought to be less metamorphosed than the type 3 CK chondrites [e.g. 4,6,7], very little work has been done to characterize the thermal histories of the unequilibrated CK and CV chondrites. Here, we continue an ongoing study to determine the petrologic subtypes of the type 3 CK chondrites.

**Methodology:** We have analyzed chondrule olivine and magnetite in seven type 3 CK chondrites and one CV3 chondrite. Mineral compositions were determined using a JEOL JXA 8200 electron microprobe at Washington University in St. Louis, MO and a CAMECA SX 100 at the American Museum of Natural History, NY. Operating conditions: 15 kv potential, 25 nA beam current, and 2 μm beam size. Typically 10-15 magnetite grains were analyzed in each sample. Average mineral compositions in Dhofar 015 were provided by Marina Ivanova at the Vernadsky Institute in Russia [12].

**Establishing a Metamorphic Sequence:** In ordinary chondrites, Cr<sub>2</sub>O<sub>3</sub> decreases (as FeO increases) during progressive metamorphism. Thus, samples with lower Cr<sub>2</sub>O<sub>3</sub> represent higher petrologic type than those with higher Cr<sub>2</sub>O<sub>3</sub>. Our previous work [13-14] has demonstrated Cr<sub>2</sub>O<sub>3</sub> content of olivine in type

II chondrules can also be used as a geochemical indicator of metamorphism in the CK chondrites (Fig. 1).

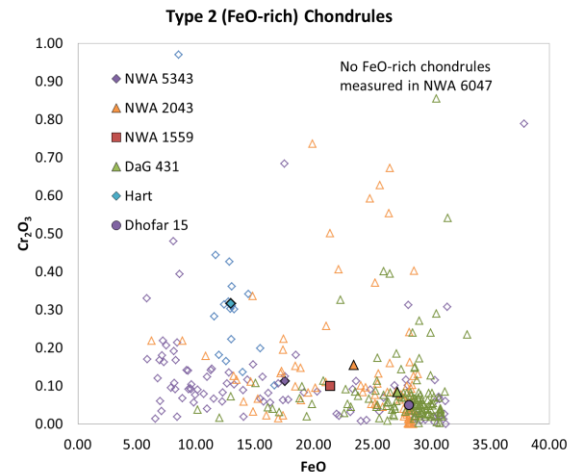


Fig. 1. Based on Cr<sub>2</sub>O<sub>3</sub> content, there is a clear pattern of progressive metamorphism within the CK chondrites analyzed, with Hart being the least metamorphosed and Dhofar 015 being the most.

We have also demonstrated that NiO content in type II chondrule olivine is sensitive to metamorphism [13-14]. As shown in Fig. 2, NiO content in olivine follows an increasing trend along the same sequence of samples established by Cr<sub>2</sub>O<sub>3</sub> (from Hart to Dhofar 015). This suggests that nickel in olivine increases during progressive metamorphism of the CK chondrites.

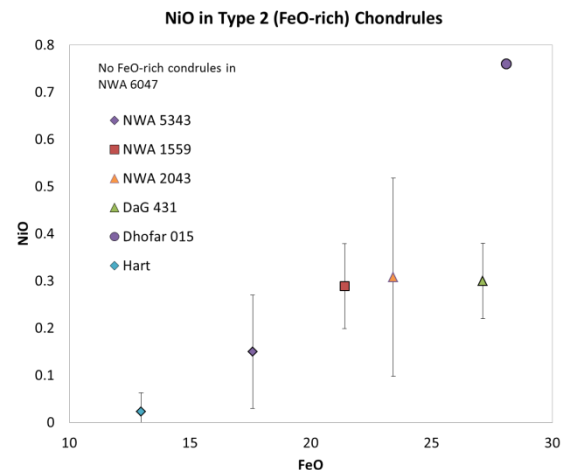


Fig. 2 Average NiO in FeO-rich chondrules increases from Hart to Dhofar 015, in the same sequence established by Cr<sub>2</sub>O<sub>3</sub>. Error bars represent standard deviation of NiO.

**Chemical composition of magnetite:** Because oxides diffuse between chondrules and matrix material during metamorphism, we might expect there to be parallel trends in NiO and Cr<sub>2</sub>O<sub>3</sub> content in magnetite during metamorphism. Average Cr<sub>2</sub>O<sub>3</sub> and NiO content in the samples analyzed in this study are plotted in Figures 3 and 4, respectively.

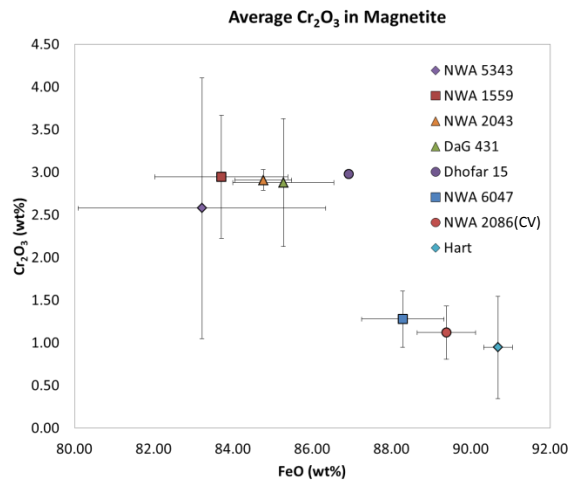


Fig. 3. Average Cr<sub>2</sub>O<sub>3</sub> in magnetite plots in two clusters. Error bars represent standard deviations of analyses.

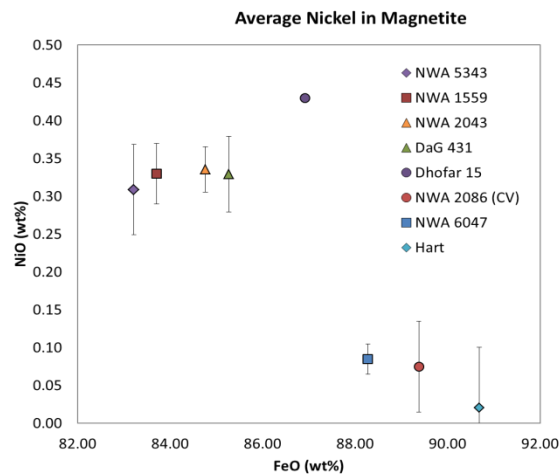


Fig. 4 Average NiO in magnetite also plots in two clusters. Error bars represent standard deviations of analyses.

Somewhat surprisingly, there is no apparent geochemical trend within magnetite. Instead, average Cr<sub>2</sub>O<sub>3</sub> and NiO content of the eight samples analyzed plot in two clusters, one with high oxide abundances and the other with low abundances (Figs. 3 & 4). Though figures 3 and 4 show only average abundances, these clusters are present when all analyses are considered. To confirm this trend we examined other oxide abundances from magnetite and discovered the same clusters in TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>. The only difference between these clusters is the placement of Dhofar 015,

which plots with the high abundance cluster in Cr<sub>2</sub>O<sub>3</sub> and NiO (Figs. 3 & 4, respectively) but with the low abundance clusters in TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>.

Table 1. Compositions of magnetite in samples analyzed

	NiO		Cr <sub>2</sub> O <sub>3</sub>		TiO <sub>2</sub>		Al <sub>2</sub> O <sub>3</sub>	
	min	max	min	max	min	max	min	max
low-oxide	0.0	0.2	0.1	2.8	0.0	0.1	0.0	1.2
high-oxide	0.2	0.5	0.7	5.1	0.1	1.7	1.9	3.7

**Conclusions:** There appears to be two compositional varieties of magnetite in the samples analyzed, one with high-oxide abundances and the other with low oxide abundances (Table 1). Four samples contain high-oxide magnetite abundances, while three samples consist of low-oxide magnetite, including CV chondrite NWA 2086. All samples with high-oxide magnetite are dominated by FeO-rich chondrules, while samples with low-oxide magnetite consist mostly of FeO-poor chondrules. Though Dhofar 015 does not fall firmly into either group, its olivine compositions suggest that it is better suited to the high-oxide group.

Because nickel is a strong indicator of oxidation state, the two contrasting magnetite compositions may represent different oxidizing conditions, with samples in the high-oxide group forming under a higher oxidation state than samples in the low-oxide group. Because the only CV chondrite analyzed contains low-oxide magnetite, it is possible that NWA 6047 and Hart, which also contain low-oxide magnetite, have been incorrectly classified as CK chondrites. This would be consistent with their olivine compositions, which are lower in FeO than is typical for CK chondrites. Samples in the high-oxide group are likely true CK chondrites. This would suggest that the CK and CV chondrites represent two different parent bodies. However, more CV chondrites need to be examined before this trend in magnetite compositions can be confirmed.

**References:** [1] Kallemeyn G.W. et al. (1991) *GCA* 55:881-892. [2] Nogouchi T. (1993) *Proceed. NIPR Ant. Met.* 2, 204-233. [3] Geiger T, and Bischoff. A. (1995) *Planet. Space Sci.* 43, 485-498. [4] Greenwood R.C. et al. (2010) *GCA* 74, 1684-1705. [5] Wasson J.T. et al. (2013) *GCA*, 108, 45-62. [6] McSween H.Y. et al. (1977a) *GCA*, 41, 479-491. [7] McSween H.Y. et al. (1977b) *GCA*, 41, 1777-1790. [8] Van Schmus and Wood (1967) *GCA*, 31, 704-714. [9] Sears et al. (1980) *Nature*, 287, 791-795. [10] Sears et al. (1991) *Proc. NIPR Symp. Antarct. Met.*, 4, 319-343. [11] Chizmadia et al. (2002) *GCA*, 37, 1781-1796. [12] Ivanova et al. (2000), *MAPS*, 35, A83. [13] Dunn T.L. (2013) *MAPS* 74, 5291. [14] Dunn T.L. 2014. Abstract #1038, 45th LPSC. [17] Geiger and Bischoff (1995) *Planet. Space Sci.*, 43, 485-498.