Nickel in Type II Chondrule Olivine as an Indicator of Petrologic Subtype in CK Chondrites.

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Introduction: The CK chondrites are the only carbonaceous chondrite group to exhibit the full range of thermal metamorphism (from petrologic 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 [2]. 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) [3-5].

Most CK chondrites are equilibrated (types 4-6). However, twelve type 3 CK chondrites have been identified. With the exception of Northwest Africa 2921 (NWA 2921), which is classified as petrologic subtype 3.8 [6], the petrologic subtypes of the CK3 chondrites have not been determined. However, [7] suggested that all CK3 chondrites are type 3.5 or higher, based on the abundance of refractory inclusions noted in published descriptions.

The most easily recognizable effects of thermal metamorphism are textural changes, including recrystallization of matrix material (blurring of chondrules) and crystallization of feldspar from chondrule glass [8-11]. However, chemical homogeneity and composition of olivine are two of the most useful indicators of metamorphic grade, particularly in unequilibrated samples [10]. In ordinary chondrites, Fa content in olivine becomes increasing uniform with increasing petrologic type, eventually converging on values for equilibrated chondrites. In addition, FeO content of chondrule olivine increases during metamorphism while FeO content in matrix olivine decreases during metamorphism [12-13]. In Type I (FeO-poor) chondrules, CaO content of olivine in decreases to near equilibrium values during metamorphism [14]. In Type II (FeO-rich) chondrules, Cr_2O_3 content decreases during the early stages of metamorphism [12, 15, 16].

Olivine in ordinary chondrites does not contain appreciable abundances of nickel, so its behavior during metamorphism has not been studied. However, it is possible that nickel may be sensitive to the degree of metamorphism in samples that are nickel-rich. CK chondrites are characterized by NiO-rich olivine and magnetite. It has been suggested that NiO diffuses from magnetite into olivine under increased oxygen fugacity conditions [17]. If this is correct (and assuming oxygen fugacity increases during metamorphism), then NiO in olivine should increase during progressive metamorphism (as FeO increases). It would then be possible to use nickel content in olivine an indicator of petrologic subtype in the CK chondrites.

Geochemical Analysis: To test this hypothesis, I analyzed chondrules and matrix olivine in four type 3 CK chondrites: Hart, Northwest Africa (NWA) 1559, NWA 5956, and Dar al Gani (DaG) 431. Olivine compositions were determined using a JEOL JXA 8200 electron microprobe at Washington University in St. Louis, MO. Operating conditions: 15 kv potential, 25 nA beam current, and 2 µm beam size. Typically 50-60 olivine grains were analyzed in each sample. Average olivine compositions in Dhofar 015 were provided by Marina Ivanova at the Vernadsky Institute in Russia.

Establishing a Metamorphic Sequence: Of the five samples analyzed so far, all consist primarily of Type II chondrules containing FeO-rich olivine. In ordinary chondrites, Cr_2O_3 decreases (as FeO increases) during progressive metamorphism. So, samples with lower Cr_2O_3 represent higher petrologic type than those with lower higher Cr_2O_3. As shown in Figure 1, Hart contains the highest average abundance of Cr_2O_3 and Dhofar 015 the lowest. Samples NWA 1559, NWA 5956, and DaG 431 fall between Hart and Dhofar 015, in that order.

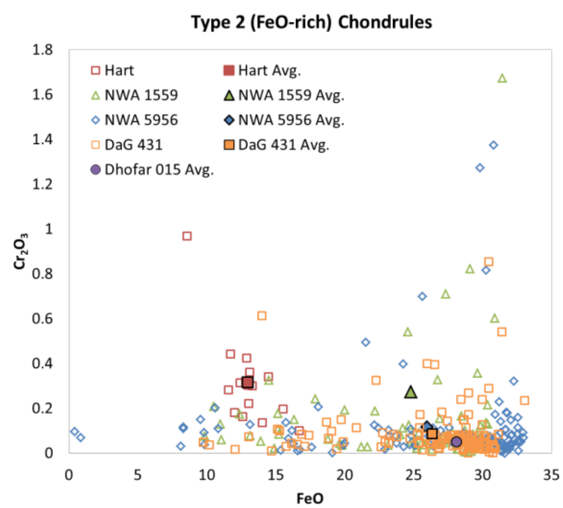

Fig. 1. Based on FeO and Cr_2O_3 content, there is a clear pattern of increasing metamorphism within the five CK chondrites analyzed., with Hart being the least metamorphosed and Dhofar 015 being the most metamorphosed.

This metamorphic sequence is also supported by percent mean deviation (PMD) of Fa in olivine, CaO content in Type I chondrules, and FeO content in matrix olivine. PMD, which is a measure of the mean deviation of Fa in individual measurements from the mean of all measurements [18], decreases during metamorphism as samples become more equilibrated. In the samples analyzed, PMD decreases from Hart to NWA 1559 to NWA 5956 to DaG 431. Only two samples, Hart and NWA 1559, contain Type I (FeO-poor) chondrules, but the abundances of CaO are consistent with NWA 1559 being more metamorphosed than Hart. Also, the average FeO content in matrix olivine decreases from NWA 1559 to NWA 5956 to Dhofar 015 (not measured in Hart and DaG 431).

These parameters together suggest that there is a clear metamorphic sequence among the five samples analyzed. This sequence, from least to most metamorphosed, is Hart → NWA 1559 → NWA 5956 → DaG 431 → Dhofar 015.

NiO in Type II Chondrule Olivine. If nickel content is sensitive to metamorphism, then NiO in chondrule olivine should increase during progressive metamorphism (as nickel diffuses from magnetite into olivine). Because nickel content in chondrule olivine is higher in Type II chondrules than in Type I chondrules, olivine in Type II chondrules should be more senstive to metamorphic effects. Based on the sequence previously established, NiO in olivine should increase from Hart to NWA 1559 to NWA 5956 to DaG 431 to Dhofar 015. As shown in Fig. 2, nickel content does increase among samples in this sequence, with the exception of NWA 5956.

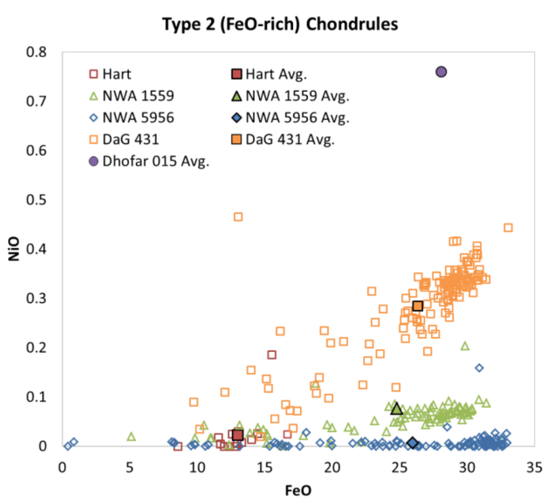

Fig. 2 NiO in FeO-rich chondrules increases from Hart to NWA 1559 to DaG 431 to Dhofar 015, but values in NWA 5956 are lower than all other samples. With the exception of NWA 5956, this is consistent with the petrologic sequence established based in Cr_2O_3 in Type II chondrules, PMD, and Cao in Type I chondrules.

The nickel content of olivine in NWA 5956 is much lower than expected based on the metamorphic sequence established using known geochemical parameters. Based on its place in the metamorphic sequence, NWA 5956 should have a higher NiO content than both Hart and NWA 1559. However, nickel in NWA 5956 is extremely low (0.007 wt%) compared to the other CK chondrites in this study (Hart - 0.02 wt%, NWA 1559 – 0.08 wt%, DaG 431 – 0.28 wt%, and Dhofar 015 – 0.76 wt%).

It seems likely that NWA 5956 has been misclassified as a CK chondrite. CK chondrites are characterized by Ni-rich olivine, so an average nickel content of 0.007 wt% is not consistent with classification as a CK chondrite. Also, NWA 5956 contains more metal than is typical for a CK chondrite and it appears to be lacking magnetite.

Therefore, it would appear that NiO content in chondrules olivine can be used as a geochemical indicator of the degree of metamorphism in the CK chondrites. However, the remaining CK chondrites need to be examined before this trend can be confirmed.

Petrologic Subtypes of the CK Chondrites: Dhofar 015 is clearly the most metamorphosed sample in this study. It's olivine compositions are very close to the equilibrium values found in type 4 CK chondrites (e.g. 0.01 wt% Cr_2O_3, 0.51 wt% NiO, and Fa_{31}) [19]. Dhofar 015 is likely petrologic subtype 3.9. Because not all type 3 CK chondrites have been analyzed, it is impossible to determine where the lower limit for these values lies. So, the petrologic subtype of Hart, which is the least metamorphosed, cannot be determined based on geochemical parameters alone. If all CK3 chondrites are petrologic subtype 3.5 or higher, as suggested by [7], then Hart may correspond to a subtype 3.5 while NWA 1559 and DaG 431 may be classified as subtypes 3.7-3.8.

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