**FE-NI METAL IN PRIMITIVE CHONDRITES: INDICATORS OF CLASSIFICATION AND METAMORPHIC CONDITIONS.**

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**Introduction:** Unequilibrated ordinary chondrites are classified into petrologic types 3.0-3.9 [1]. Recently Grossman and Brearley [2] showed that the distribution of Cr in olivine changes systematically as metamorphism increases in type 3 ordinary (O) and CO chondrites. The Cr distribution in olivine can be used to divide types 3.0 and 3.1 into 3.00 through 3.15 in O chondrites. Kimura et al. [3] found that the characteristic features of Fe-Ni metal, such as texture and composition, in LL chondrites are highly sensitive to thermal metamorphism, and seem to be consistent with the classification system proposed by [2].

Here we report the relationship between metamorphic grade and the characteristic features of Fe-Ni metal in O and CO chondrites. Our goals are to explore the classification criteria and metamorphic conditions of the highly primitive chondrites.

**Mineralogy of Fe-Ni metal:** We studied 11 L and LL chondrites of type 3.00-3.5 and 3 CO chondrites. Metal in all of these samples does not show shock-induced features, as reported by [4,5]. Fe-Ni metal occurs as spherical grains in chondrules, as irregularly shaped grains on chondrule surfaces and as isolated grains in the matrix. The texture of Fe-Ni metal in Semarkona clearly depends on the occurrence. Chondrule metal typically shows a plessitic intergrowth (Fig. 1), as noted by [6], whereas metal grains on chondrule surfaces and isolated grains are always homogeneous, and generally show an intergrowth of kamacite and Ni-rich metal. Fe-Ni metal in the other chondrites, especially those of type LL3.15-3.5 and A-882094 (CO), never show plessitic intergrowths in any occurrences. Instead, their chondrule metal commonly shows an intergrowth of medium to coarse-grained kamacite and high Ni metal. The textures of some metal grains in chondrules in L/LL3.05-3.10 chondrites, ALHA77307 (CO) and A-881632 (CO) seem to be intermediate between those in Semarkona and LL3.15-3.5 chondrites.

The compositions of Fe-Ni metal in L/LL3.00-3.10, an LL3.15 (Y-74660) and two CO (ALHA77307 and A-881632) chondrites are related to their occurrences. The Co content of metal in chondrules is usually low (Fig. 2). However, metal on chondrule surfaces and isolated grains is enriched both in Ni and Co. In the other chondrites, kamacite always has higher Co content than Ni-rich metal, regardless of its occurrence.

**Discussion:** The composition and plessitic intergrowth of Semarkona metal are evidently distinct from those of higher petrologic type chondrites. Fe-Ni metal in Semarkona chondrules records the earliest stages of metal decomposition. Metal in the other chondrites was modified by metamorphism, although that in L/LL3.05-3.15 and two CO chondrites seems to partly preserve its primordial features.

Metal textures in chondrules vary continuously from typical plessite in Semarkona to coarse-grained aggregates of kamacite and Ni-rich metal in LL3.15-3.2 chondrites. In order to evaluate such textural changes quantitatively, we measured the number density and average area of individual Ni-rich metal grains in each metal spherule in chondrules. Figure 3 shows the data from L/LL3.00-3.2 and 3 CO chondrites. There is a clear negative correlation between the number density and area of Ni-rich metal. With increasing petrologic type, the number density of Ni-rich metal grains drastically decreases and the area increases, as fine-grained plessite is replaced by coarse-grained Ni-rich metal coexisting with kamacite. From this diagram, the textural features of metal can distinguish between type 3.00, 3.05-3.10, 3.15 and 3.2. It is evident that the metal texture reflects the petrologic type for O chondrites proposed by [2].

ALHA77307 is the most primitive CO chondrite [2]. Olivine compositions of two CO chondrites, A-881632 and A-882094, are similar to those of O chondrites of types 3.15 and ≥3.2, respectively, according to the criteria by [2]. Metal in ALHA77307 and A-881632 plot in the region of L/LL3.05-3.10 chondrites. On the other hand, metal in A-882094 has similar features to that in LL3.2. Thus, metal as well as olivine can be used to determine metamorphic grade in CO chondrites and identify the least equilibrated ones. Petrological features, such as Co content in metal and the alteration degree observed in refractory inclusions, change with petrologic type in CO chondrites [7,8]. The classification based on olivine and metal described here is consistent with other petrologic indicators of metamorphism, e.g., abundant nepheline-rich refractory inclusions in A-882094 and almost nepheline-free inclusions in A-881632.

The intergrowth of kamacite and Ni-rich metal in chondrules of L/LL3.05-3.2 chondrites formed at temperatures of 350-500°C, as determined by the method of [9]. It is probable that these chondrites experienced metamorphism under such low-temperature conditions. However, Alexander et al. [10] suggested that the metamorphic temperature for Semarkona did not exceed 250°C. This is much lower than the temperature derived from metal. Metal and other minerals in Semarkona mostly preserve their primordial features, and Semarkona is clearly the most primitive O chondrite [2], except for small degrees of hydrous alteration [10]. The metal temperatures for CO chondrites are also 350-500°C. The characteristic features of olivine and metal suggest that CO chondrites were also metamorphosed under temperature conditions similar to O chondrites.

We conclude that Fe-Ni metal is one of the most sensitive indicators for the lowest grades of metamorphism. This is due to the higher diffusion rates in Fe-Ni metal than silicates and oxide minerals. Even chondrites of low type 3 were subjected to metamorphism on their parent bodies. A number of petrologic features (Cr in olivine [2], spinel composition and abundance [11], and now metal composition and texture) form a consistent set of sensitive gages for low levels of thermal metamorphism in O and CO chondrites. They can be applied to classification of petrologic types (3.00-3.5), resolving between degrees of metamorphism in mildly altered chondrites and identification of the most primitive (least metamorphosed) chondrites.

**References:** [1] Sears D. W. et al. (1980) *Nature*, *287*, 791-795. [2] Grossman J. N. and Brearley A. J. (2005) *Meteoritics & Planet. Sci.*, *40*, 87-122. [3] Kimura M. et al. (2005) *Antarc. Meteorites XXIX*, 28-29. [4] Smith B. A. and Goldstein J. I. (1977) *GCA*, *41*, 1061-1072. [5] Bennett M. III and McSween H. Y. Jr. (1996) *Meteoritics & Planet. Sci.*, *31*, 255-264. [6] Reisener R. J. and Goldstein J. I. (1999) *LPS XXX*, Abstract #1868. [7] McSween H. Y., Jr. (1977) *GCA*, *41*, 477-491. [8] Rubin A. E. (1998) *Meteoritics & Planet. Sci.*, *33*, 385-391. [9] Afiattalab F. and Wasson J. T. (1980) *GCA*, *44*, 431-446. [10] Alexander C.M.O. et al. (1989) *GCA*, *53*, 3045-3057. [11] Kimura M. et al. (2003) *Meteoritics & Planet. Sci.*, *38*, A33.

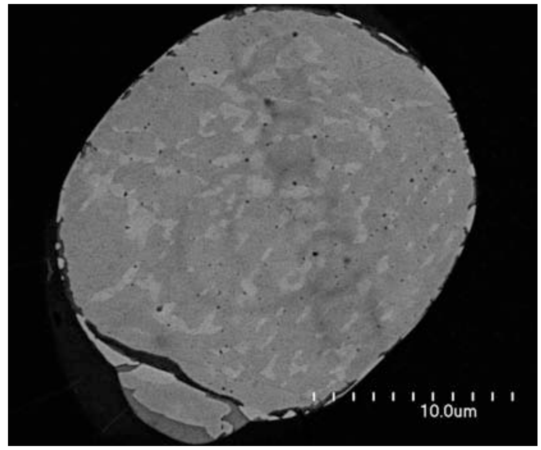


Fig. 1. Metal spherule in a Semarkona chondrule, showing a plessitic intergrowth. Back-scattered electron image by FE-SEM. Width is 26 microns.

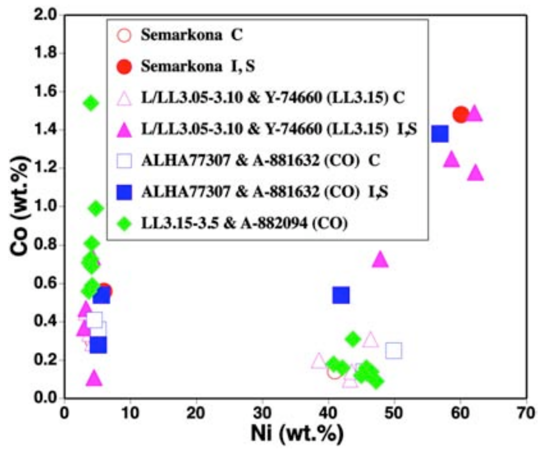


Fig. 2. Ni vs. Co plot of Fe-Ni metal in L/LL3.00-3.5 and CO chondrites. Average data of kamacite and Ni-rich metal are plotted. C=chondrule interior, S=chondrule surfaces, and I=isolated grain in matrix.

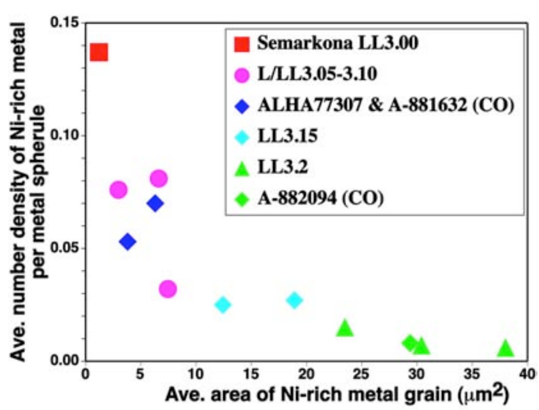


Fig. 3. Plot of average area of individual Ni-rich metal grain and average number density of Ni-rich metal per metal spherule area in chondrule of L/LL3.00-3.2 and CO chondrites.