RELATION BETWEEN SILICATE CHONDRULES AND METAL-SULFIDE NODULES IN EH3 CHONDRITES.

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Introduction: The most primitive EH3 chondrites contain numerous metal-sulfide nodules (MSN) and silicate chondrules, both of which appear to have experienced repeated melting before they were accreted into their parent bodies [1, 2]. Silicates are common in MSN [1, 3-5], and opaque minerals are common in silicate chondrules [6-8]. However, the relation between MSN and chondrules is poorly understood. Although oldhamite, niningerite, and kamacite within MSN are widely considered to be condensates from a reduced (C/O~1) nebular gas [3, 9, 10], many MSN contain minor ferromagnesian silicates with >1wt. % FeO, which is inconsistent with their formation under highly reducing conditions. Ikeda interpreted the sulfide and silicate inclusions within MSN as remnants of sulfidized Ca and Mg silicates [4].

Some silica-sulfide-rich chondrules contain ferromagnesian silicates with replacement intergrowths of silica, troilite, and niningerite [11, 12]. Mineral relationships in these chondrules are consistent with the formation of niningerite by silicate sulfidation in a H-depleted, dust-enriched, environment with the fS_2 resulting from molten metal-sulfide assemblages [13, 14]. Objects with mineralogy intermediate between chondrules and MSN support this possibility.

Here we report on the composition of sulfides in MSN and in silica-sulfide-rich chondrules, the occurrence of spheroidal aggregates of ferromagnesian silicates, silica, metal, and sulfides, and the gradational variation in the abundance of opaque and non-opaque minerals comprising MSN and silicate chondrules. Our goal is to assess whether MSN and silicate chondrules were exposed to the same or similar fS_2, fO_2, temperature, and pressure.

Methods: Thin sections of EH3s Sahara 97072, ALH 84170, and LAR 06252 were studied using petrographic microscopy and scanning electron microscopy. Sulfides in MSN and silica-sulfide-rich chondrules were measured using a JEOL JXA 8600 electron microprobe.

Petrographic observations: In EH3 meteorites, silicate chondrules lacking sulfides and MSN lacking silicate inclusions are end-members of a continuous series. In the middle of this series are spheroidal aggregates of unequilibrated pyroxene, plagioclase, silica, troilite, niningerite, oldhamite, and minor kamacite, with the silicates and opaque minerals in approximately equal amounts (Figs. 1, 2). In some cases, enstatite laths occur enclosed in niningerite and troilite (Fig. 1). More commonly, niningerite, silica, and troilite appear to be replacing silicates (Figs. 2, 3). The silica in these aggregates is commonly porous and like the silica in the silica-sulfide-rich chondrules and MSN [8, 11, 12].

Many of the spheroidal aggregates, and a few MSN [8], have ferromagnesian silicate mantles with typical igneous textures (Figs. 2, 3) similar to the silica-sulfide-rich chondrules. The mantles enclose mixtures of silicate and opaque minerals in a wide range of proportions from the more typical radial pyroxene and porphyritic pyroxene chondrules enclosing minor sulfides to chondrules enclosing MSN [8].

Many MSN have layered metal-troilite mantles with silicate inclusions between the layers (Fig. 4). Commonly MSN are comprised of up to 50% Si-bearing inclusions, which primarily consist of S-rich, porous silica with sulfides similar to that in silica-sulfide-rich chondrules (Fig. 5) and in the core of some MSN [8, 12] (Fig. 4) but also include roedderite, pyroxene, and plagioclase [4].

Although end-member chondrules and MSN are abundant, EH3s also contain spheroidal objects that are difficult to classify as either MSN or silicate chondrules. In most cases the minerals match the products of silicate sulfidation reactions such as $(Fe_xMg_{2-x})Si_2O_6 + S_2 = 2\text{-x}\ MgS + xFeS + 2SiO_2 + O_2$, although the proportions of the products are variable probably due to mechanical processing.

Sulfide chemistry: The minor element compositions of troilite, oldhamite, djerfisherite, sphalerite, and niningerite in the silica-sulfide-rich chondrules [11, 12] and sulfides in MSN are the same. A few niningerite grains in the MSN are more Fe-rich and several troilite grains in the silica-sulfide-rich chondrules are more Mg-rich (Fig. 6), but these outliers could result from inadvertent analyses of mixtures of phases.

Conclusion: The occurrence of a continuous series of spheroidal objects linking MSN with silicate chondrules, including the spheroidal aggregates of silicate and opaque minerals in equal proportions, suggests co-evolution of these objects. The matching porous silica and composition of sulfides in chondrules and MSN suggests that all these objects experienced similar physicochemical conditions consistent with the hypothesis that fS_2 in equilibrium with metal-sulfide assemblage is sufficient to drive sulfidation of silicates in chondrules [13, 14].

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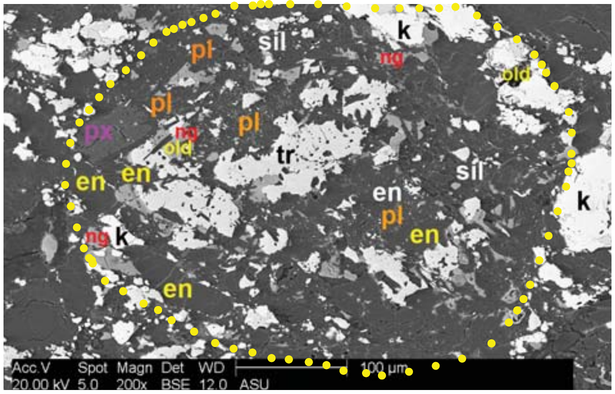

Fig. 1. BSE image of spheroidal aggregate (dotted line) of unequilibrated mixtures of silicates and opaque minerals in approximately equal amounts. en = enstatite, k = kamacite, ng = niningerite, pl = plagioclase, px = pyroxene, old = oldhamite, sil = silica, tr = troilite.

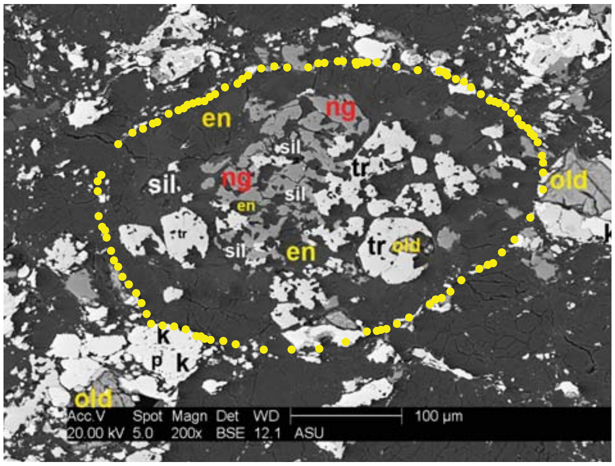

Fig. 2. BSE image of spheroidal aggregate with more pronounced silicate mantle than that in Fig 1. p = perryite; other abbreviations as in Fig. 1.

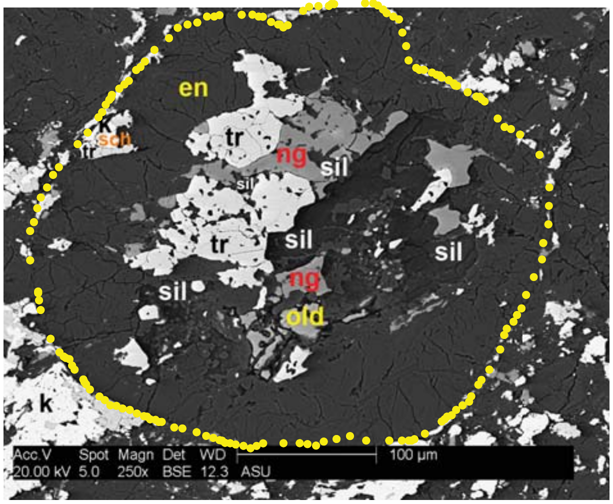

Fig. 3. BSE of spheroidal aggregate resembling one of the silica-sulfide-rich chondrules containing abundant porous silica. (dark areas marked 'sil'), sch = schreibersite; other abbreviations as in Fig. 1.

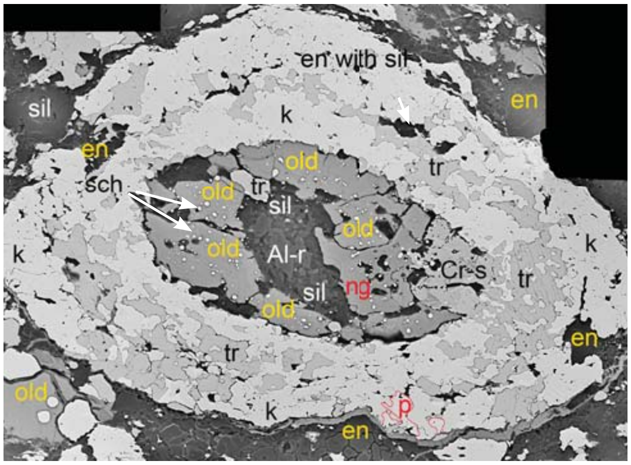

Fig. 4. Fig. 4. BSE of MSN with concentric layers. Porous silica is adjacent to oldhamite and niningerite in the core. Arrows point to schreibersite spherules and to Si-bearing inclusion. Al-r = Al-rich; other abbrev. as in Fig 1.

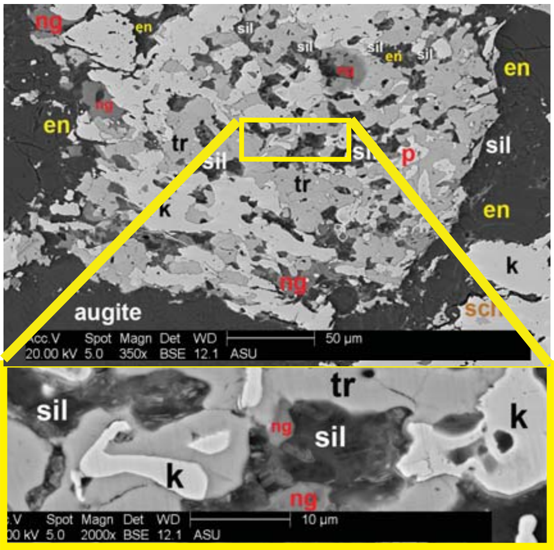

Fig. 5. BSE image of MSN with abundant silica inclusions bearing minor niningerite. Abbreviations as in Fig. 1.

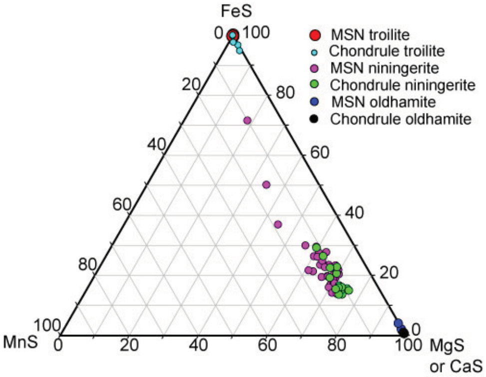

Fig. 6. Composition of sulfides from MSN and silica-sulfide-rich chondrules. Bottom right corner is CaS for oldhamite and MgS for niningerite and troilite compositions. FeS-rich niningerite and MgS-rich troilite could result from inadvertent analyses of mixtures of fine-grained phases.