VOLATILE-POOR CHONDRULES IN CH CARBONACEOUS CHONDRITES: FORMATION AT HIGH AMBIENT NEBULAR TEMPERATURE.

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Abstract. CH carbonaceous chondrites contain chondrules of several populations [1-5]. A population of small (~20 µm) magnesian chondrules (<2-4 wt% FeO) with cryptocrystalline and microporphyritic textures shows a continuous range in refractory lithophile elements (Ca, Al, Ti) from 2-4xCI to ~0.01xCI, contains no metallic Fe,Ni, and is highly depleted in moderately volatile elements (Mn, K, Na, S). These chemical and mineralogical signatures are similar to those of chondrules from the Bencubbin/CH-like chondrites QUE94411 and Hammadah al Hamra 237 [6]. We suggest that this population of CH chondrules formed at high ambient nebular temperatures prior to condensation of Fe,Ni-metal following a large scale thermal event that resulted in complete vaporization of a solar nebula region [6,7]. These chondrules were subsequently removed from the hot nebular region prior to condensation of moderately volatile elements and may represent chondrules of the very first generation, which escaped remelting at low ambient nebular temperatures. In contrast, magnesian chondrules of porphyritic textures have ~CI level of refractory lithophile elements and contain abundant Fe,Ni-metal nodules and detectable concentrations of Na in mesostases. We infer that these chondrules resulted from melting of metal+silicate precursors or chondrules of an earlier generation at lower ambient nebular temperatures.

Introduction: CH chondrites (Acfer 182, ALH85085, EET96238, PAT91546, PCA91467, RKP92435) are characterized by (a) small sizes of chondrules and CAIs (~20 µm in average; ~90 µm in Acfer 182), (b) absence of fine-grained matrix attached to these components, (c) presence of completely hydrated matrix lumps, (d) bulk enrichment in siderophile elements, depletion in moderately and highly volatile elements, and (e) absence in enrichment in refractory lithophile elements [1-5]. Two populations of chondrules were reported in CHs: a population of small (~20 µm) cryptocrystalline (CC) to microporphyritic (MP) chondrules and a population of "normal" (>50 µm) chondrules (largely present as chondrule fragments) with porphyritic olivine (PO), porphyritic olivine-pyroxene (POP) and radial pyroxene (RP) textures. The CC- and MP-chondrules are free of metallic Fe,Ni and have Cr, Mn, K, and Na abundances decreasing smoothly with increasing elemental volatility. Wasson and Kallemeyn [5] hypothesized that large impacts on the CH parent asteroid resulted in devolatilization, reduction, and formation of small chondrules and metal by gas-liquid condensation in the impact vapor cloud. Other researchers concluded that CH chondrules formed by nebular processes and suggested that low concentrations of moderately volatile elements are due to their loss from chondrule melts which experienced prolonged heating above the liquidus. Based on the observed negative correlation between refractory Be and volatile B, Brearley [8] argued that low abundance of moderately volatile elements in CC-chondrules from CHs is a condensation signature of chondrule precursors. Here we present our observations on volatile-poor magnesian chondrules from CH chondrites.

Results: Meibom et al. [7] recently showed that some Fe,Ni-metal grains in CHs formed by gas-solid condensation from a gas of solar composition and subsequently escaped melting and thermal metamorphism above 300°C. Later, Meibom et al. [9] suggested that condensation of the metal grains took place in the solar nebula region which experienced complete vaporization following a large scale thermal event. In our companion abstracts [6,10-12], we show that most Fe,Ni-metal grains from the Bencubbin/CH-like meteorites QUE94411 (QUE) and Hammadah al Hamra 237 (HH 237) formed in a similar setting and escaped subsequent melting. In spite of the very high metal abundances similar to those of Bencubbin, QUE and HH 237 appear to have more mineralogical similarities to CHs than to Bencubbin. These include: (a) presence of CAIs which are mineralogically most similar to those in CHs, (b) high abundance of chemically-zoned Fe,Ni-metal grains, (c) smaller sizes of chondrules and metal grains, and (d) presence of heavily hydrated matrix lumps composed of phyllosilicates, framboidal magnetite, Fe,Ni-sulfides and Ca-carbonates. Chondrules in QUE and HH 237 have only CC- and MP-textures, show a continuous range in abundances of refractory lithophile elements from 2-4xCI in MP- to <0.01xCI in CC-chondrules, are free of metallic Fe,Ni and are highly depleted in moderately volatile elements (Mn, K, Na, S). Some of the CC-chondrules in QUE and HH 237 are observed as inclusions inside chemically-zoned Fe,Ni-metal grains. Based on these observations, we concluded that chondrules in QUE and HH 237 formed at high ambient nebular temperatures prior to condensation of Fe,Ni-metal (probably in the same nebular region) and were not subsequently remelted, and, hence, may represent chondrules of the very first generation [6].

Our and previously published mineralogical observations [1-5] indicate that the dominant population of magnesian (<2-4 wt% FeO) CC- and MP- chondrules in CHs are texturally, mineralogically and chemically very similar to those in QUE and HH 237 (Fig. 1; see Fig. 2 in [6]). We infer that this population of CH chondrules is also formed at high ambient nebular temperatures prior to condensation of Fe,Ni-metal grains, escaped subsequent remelting, and may belong to the very first generation of chondrules. This implies that the observed depletion in moderately volatile elements in CH chondrules is a condensation signature, not a result of volatilization during chondrule formation. Although the absence of Fe,Ni-metal inside magnesian CC- and MP-chondrules from CHs could be interpreted as a result of spinning out metal nodules from small chondrule melts [Brearley, pers. comm.], this appears unlikely for two reasons. (1) SiO_2-rich compositions of CC-chondrules from CHs suggest high viscosity of chondrule melts which would make loss of metal nodules difficult. The latter is supported by the presence of rounded-to-euhedral Fe,Ni-metal grains in ferrous CC-chondrules [13]. (2) In spite of large variations in sizes of magnesian CC- and MP-chondrules from QUE, HH 237, Acfer 182 (the most coarse-grained CH) and other CHs, they are all highly-depleted in Fe,Ni-metal.

The CC- and MP-textures of CH chondrules indicate that crystallization of chondrule melts occurred in a dust-free environment (no crystalline nuclei were present inside or outside these melts). This is consistent with the absence of fine-grained matrix material attached to chondrules. Following the formation, the chondrules and most Fe,Ni-metal grains must have been isolated or removed from the hot nebular region to prevent condensation of volatile elements (Mn, K, Na, S). Because chemically-zoned, metastable Fe,Ni-metal grains would not survive even mild thermal metamorphism, isolation by hot accretion seems unlikely [14]. At the same time, the presence of heavily hydrated and volatile-rich matrix lumps in CHs could be interpreted as a result of mixing of volatile-poor (chondrules and metal) and volatile-rich (matrix lumps) materials in the cold nebular regions. If this is the case, matrix lumps must have been altered close in time to chondrule formation in CHs. Alternatively, the matrix lumps were added to the CH parent body during regolith gardening. Dating of aqueous alteration of CH matrix lumps (e.g., Mn-Cr-isotope study of carbonates) may help to resolve this issue.

In contrast to CC- and MP-chondrules, those of porphyritic textures have ~CI level of refractory lithophile elements (Fig. 1), contain abundant Fe,Ni-metal nodules and detectable concentrations of Na_2O (~1 wt%) in the mesostases. We infer that these chondrules formed as a result of melting of metal+silicate precursors or by remelting of chondrules of an earlier generation at lower ambient temperatures. Compositions of Fe,Ni-metal grains in these chondrules are correlated with their locations: metal grains in chondrule cores have higher Ni and Co contents than those in chondrule peripheries (Fig. 2). A similar correlation is observed for metal grains from porphyritic chondrules from CRs [15, 16]; this suggests a genetic relationship between porphyritic chondrules from CHs and CRs. Because CH chondrites appear to have experienced no thermal metamorphism above 300°C and show no layered textures, we infer that the observed correlation (Fig. 2) is most likely due to reduction during chondrule formation, rather than incomplete homogenization of metal compositions formed by condensation.

CRs, CHs, QUE and HH 237 share many chemical and mineralogical signatures and belong to the CR-clan of meteorites [17]. There is a general trend in increase of abundances of porphyritic chondrules from the QUE and HH 237 (~0%) to CHs (~20%) and to CRs (~100%), which correlates with decrease of abundances of chemically-zoned metal grains and increase of metal and volatile abundances (Na, K, Mn) in chondrules. We interpret these features as an indicator of chondrule formation at decreasing ambient nebular temperatures in the order of QUE/HH 237 - CHs - CRs. However, even magnesian chondrules from CRs formed at high ambient nebular temperatures, above condensation temperature of S [18].

References: [1] Scott (1988) *EPSL*, **91**, 1-18; [2] Grossman et al. (1988) *EPSL*, **91**, 33-54; [3] Weisberg et al. (1988) *EPSL*, **91**, 19-32; [4] Bischoff et al. (1991) *GCA*, **57**, 2631-2648; [5] Wasson J. T. and Kallemeyn G. W. (1990) *EPSL*, **101**, 148-161; [6] Krot et al. (2000) *LPSC*, **31**; [7] Meibom et al. (1999); [8] Brearley A. J. and Jones R. H. (1995) *LPSC*, **26**, 167-168; [9] Meibom et a. (2000) *Science* (in press); [10] Campbell et al. (2000) *LPSC*, **31**; [11] Meibom et al. (2000) *LPSC*, **31**; [12] Petaev et al. (2000) *LPSC*, **31**; [13] Krot et al. (2000) *LPSC*, **31**; [14] Meibom et al. (2000) *LPSC*, **31**; [15] Lee et al. (1992) *GCA*, **56**, 2521-2533; [16] Weisberg et al. (1993) *GCA*, **57**, 1567-1586; [17] Weisberg et al. (1995) *Proc. NIPR*, **8**, 11-32; [18] Krot et al. (2000), *LPSC*, **31**.

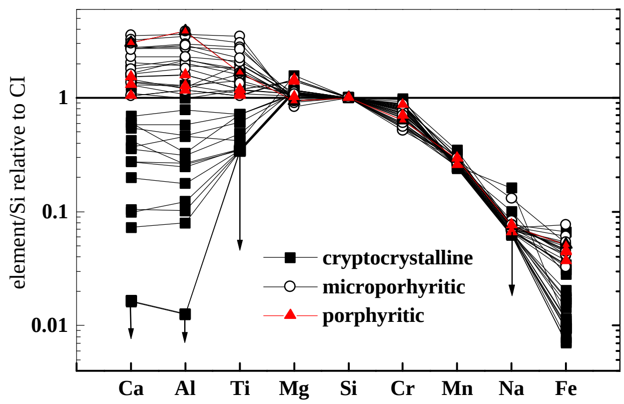

Fig. 1. Bulk compositions of magnesian chondrules from CH carbonaceous chondrites PAT91546 and PCA91328. Arrows indicate element concentrations below detection limits of electron microprobe analysis.

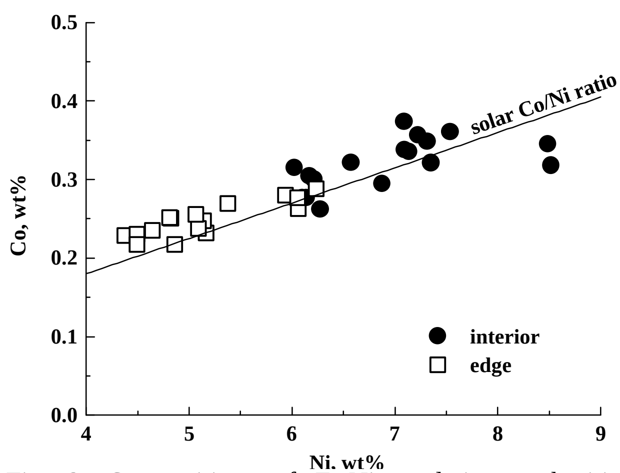

Fig. 2. Compositions of Fe,Ni-metal in porphyritic chondrules from PCA91328. The observed depletion in Ni and Co in metal grains in chondrule peripheries could be due to reduction of Fe during chondrule formation.