EVIDENCE FOR FRACTIONAL CONDENSATION AND FLASH REHEATING FROM VOLATILE RICH OBJECTS IN CH-CHONDRITES.

D. C. Hezel, F. E. Brenker and H. Palme, Institut für Mineralogie und Geochemie, Universität zu Köln, Zülpicherstraße 49b, 50674 Köln, Germany d.hezel@uni-koeln.de.

Introduction: CH-carbonaceous chondrites have excess FeNi-metal and are strongly depleted in moderately volatile and volatile elements (Mn, Na, Zn, Se), but have CI refractory element/Mg ratios [1]. In contrast to other carbonaceous chondrites, CHs have high modal abundances of chondrules (~70 vol.%) with a mean diameter of 70-90 µm, FeNi-metals (~20 vol.%) and very low fractions of matrix (~5 vol.%), heavily altered by terrestrial weathering. Chondrules, however, show no signs of weathering [1]. The low FeO-content in silicates and the high Cr-concentrations in metal reflect reducing conditions during formation. Rare SiO_2-rich components contain abundant free silica [2, 3]. Some zoned metal grains have preserved the signatures of nebular condensation [4, 5].

Despite the low volatile element contents of CH-chondrites, two chondrules with very high concentrations of Mn, Na and K were discovered in Acfer 182. These unusual objects provide insight into the conditions of formation of these unusual meteorites.
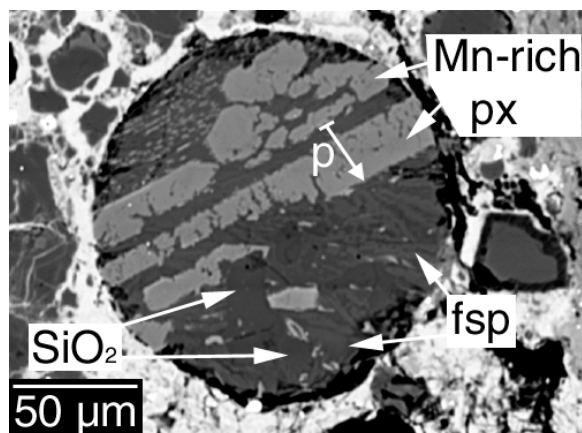

Figure 1: BSE-image of a Mn-rich chondrule in Acfer 182. The mesostasis is a mixture of SiO_2 and fsp.

Results: The compositions of the two chondrules with high enrichments in Mn, Na , K and also Cr are given in Table 1. Both chondrules are rich in Si with CI-normalized atomic Mg/Si-ratios of 0.15 and 0.25, respectively. Both chondrules are about 200 µm in diameter, but differ in appearance:

The first chondrule (Fig. 1) contains large pyroxene crystals and a mesostasis with intergrown silica and feldspar with An_{32}. The pyroxenes contain up to 6.68 wt.% MnO. Pyroxenes with such high MnO-

concentrations have never been encountered in meteorites. Rubin et al. [6] reported MnO-rich orthopyroxenes in a rim around an Allende chondrule with MnO-concentrations of about 4.5 wt.% and [7] found a Mn-rich augite (MnO = 2.6 wt.%) in the matrix of the Tieschitz chondrite. In addition, [8] reported MnO-rich olivines and pyroxenes with up to 5 wt.% MnO in interplanetary dust particles.

A compositional profile (marked p in Fig. 1) over one pyroxene lath and adjacent mesostasis is shown in Fig. 2. The mesostasis between the two pyroxene crystals has high concentrations of SiO_2, Al_2O_3, Na_2O and K_2O, which are decreasing towards the pyroxene. In contrast, the concentrations of FeO, MnO, MgO, Cr_2O_3 and CaO are low in the mesostasis and increase towards the pyroxene. The pyroxene has a complex zoning pattern: Some elements such as Mg and Ca show strong zoning within the pyroxene crystal, whereas other elements have uniform distribution (e.g. Si, Ti).

The second Mn-rich chondrule consists of a fine grained intergrowth of pyroxene and feldspar and comparatively large cristobalite crystals of up to 50µm in length [2].

	chd 1			chd 2			A182
	px	fsp	bulk	px	fsp	bulk	bulk
SiO_2	51.87	69.04	72.34	56.54	62.11	65.48	
TiO_2	0.41	0.32	0.26	0.34	0.29	0.28	
Al_2O_3	2.77	18.13	6.05	5.70	17.47	7.79	1.91
Cr_2O_3	1.46	0.03	0.59	2.27	0.66	1.46	0.43
FeO	8.38	1.16	3.74	2.56	0.88	1.82	44.46
MnO	6.27	0.35	2.59	3.09	0.93	1.99	0.12
MgO	16.09	0.47	6.51	22.34	6.50	14.27	
CaO	13.07	4.63	6.43	7.47	9.21	6.61	17.81
Na_2O	0.16	5.42	1.55	0.67	2.63	1.08	2.29
K_2O	0.03	0.47	0.14	0.03	0.10	0.04	0.08
total	100.52	100.01	100.21	101.01	100.79	100.82	

Table 1: Chemical composition of the two Mn-rich chondrules and bulk composition of the CH-chondrite Acfer 182 (A182). "chd 1" is shown in Fig. 1.

Discussion: The occurrence of volatile rich chondrules in a CH-chondrite is unexpected. For example, bulk Acfer 182 has only 0.13 wt.% MnO and the bulk MnO-concentration of chondrules of CHs as well as of all other types of chondrites is generally below 0.5 wt.% [6], whereas the bulk chondrules described here have 2.59 and 1.99 wt.% MnO, respectively. Such high contents of the compatible element Mn cannot be produced by igneous processes.

High Mn in the nebular gas from which these chondrules or their precursors formed is required. This may be achieved in the late stage of fractional condensation from an evaporated nebular compartment [9].
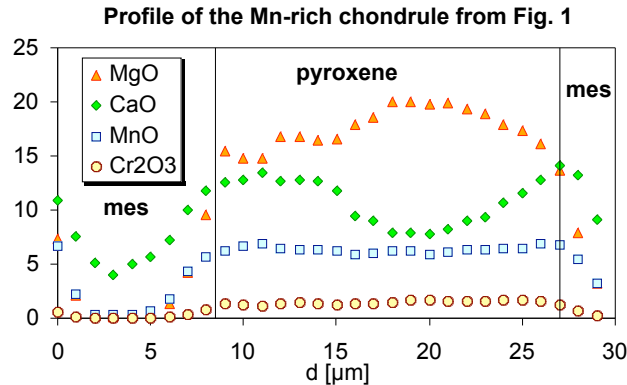
Profile of the Mn-rich chondrule from Fig. 1

Figure 2: Chemical profile over a Mn-rich pyroxene and adjacent mesostasis (mes). The profile is indicated in Fig. 1.

Forsterite is the first major phases to condense in a cooling gas of solar composition. Fast nebular cooling leads to fractional condensation where condensed minerals remain chemically inert against the gas. Forsterite condensation leaves a SiO-rich gas phase, which will be reacting with condensed forsterite to produce enstatite. Incomplete conversion of forsterite to enstatite leads to a SiO-rich gas, which will also contain high concentrations of moderately volatile elements such as Mn at sufficiently low temperatures. Fast cooling will also delay Mn condensation, as Mn is expected to condense in solid solution with olivine and pyroxene. On further nebular cooling, Si and Mn will both condense together leading to Si- and volatile-rich mineral aggregates.

The two Mn-rich objects are chondrules and therefore were once molten. The Mn-rich pyroxenes in the chondrule from Fig. 1 show typical crystallization profiles with high MgO and low CaO in the center and low MgO and high CaO at the rim (Fig. 2). At a nebular pressure of 10^{-4} bar the condensation temperature of Mn is 1190 K and that of Na 970 K compared to the forsterite condensation temperature of 1340 K [10]. The calculated MELTS liquidus temperatures [11] give, however, 1674 K for the first chondrule (Fig.1) and 1900 K for the second. As Mn is concentrated in the pyroxene, it must have been present during pyroxene crystallization and cannot have condensed onto the chondrule at low temperatures after solidification of the chondrule.

The pyroxenes in the Mn-rich chondrule of Fig. 1 are extremely enriched in MnO (up to 6.86 wt.%;

Table 1). The coexisting mesostasis has, however, much lower MnO concentrations (0.18 wt.%) apparently contradicting the partitioning of Mn between melt and pyroxene in most igneous systems, where the pyroxene/melt partition coefficients are ~1. However, pyroxene crystallizing from rhyolithic melts – compositionally similar to these chondrules – have much higher pyroxene/melt partition coefficients, between 25.4 and 57, depending on the CaO-concentration [12]. The pyroxene/ mesostasis ratios of Mn are 34.7 for the chondrule in Fig. 1, in agreement with the high partition coefficients obtained in experiments. There is, therefore, no doubt that chondrules were rich in Mn (and presumably also in Na and K) before pyroxene crystallization at high temperatures. Since Mn enrichment must have occurred at lower temperatures, as mentioned above, reheating of the Si- and Mn rich assemblages formed at low temperatures is required. The reheating process must have been fast, because Na and K did not evaporate during the reheating event.

Conclusion: In summary, the two Mn-rich chondrules provide clear evidence for fractional condensation and subsequent fast reheating to high temperatures of up to 1900 K. Similar conclusions were obtained in previous studies: Silica rich chondrules of CH-chondrites experienced minimum temperatures of 1968 K, whereas their precursors must have formed by fractional condensation at much lower temperatures [2]. Zoned FeNi-grains in CH-chondrites indicative of fast cooling also reflect fractional condensation of various metals in FeNi [4, 5]. Thus there is abundant evidence that components of CH-chondrites initially condensed from a rapidly cooling nebular compartment with subsequent chondrule forming events leading in some cases to temperatures >1968 K. The reheating- or chondrule forming process did not affect the zoned metal grains which have retained their record of fast nebular cooling.

References: [1] Bischoff A. et al. (1993) *GCA, 57,* 2631-2648. [2] Hezel D. C. et al. (2003) *MAPS,* submitted. [3] Krot A. N. et al. (2000) *MAPS, 35,* 1249-1258. [4] Meibom A. et al. (1999) *J. Geophys. Res., 104,* 22053-22059. [5] Meibom A. et al. (2000) *Science, 288,* 839-841. [6] Rubin A. E. (1986) *Am. Min., 69,* 880-888. [7] Hutchinson R. (1987) *Min. Mag., 51,* 311-316. [8] Klöck W. et al. (1989) *Nature, 339,* 126-128. [9] Petaev M. I. and Wood J. A. (1998) *MAPS, 33,* 1123-1137. [10] Lodders K. and Fegley B. Jr. (1998) The Planetary Scientist's Companion, *Oxford University Press*, 371p. [11] Ghiorso, Mark S. and Sack, Richard O. (1995) *Contrib. Mineral. Petrol., 119,* 197-212. [12] Mahood G. and Hildreth W. (1983) *GCA, 47,* 11-30.