RELICT FORSTERITE IN CHONDRULES: IMPLICATIONS FOR COOLING RATES.
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Introduction: Forsterite (Fo_{99-100}) is often present in chondrules as relict grains that did not crystallize *in situ* and as "isolated grains" outside of chondrules [1,2]; both are surrounded by ferrous overgrowths which clearly formed at a later time [3], probably during chondrule formation [4; Ruzicka & Floss, this vol.]. We performed microprobe analyses across forsterite-overgrowth interfaces in 12 chondrules and 4 isolated grains in the Sahara-97210 LL3.2 ("Sahara"), Wells LL3.3, and Chainpur LL3.4 chondrites and modelled diffusional exchange between forsterite and overgrowths, with the goal of constraining the thermal histories during chondrule formation. The cooling rates experienced by chondrules provide an important constraint on the origin and setting of these objects.

Methods: Interfaces between forsterite and overgrowths are locally straight, and we obtained traverses perpendicular to interfaces and sought instances amenable to a simple diffusion model involving exchange between two infinite halfspaces. As chemical discontinuities are typically sharp, measured concentration profiles were deconvolved to take into account the spatial averaging effect of electron microprobe analyses [5]. We assumed that cooling occurred in an "asymptotic" fashion [6], with cooling rates starting high and slowing to progressively lower values. Diffusion coefficients were assumed to be independent of concentration. It is well established that cation diffusion in olivine depends on fO_2 [7,8,9], so experimentally determined diffusion coefficients were corrected to consistent fO_2 values using a procedure similar to that of Nakamura & Schmalzried [9] but assuming a $D \propto fO_2^{1/6}$ dependence [7]. We considered plausible fO_2 values ranging from solar to the IW buffer. We found the diffusion coefficients of Chakraborty [7] and Jurewicz and Watson [8] for relatively forsteritic olivine ($\sim Fo_{90}$) to give the most self-consistent results between different cations and used these in our models.

Results: Chemical profiles between forsterite and overgrowths in both chondrules and isolated objects of all three meteorites are qualitatively similar. Of the elements analyzed, Ca, Mn, and Fe-Mg best show profiles consistent with diffusion (Fig. 1, 2). Cr and Al often show spikes near the original interfaces [3] that we interpret as reflecting submicroscopic spinel inclusions; similar zones are found in normal chondrule olivines and these too may reflect growth boundaries.

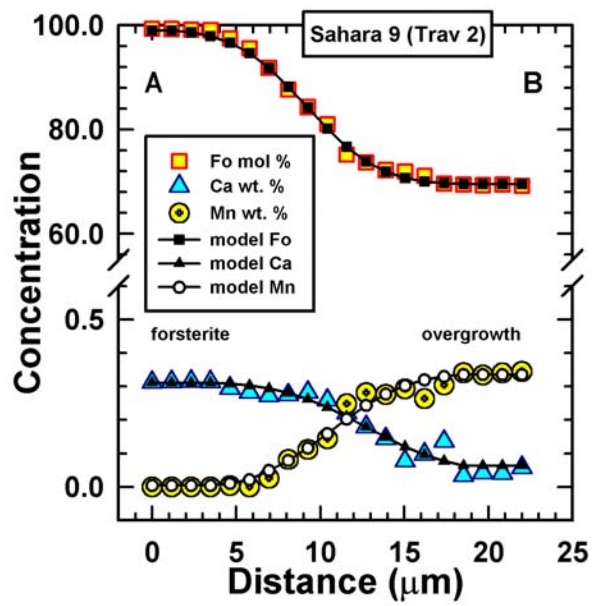
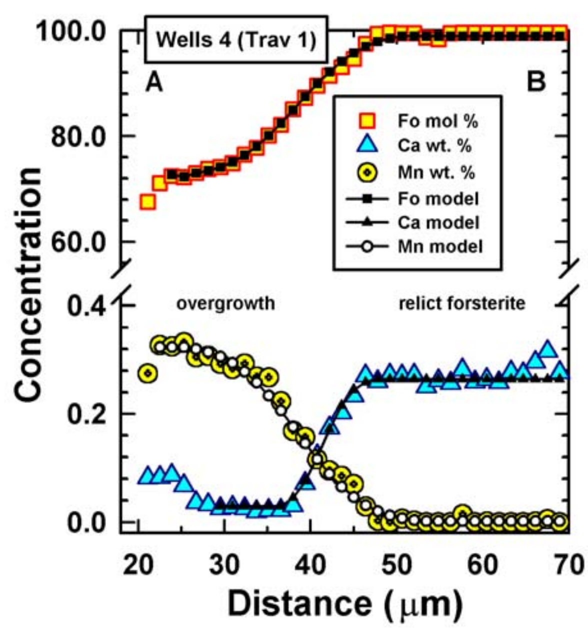


Figure 1 (above) and Figure 2 (below).



Examples: Four traverses in three chondrules (Sahara-9, Wells-4, Chainpur-3) illustrate representative results. Each chondrule has a porphyritic olivine texture and contains one unusually forsteritic olivine grain with an overgrowth. Fig. 1 and 2 show the observed and modelled variations in Sahara-9 and Wells-4; Chainpur 3 is analogous. In Fig. 1 and 2, good fits between observed and modelled points are apparent, which imply that the observed variations were indeed formed by diffusion. In Wells-4 (Fig. 2) and Chainpur-3, inflections occur at the edge of the overgrowth adjacent to the chondrule; these probably reflect igneous fractionation.

Table 1 compares the cooling rates for these objects assuming that cooling occurred at an intermediate log fO_2 value (IW buffer – 2) and began at a representative liquidus temperature of 1950 K [10]. Mn profiles give the fastest cooling rates, whereas Fe-Mg profiles give the slowest rates. Agreement between Ca and Mn is good for Wells-4 (~950-1650 K/hr), and between Ca and Fe-Mg for Chainpur-3 trav4 (~210-410 K/hr). It is noteworthy that the cooling rates obtained by modelling Fe and Ca diffusion for the two Chainpur traverses (3-1, 3-4) are relatively consistent within the same traverse, but generally inconsistent between the two traverses. These two traverses were obtained parallel to one another across the same forsterite-overgrowth contact. As is apparent in BSE images, this contact is compositionally sharper in some areas than others. Together with the results shown in Table 1, this suggests that local variations in diffusion extent control some of the scatter in the derived cooling rates. Such variations could be caused by differences in defect density allowing more or less diffusion.

Cooling rates: Table 2 summarizes all our cooling rate determinations at 1950 K, a representative liquidus temperature. Results are shown for three fO_2 values. Cooling rates are appreciably faster at higher fO_2 because of the more rapid diffusion rates, showing the importance of fO_2. Cooling rates based on Fe-Mg interdiffusion generally agree using the data either of Chakraborty [7] or Jurewicz and Watson [8]. Cooling rates based on Mn diffusion are generally higher than those based on Ca or Fe diffusion, with the discrepancy being higher at higher fO_2. At lower fO_2, the ranges in cooling rates based on different diffusing systems overlap substantially: ~130-3200 K/hr at ~solar fO_2, and ~340-8400 K/hr at 2 log units below IW (Table 2). The improving agreement at lower fO_2 suggests that diffusion may have occurred predominantly under relatively reducing conditions, substantially below the IW buffer. These lower fO_2 values are in agreement with what would be expected for olivine-metal-gas equilibrium [11] and the composition of olivine analyzed.

Summary: Altogether, the data suggest typical cooling rates of ~200-6000 K/hr under reducing conditions (Table 1, 2). These values are similar to those that have been inferred for chondrules based on textures and zoning within normal olivine grains [10]. They are distinctly lower than recently inferred for an olivine-rich inclusion based on O-isotopic and Fe-Mg data [12] and higher than recently inferred using subsolidus indicators such as pyroxene microstructures [13]. The results support the idea that diffusional exchange occurred between forsterite and overgrowths during chondrule formation, and that this can be used to constrain chondrule cooling rates and perhaps redox conditions.

References: [1] Jones R.H. (1996) In *Chondrules & the Protoplanetary Disk*, 163-172. [2] Steele I.M. (1986), *GCA 50,* 1379-1395. [3] Hua X. et al. (1988) *GCA, 52,* 1389-1408. [4] Ruzicka A. and Floss C. (2003), *LPS XXXIV,* Abstract #1243. [5] Ganguly J. et al. (1988) *Am. Min. 73*, 901-909. [6] Ganguly J. (2002) *EMU Notes in Mineralogy, 4*, 271-309. [7] Chakraborty S. (1997), *JGR, 102*, 12317-12331. [8] Jurewicz A.J.G. and Watson E.B. (1988) *CMP, 99*, 186-201. [9] Nakamura A. and Schmalzried H. (1984*) B.B. Phys. Chem. 88,* 140-145. [10] Hewins R.H. (1997) *Annu. Rev. Earth Planet. Sci., 25,* 61-83. [11] Rubin A.E. et al. (1988) In *Meteorites in the Early Solar System*, 488-511. [12] Yurimoto H. and Wasson J.T. (2002) *GCA, 66,* 4355-4365. [13] Weinbruch S. et al. (1998) *MAPS, 33,* 65-74.

Acknowledgment: This work was supported by NASA grant NAG5-13044 (A. Ruzicka).

Table 1. Cooling rates (K/hr) at log fO_2 = IW-2

Assuming c-axis diffusion coefficients [8]			
Object – Traverse	*Ch 3 – 1*		
	Fe-Mg	**Ca-Mg**	**Mn-Mg**
Solidus (1500 K)	1100	2130	4960
Liquidus (1950 K)	1870	3600	8380
Object – Traverse	*Ch 3 – 4*		
	Fe-Mg	**Ca-Mg**	**Mn-Mg**
Solidus (1500 K)	240	210	3480
Liquidus (1950 K)	410	360	5890
Object – Traverse	*Sah 9 – 2*		
	Fe-Mg	**Ca-Mg**	**Mn-Mg**
Solidus (1500 K)	850	400	3520
Liquidus (1950 K)	1430	690	5940
Object – Traverse	*Wells 4 – 1*		
	Fe-Mg	**Ca-Mg**	**Mn-Mg**
Solidus (1500 K)	270	950	980
Liquidus (1950 K)	460	1600	1650

Table 2. Cooling rates (K/hr) at 1950 K

Log fO_2	*IW*	*IW – 2*	*IW - 4.5*
Fe-Mg [7]	730 – 3310	340 – 1530	130 – 590
Fe-Mg [8]	890 – 4020	410 – 1870	160 – 720
Ca-Mg [8]	780 – 7750	360 – 3600	140 – 1380
Mn-Mg [8]	3550 –18500	1650 – 8380	630 - 3210