

FORSTERITE AND OLIVINE IN SAHARA-97210 (LL3.2) AND CHAINPUR (LL3.4) CHONDRULES: COMPOSITIONAL EVOLUTION AND THE INFLUENCE OF MELTING. A. Ruzicka¹ and C. Floss²,
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Introduction: It is generally accepted that chondrules contain relict grains that did not crystallize *in situ* [1], and that forsterite is one type of relict grain which is a likely precursor for chondrules [1,2,3]. Chemically and morphologically similar forsterite is also found as “isolated grains”, especially in carbonaceous chondrites [2,3]. Using SIMS, we analyzed forsterite, ferrous overgrowths around forsterite, and co-existing normal olivine in 5 chondrules and 2 isolated grains in the Sahara-97210 (“Sahara”) LL3.2 chondrite. We earlier used the same methods to study olivine in 3 Chainpur chondrules that contain relict forsterite [4]. Our new data for Sahara provide additional insight into the processes affecting chondrules and their precursors.

Evidence for melting & elevated cooling rates: Both Alexander [5] and Ruzicka and Floss [4] concluded that olivine and forsterite in chondrules could have crystallized from rapidly-cooling melts. Fig. 1 shows calculated CI-normalized abundances for refractory elements in melts co-existing with forsterite and normal olivine from Sahara, using (a) best estimates of literature equilibrium mineral/melt D-values, and (b) apparent D-values obtained in a dynamic cooling experiment. Elements are arranged in order of increasing cooling-rate sensitivity, defined here as the difference between the apparent D for the same composition melt at 2191 °C/hr and at 100 °C/hr [6]. Fig. 1 shows that for relatively slow cooling rates (≤ 100 °C/hr) allowing a close approach to equilibrium [6], both forsterite and normal olivine would have had to crystallize from melts that were enriched in cooling-sensitive elements to levels of $\sim 10^2$ - 10^5 x CI-chondrites, which is highly unlikely. In contrast, if cooling rates were ~ 2000 °C/hr, both forsterite and normal olivine could have crystallized from melts with relatively moderate and uniform abundances of refractory elements (Fig. 1), which is more likely. Thus, cooling rates were probably closer to ~ 2000 °C/hr, which is consistent with the conclusions of Greeney and Ruzicka [this vol.]. Moreover, the similar pattern shown by forsterite and normal olivine (Fig. 1), which is clearly igneous, argues that igneous processes were important in the formation of forsterite [4,5], as does the presence of melt inclusions associated with forsterite [2].

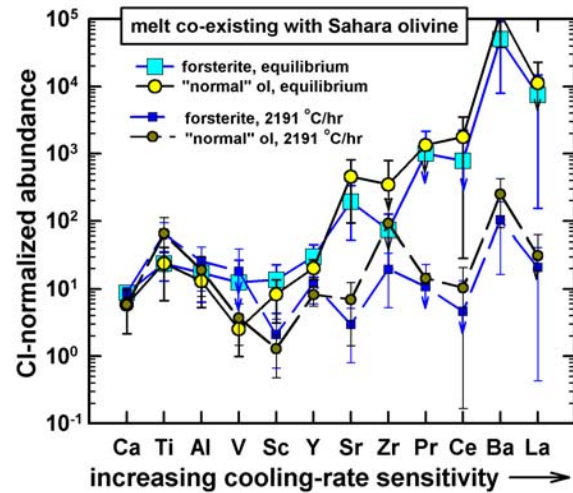
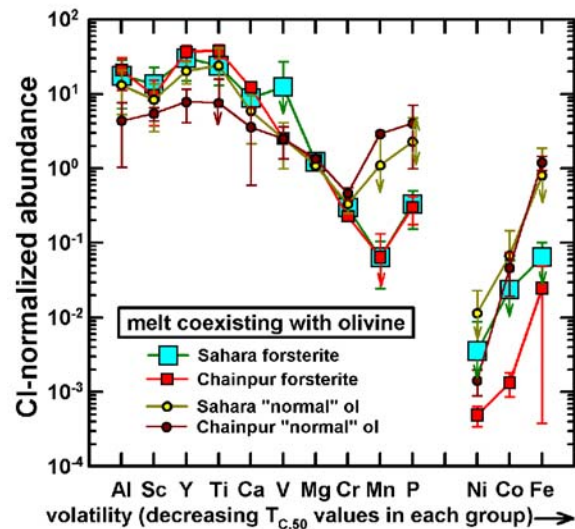
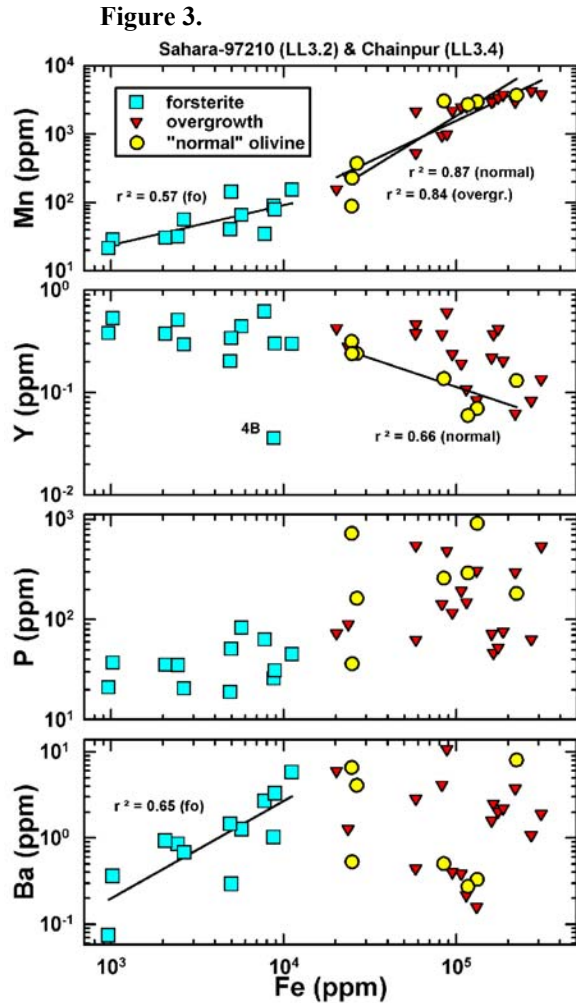


Figure 1 (above) and Figure 2 (below).



Compositional evolution: For cooling-rate-insensitive elements, Fig. 2 shows calculated melt abundances for forsterite and normal olivine, using best estimates of equilibrium D-values. In both Sahara and Chainpur, forsterites tend to be enriched in refractory lithophile elements and depleted in siderophiles and in volatile lithophile elements compared to normal olivine grains, with the difference between forsterite and normal being more pronounced in Chainpur (Fig. 2). If forsterites represent precursor grains, and if both forsterites and normal grains crys-

tallized from melts, Fig. 2 implies that later generations of melts became more volatile-rich, and probably more oxidizing (resulting in higher NiO and CoO), with time. Volatile-enrichment of secondary melts may have occurred to a greater extent in Chainpur chondrules.



Variation diagrams: Although the compositions of forsterite, overgrowths, and normal olivines overlap to some extent, element correlations are sometimes found that provide additional clues about the processes involved during chondrule formation. Elements define at least 4 groups indicative of different processes.

Forsterite-melt diffusional exchange. Mn and Cr show positive correlations, and Ca negative correlations, with Fe in forsterite. These are probably produced by diffusion in forsterite exchanging with a surrounding melt depleted in Ca and enriched in Mn, Fe, and Cr. Apparent diffusion profiles for Mn, Ca, and Fe occur between forsterite and overgrowths [Greeney & Ruzicka, this vol.], and some diffusion of these ele-

ments within forsterite is expected. Fig. 3 shows a positive correlation between Mn and Fe in forsterite, and (with different slope) positive correlations in overgrowth and normal olivine. The correlations in normal and overgrowth olivine are probably controlled by igneous fractionation, and their similarity (Fig. 3) reinforces the conclusion that overgrowth olivine formed in part by igneous crystallization [4].

Formation of secondary volatile-rich melts. Other elements (e.g., Y, P, Al, V) (1) lack correlations with Fe in forsterite and (2) have different abundances between forsterite and other olivine. The former can be explained if diffusion of these elements in forsterite was sluggish compared to that of Fe; the latter can be explained by crystallization of forsterite and other olivine from melts of different compositions, with secondary melts being richer in volatile P and poorer in refractory Y, Al, and V compared to the melts that crystallized forsterite. For example, Y is enriched, and P depleted, in forsterite compared to overgrowth and normal olivine, but neither shows much tendency to correlate with Fe in forsterite (Fig. 3). Both Y and V have heterogeneous contents in forsterite, and this is consistent with limited diffusion in forsterite of these elements.

Formation of secondary oxidizing melts. Co and Ni abundances scatter but are weakly correlated with Fe in forsterite, and tend to be lower in forsterite than in other olivine (Fig. 2). The higher Co and Ni abundances likely reflect more oxidizing conditions during the formation of secondary chondrule melts, enabling more Ni and Co to enter olivine and less to be sequestered in metal.

Immersion of forsterite in a melt. The abundances of Ba, Sr, Pr, Ce, and La tend to correlate positively with Fe in forsterite but are not significantly different between forsterite and other olivine (Fig. 3). These elements are all highly incompatible. Correlations with Fe could be caused by the incorporation of submicroscopic melt inclusions in forsterite, perhaps caused by partial melting or by melt injection, or by diffusion in olivine. In any case, the distribution of these elements in forsterite likely reflects the immersion of forsterite in chondrule melts.

References: [1] Jones R.H. (1996) In *Chondrules & the Protoplanetary Disk*, 163-172. [2] Weinbruch S. et al. (2000) *MAPS*, 35, 161-171. [3] Steele I.M. (1986) *GCA*, 50, 1379-1395. [4] Ruzicka A. and Floss C. (2003), *LPS XXXIV*, Abstract #1243. [5] Alexander C.M. O'D. (1994) *GCA*, 58, 3451-3467. [6] Kennedy A.K. et al. (1993) *EPSL*, 115, 177-195.

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