RELICT FORSTERITE AND IGNEOUS OLIVINE GRAINS IN CHAINPUR (LL3.5) CHONDRULES: MAJOR- AND TRACE-ELEMENT EVIDENCE FOR VAPOR-FRACTIONATION AND IGNEOUS PARTITIONING.

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Introduction: It is generally accepted that in addition to igneous olivine grains, chondrules contain relict olivine grains that did not crystallize *in situ* [e.g., 1]. Chondrule melts cooled relatively fast [e.g., 2], which aided in the preservation of relict grains. One type of relict olivine grain, found both inside chondrules and as isolated olivine grains outside chondrules, and found both in ordinary and carbonaceous chondrites, is highly forsteritic (mainly Fo_{98-100}), cathodoluminescing, and is often enriched in Al, Ca, Ti, V, Sc, and in an ^{16}O component [e.g., 3-8]. Jones and coworkers [e.g., 8-9] and Alexander [10] argued for a predominantly igneous origin for such relict forsterite grains, whereas condensation (gas to solid or gas to liquid) was advocated by Steele [e.g., 3-4] and Weinbruch et al. [e.g., 5].

We used SIMS to obtain major- and trace-element abundances for 23 elements in forsteritic and cathodoluminescing (“type R1") relict olivine grains and in normal igneous (“type I”) olivine grains in three chondrules in the Chainpur chondrite. The analyzed elements have widely varying 50% condensation temperatures and olivine/melt partition coefficients. Altogether, we obtained three analyses of type R1 relict grains, three analyses of type I igneous grains, and five analyses of “overgrowths” (less forsteritic rim areas) on the relict grains. These preliminary data can be used to evaluate condensation and igneous models for the relict grains, and to shed light on the nature of chondrule precursors and the chondrule-forming process.

Volatility, igneous partitioning & cooling rate: Elemental abundances in type R1 and type I olivine grains are not simply correlated with either 50% condensation temperatures or with olivine/melt D-values. This implies that neither condensation nor equilibrium igneous crystallization was solely responsible for the formation of either type of grain. However, it appears that both vapor-fractionation and igneous processes were important. Kennedy et al. [11] found that olivine/melt D-values depend in part on cooling rate and whether or not equilibrium was achieved. Apparent D-values for compatible and semi-incompatible elements do not depend much on cooling rate, whereas those for highly incompatible elements are strongly dependent on cooling rate [11]. Fig. 1 and 2 separately show data for these two classes of elements (“cooling rate insensitive” and “cooling rate sensitive”, respectively). In these plots, measured abundances have been normalized to the predicted composition of olivine in equilibrium with a chondritic (CI-chondrite) melt, using the equilibrium D-values of Kennedy et al. [11].

Cooling-rate-insensitive elements: For lithophile elements, type R1 grains are consistently enriched in refractory elements (Al, Sc, Y, Ti, and Ca) and depleted in volatile elements (Cr, Mn, and P) compared to type I grains (Fig. 1). Elements of intermediate volatility, V and Mg, have similar abundances in type R1 and I grains (Fig. 1). This suggests that the two grain types are related by vapor-fractionation. Moreover, the abundances of lithophile elements in type R1 grains tend to decrease as the 50% condensation temperatures decrease, whereas this effect is less pronounced in type I grains (Fig. 1). This suggests that type R1 grains formed at an elevated temperature either as condensates or by crystallization in a melt that was more refractory than that which crystallized type I grains. The overgrowths on the relict grains have compositions either similar to those of type I grains or intermediate to type I and R1 grains (Fig. 1). This can be explained by partial re-melting of the relict grains to form overgrowths.

With regard to siderophile elements, both type R1 and type I grains are strongly depleted in Ni and Co compared to what is expected if the olivine grains crystallized from a chondritic melt, and Fe is also depleted in the relict grains compared to such a melt (Fig. 1). These data can be explained by the sequestering of the siderophile elements in a metallic phase. The lower abundances of siderophile elements in the relict grains compared to igneous grains (Fig. 1) implies more effective removal of the siderophile elements into metal during the formation of the R1 grains, perhaps caused by lower f_{O2} during formation of the latter. An inverse correlation between normalized abundance and condensation temperature (Fig. 1) suggests that the sequestered metal was refractory in composition. Data for siderophile elements in the overgrowths (Fig. 1) are consistent with the idea that these overgrowths formed by partial re-melting of the relict grains.

Cooling-rate-sensitive elements: Fig. 2 shows normalized abundances of cooling-rate-sensitive (highly incompatible) elements. For these elements, there is a rough correlation between abundance and cooling-rate sensitivity (difference between effective D-values for equilibrium and rapid cooling cases) for both type R1 and I grains (Fig. 2). The abundances of both incompatible refractory (Sr, Zr, Ba, Pr, Ce, La) and volatile (Na, K, Rb) elements are higher than one would expect for equilibrium with a chondritic melt (Fig. 2), and they are higher (by a factor of ~10-100) than one would expect based on cooling-rate-insensitive elements of similar volatility (Fig. 1). These data suggest that the abundances of highly incompatible elements in both type I and R1 grains were significantly affected by mineral-melt partitioning during rapid cooling. Vapor-fractionation alone cannot explain the high abundances. The data for type I grains can be explained by igneous crystallization during rapid cooling in the last chondrule-forming episode. If the relict grains were incompletely melted during this last episode, then the unexpectedly high abundances of incompatible elements in them suggests either that these elements (1) partly diffused into the cores of the grains during the last chondrule melting event, or (2) were incorporated into the grains by igneous crystallization during rapid cooling in an earlier chondrule-forming episode. In either case, rapid cooling during chondrule formation is implied.

Conclusion: In summary, SIMS analyses of Chainpur chondrule olivine grains suggest that the compositions of forsteritic (type R1) and normal igneous (type I) grains were established by complex processes. The data are consistent with type I grains having formed mainly by igneous crystallization during rapid cooling, from melts of broadly chondritic composition. Type R1 grains probably formed before type I grains, either from a melt of more refractory composition, or as condensates at elevated temperature, before becoming immersed in melts of the presently existing chondrules. The relict grains were probably partly remelted in their margins to form overgrowths. Additional data and modelling are needed to better constrain these processes.

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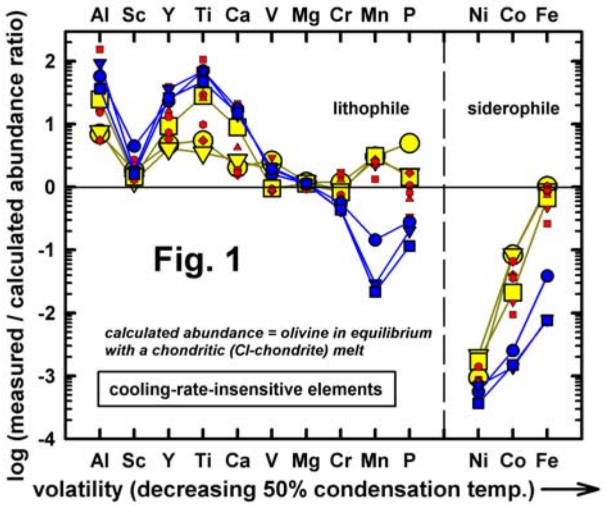

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