FORMATION CONDITIONS OF ALUMINUM-RICH CHONDRULES. E. J. Tronche¹, R. H. Hewins¹,² and G. J. MacPherson³

Introduction: Aluminum-rich chondrules are a rare but ubiquitous and interesting type of chondrule. They have a chemical composition intermediate between ferromagnesian chondrules and plagioclase-rich CAIs [1]. The questions that can be asked are: are Al-rich chondrules the petrographic link between those two kinds of chondrite objects? Was the Al-rich chondrule thermal event the same as that which formed chondrules or CAIs, or both? There are large textural and mineralogical variations within the family of Al-rich chondrules, and this has been explained [1] as due in part to the differing phase equilibria for such a wide range of liquid bulk compositions. Experimental studies have not been done on ferromagnesian chondrules and CAIs to define their formation conditions, but such studies have not been done for Al-rich chondrules. The work of [2] showed that type B CAI formation temperatures were probably lower than 1400°C, and the cooling rates were between 0.5 and 50°C/h; in contrast, the maximum temperature of ferromagnesian chondrule formation was 1400-1850°C and the cooling rates were 10-1000°C/hr [3]. Here we report dynamic crystallization experiments on four different aluminous chondrule compositions and one type C CAI composition, based on the essential controlling phase boundaries defined by [1]. These experiments allow us to constrain peak temperatures and cooling rates, and to see if the varied mineralogy evident in natural samples is related to predicted crystallization sequences for specific bulk compositions as proposed by [1].

Experimental method: Five different compositions (four representing different Al-rich chondrules compositions: PL1, PL2, OL1 and OL2; and one Type C CAI) were made with glass powder from different mixes of quartz, corundum, calcite and MgO oxide. The Al-rich chondrule compositions are separated from one another by an anorthite-forsterite reaction curve and a thermal divide represented by the line between anorthite and forsterite in the spinel saturated Al₂O₃-Mg₂SiO₄-Ca₂SiO₄ liquidus diagram (Fig.1: taken from [1]). For each composition, 30-25mg pellets were heated for 2.5 to 4.5 hours at two different temperatures (near liquidus and 50-65°C under liquidus), then cooled to 1000°C at a constant rate (5 to 1000°C/hr) and quenched in water.

Results: Observed textures for CAI and PL1 experiments are all ophitic and dominated by anorthite laths: within each set of experiments for each composition, results are similar for all values of temperature and cooling rate. Anorthite laths become longer when cooling rate increases, but this variation is seen only for sets of experiments made with the higher peak temperature. Differences between experiments on the CAI and PL1 compositions are mainly mineralogic and conform to the predictions of [1]: spinel+anorthite+mellilit+diopside for CAI, and olivine+anorthite+diopside+glass (Si-rich) for PL1. The textures of the dynamic crystallization runs on PL1 composition suggest incomplete melting (high number of nuclei before cooling begins), and it is likely that textures would be porphyritic for slightly higher temperature heating, for both compositions, with cooling rate playing a more important role. Results of the PL2 set of experiments are quite distinct from the CAI and PL1 results, and very depending on the starting temperature. Experiments started at subsolidus temperature have textures similar to PL1 textures, despite different mineralogy owing to higher Al₂O₃ and MgO contents and lower CaO content in PL2 composition that lead to the presence of orthopyroxene and less clinopyroxene. In PL2 experiments started at liquidus temperature, observed textures are completely different, because the anorthite entry temperature is so much lower than the liquidus: they vary from porphyritic to barred anorthite texture as cooling rate increases. OL1 and OL2 charges are very different from the three others, as expected because their Mg-rich bulk compositions plot in the olivine (+spinel) primary phase volume (Fig.1). The higher SiO₂ content and lower CaO content for OL2 compared to OL1 results in orthopyroxene in OL2 charges. Cooling rate has a very strong influence on

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Fig. 1: Composition fields of the five synthetic compositions

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the minerals appearing a couple of hundred degrees after forsterite, which go from coarsely crystalline to fine needles in the mesostasis.

**Discussion:**

*Parameters controlling texture:* Heterogeneous nucleation and degree of supercooling clearly play a role in our experiments, but even more important is the effect of bulk composition. The observed effects are exactly as predicted by [1]. When composition changes, texture changes, for the same thermal history. If charges of type C CAI, PL1, PL2, OL1 AND OL2 are all heated with the same degree of melting (for example at their liquidus temperature for 3h) and cooled at the same rate, they will have very different textures.

Our observations show that number density of crystals or nuclei at the beginning of the crystallization is controlling texture. Cooling rate is an important parameter only when the melt is supercooled relative to the entry temperature of the phase of interest and the number of nuclei is low. These entry temperatures depend strongly on starting composition. This conclusion was also reached by [4] and [5].

*Comparison between experimental charges and natural chondrules:* We stress that heating time, precursor size, grain size and some other parameters have not been studied here and could be important parameters in the formation of some chondrules. We also should note that those results are not applicable to an open system origin, which would change the chemistry of the chondrules in a dynamic way [6]. If we consider that aluminous chondrules were formed in a closed system, from a composition intermediate between plagioclase-rich CAIs and ferromagnesian chondrules, then our experiments can be used as a catalogue of possible formation conditions for those chondrules. For example, the Chainpur chondrule 1251-14-1 (see [7, 1]) has a composition similar to OL1. Its texture (Fig. 2) is strikingly similar to that resulting from the OL1#10 experiment (Tmax=1406°C, cooled at 500°C/h). Hence, if we suppose a closed system formation without significant evaporation or condensation, chondrule 1251-14-1 could have been formed by heating the precursor somewhat below its liquidus (the liquidus is estimated at 1480 ± 18°C) for about 3 hours, and subsequent cooling at 500°C/h. For many other natural chondrules, which have bulk compositions close to the ones we chose in our study, textures match those of charges, and can be explained as forming at specific conditions we investigated. For other chondrules, textures are not similar to those in our experiments, because we have not investigated a sufficiently wide range of conditions, or because their thermal histories are more complex that those employed here. It is also possible that some natural chondrules experienced evaporation or condensation while they were partially molten, which complicates the interpretation of formation conditions. Assuming that the chondrules have liquidus temperatures similar to our respective chosen bulk compositions, the near- and sub-liquidus temperatures inferred for the heating correspond to ~1400-1500°C, and cooling rates of 50-1000°C/hr are appropriate. For Al-rich barred olivine chondrules the peak temperature could be as high as 1600°C, and the peak temperature range would be generally higher if the heating time were much shorter than the one we used. For comparison, a recent review [8] of data for ferromagnesian chondrules inferred heating at 1400-1750°C, or 1500-1850°C for rapid heating, or 1400-1600°C with extensive evaporation, and cooling at 10-1000°C/hr. Al-rich and Mg-rich chondrules therefore formed at similar peak temperatures, though the peak temperatures of Al-rich chondrules are restricted to the lower part of the range estimated for ferromagnesian chondrules. The maximum temperature experienced by type B CAI was probably lower than 1400°C, and the cooling rate between 0.5 and 50°C/hr, but no estimates have been given for type C. Given the generally ophitic textures of type C CAI, peak temperatures of 1400-1450°C are plausible.

**References**