EXPERIMENTAL STUDY OF TYPE I CHONDRULE FORMATION IN CO3 CHONDRITES: WHAT CONDITIONS ARE NECESSARY FOR PLAGIOCLASE CRYSTALLIZATION?

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Introduction: Chondrules in CO3 chondrites typically contain FeO-poor olivine and pyroxene, a glassy mesostasis, Fe,Ni metal, and sulphides. Approximately 10% of type I chondrules, including type IA, IAB, and IB textures, also contain igneous plagioclase [1,2]. Experimental studies have reproduced textures of type I chondrules at cooling rates of 100˚C/hr to 1000˚C/hr [3]. Plagioclase, however, has not been observed in these chondrule analog experiments. At the conditions of previous experiments, with relatively fast cooling rates and quench temperatures above 1000˚C, plagioclase nucleation is likely to be inhibited [e.g. 4, 5]. Since the presence of igneous plagioclase may provide additional constraints on chondrule formation conditions, we have carried out one-atmosphere dynamic cooling experiments that attempt to reproduce textures of plagioclase-bearing type I chondrules.

Experimental Techniques: We measured the bulk compositions of several plagioclase-bearing type I chondrules in Kainsaz [2]. Compositions of plagioclase-bearing chondrules do not differ signifcantly from plagioclase-free chondrules [2]. We prepared a bulk composition for our experiments that resembled the composition of type IAB (porphyritic olivine / pyroxene), plagioclase-bearing chondrules (Table 1). Oxide powders were mixed and ground to provide a homogeneous oxide starting material.

Table 1: Starting Material

SiO_2	53.6
Al_2O_3	3.6
Cr_2O_3	0.5
MnO	0.1
MgO	37.4
FeO	1.0
CaO	3.6
Na_2O	0.2
Total	100.0

Experiments were conducted in a Deltech 1-atmospere vertical muffle furnace at fO_2 = IW. Starting material was pressed into pellets and suspended by Re ribbon from a sample holder in the hotspot of the furnace. The charges were heated to a maximum temperature of 1600˚C for 18 minutes at which point they were completely melted, as confirmed by a quench experiment. They were then cooled at linear cooling rates of 25˚C/hr to 5˚C/hr. Some experiments were cooled in multiple stages, with cooling rate decreasing in each successive stage. Charges continued cooling to low temperatures, as low as 650°C, before quenching. Run products were then cut, polished, and analyzed with a JEOL 8200 electron microprobe.

Results: Experimental run products contain olivine, low-Ca pyroxene, calcium-rich pyroxene, and glass. Representative textures observed in run products are shown in Fig. 1: they closely resemble textures of type I chondrules in ordinary and carbonaceous chondrites [e.g. 6,7]. Olivine is commonly poikilitically enclosed in euhedral low-Ca pyroxene. Grain sizes of olivine and orthopyroxene range from tens to hundreds of µm. Pigeonite and Ca-pyroxene appear as 1 to 50µm overgrowths on larger low-Ca pyroxene grains. Low-Ca pyroxene, presumably clinoenstatite, commonly displays a "streaky" texture, which has been observed in natural type I chondrules [6]. Streaks may be attributed to twin planes present in clinoenstatite.

Compositions of olivine, orthopyroxene, and mesostasis from experimental charges are plotted in Fig. 2, where they are compared with compositions of phases in plagioclase-bearing and plagioclase-free type I chondrules from the CO3 chondrites ALHA77307 [8,9,10] and Kainsaz [11 and this study]. Olivine and low-Ca pyroxene compositions in the experiments range from Fa_{1-2} and Fs_{1-2}.

Sodium loss occurred during the experiments, although some sodium was retained in all experiments. For a typical experiment containing approximately 10 vol.% glass, the expected concentration of Na_2O in the glass should be ~2.4 wt%. The measured concentrations of Na in glass ranged from 0.3 to 1.8 wt% Na_2O.

Discussion: Our experiments successfully reproduced textures observed in natural porphyritic type I chondrules (Fig. 1). Mineral compositions are also very similar to those observed in natural olivine and pyroxene, including Fa or Fs contents as well as the minor elements MnO, Cr_2O_3, and CaO (Fig. 2). Hence, peak temperatures of 1600 °C and cooling rates of 25˚C/hr to 5˚C/hr are plausible conditions for type I chondrule formation.

Literature values for cooling rates of type I porphyritic chondrules, determined experimentally, range from 100˚C/hr to 1000˚C/hr [3]. For type IAB compositions, it has been suggested that sub-liquidus peak temperatures are required to produce porphyritic textures [3], or that seeding is necessary to produce porphyritic textures with complete melting [12]. However, we have reproduced porphyritic textures typically seen in type IAB chondrules, with peak temperatures above the liquidus and with no seeding, indicating that these constraints are not required. In our experiments, cooling rates are relatively slow, and at this point we do not know if slow cooling is a necessary condition for production of porphyritic textures when peak temperatures are above the liquidus.

While our experiments were conducted at conditions that we considered optimized for plagioclase crystallization, plagioclase was not observed in any experiment. We tested the possibility that plagioclase would crystallize if slow cooling continued to low temperatures, but even in an experiment cooled at 5 °C/hr down to 650 °C, the mesostasis phase was still glass. Clearly, plagioclase does not nucleate readily under the conditions we examined.

Recently, evidence has been presented that chondrules formed in a region of the solar nebula with a high solid density [e.g.13,14]. Under these conditions, we would expect minimal Na loss to occur during chondrule formation. The presence of additional Na in the melt would affect the degree of polymerization of the melt, and could potentially aid nucleation of plagioclase. Therefore we plan to conduct future experiments with controlled conditions to preserve Na in melt during cooling, in an attempt to crystallize plagioclase-bearing type I chondrule analogs in the laboratory. Defining the conditions necessary for plagioclase nucleation may place important constraints on chondrule thermal histories.

References: [1] Jones R. H. (1997) *Meteorit. Planet. Sci.*, 32, A67. [2] Wick M. J. & Jones R. H. (2009) *Meteorit. Planet. Sci.*, 44, A218. [3] Radomsky P. M. & Hewins R. H. (1990) *Geochim. Cosmochim. Acta* 54, 3475-3490. [4] Lofgren G. (1989) *GCA* 53, 461-470. [5] Gibb R. G. F. (1974) *Mineral. Mag.* 39, 641-653. [6] Jones R. H. (1994) *Geochim. Cosmochim. Acta* 58, 5325-5340. [7] Kurahashi E. et al. (2008) *Geochim. Cosmochim. Acta* 72, 3865-3882. [8] Jones R. H. (1992) *Geochim. Cosmochim. Acta* 56,467-482. [9] Brearley A. J. & Jones R. H. (1998) In Planetary Materials, ed. J. J. Papike. *Reviews Mineral. Geochem.* 36, chap. 3. [10] Noguchi T. (1989) *Proceed. NIPR Symp.Ant. Met.* 2, 169-199. [11] Berlin J. 2009. Ph.D. thesis, University of New Mexico. [12] Connolly H. C. & Hewins R. H. (1995) *Geochim. Cosmochim. Acta* 59, 3231-3246. [13] Alexander C. M. O'D. et al. (2008) *Science* 20, 1617-1619. [14] Borisov A. et al. (2008) *Geochim. Cosmochim. Acta* 72, 5558-5573.

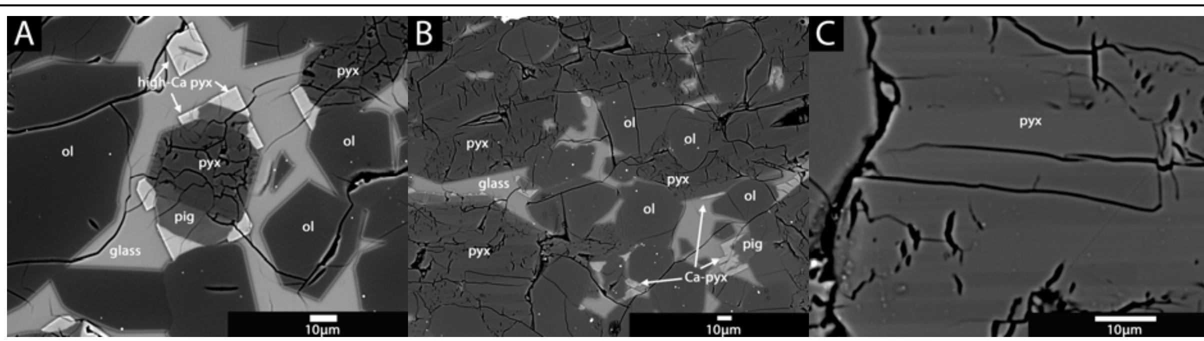

Figure 1: BSE images of typical textures observed in experimental charges. a. Porphyritic olivine / pyroxene texture with Ca-pyroxene and pigeonite overgrowths on low-Ca pyroxene (exp10: cooled at 10˚C/hr to1200˚C and at 5˚C/hr to the quench temperature of 800˚C), b. Olivine poikilitically enclosed in low-Ca pyroxene (exp8: cooled at 25˚C/hr to 1300˚C, at 10˚C/hr to 1000˚C, and 5˚/hr to the quench temperature of 800˚C), c. Streaky pyroxene texture and shrinkage cracks in clinoenstatite (exp10).

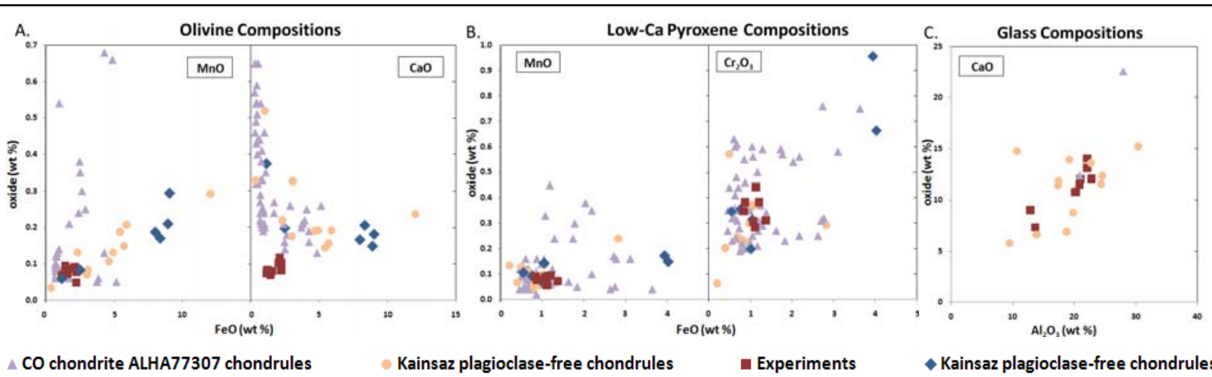

Figure 2: Compositions of (a) olivine, (b) pyroxene and (c) mesostasis from experimental charges, compared with natural type I chondrules in CO3 chondrites, including Kainsaz plagioclase-bearing chondrules (this study), Kainsaz plagioclase-free type I chondrules [11] and ALHA77307 plagioclase-free type I chondrules [8,9,10]. Elevated FeO contents of Kainsaz chondrules are a result of slight metamorphism, as Kainsas is petrologic type 3.2.