

AN EXPERIMENTAL STUDY OF THE CONDITIONS OF TYPE II CHONDRULE FORMATION IN ORDINARY CHONDRITES. S. E. Rocha and R. H. Jones, Department of Earth and Planetary Sciences, MSC03-2040, University of New Mexico, Albuquerque, New Mexico 87131-0001. crabbier@unm.edu

Introduction: Our understanding of chondrule formation conditions is furthered by the use of experimental analogs that provide constraints on chondrule thermal histories. Several experimental studies have replicated the textures of porphyritic olivine (PO) chondrules [e.g. 1]. An investigation of the formation conditions of type IIA chondrules indicated peak temperatures around 1550 °C, and cooling rates between 10 and 100 °C/hr [2,3]. Experiments at cooling rates less than 100 °C/hr had phenocrysts generally larger than those observed in chondrules [2]. Cooling rates determined for type I chondrules are similar to or higher than those of type II chondrules, 100-1000 °C/hr [4].

Igneous plagioclase is observed in some type I chondrules, particularly in CO chondrites. A recent study [5] investigated conditions under which plagioclase crystallizes as a late-stage mineral in type I chondrules. Plagioclase crystallization requires slow cooling, including cooling rates down to 1 °C, and quench temperatures below 1000 °C. The presence of plagioclase thus places upper limits on cooling rates for the type I chondrules in which it is observed.

In contrast to type I chondrules, type IIA chondrules do not contain plagioclase [e.g. 6]. Plagioclase is difficult to nucleate, and has not been reproduced in type IIA analog experiments, even at slow cooling rates of 2 °C/hr [2]. The absence of plagioclase in experiments may be because runs are typically quenched from temperatures above which plagioclase may nucleate. We are carrying out experiments that attempt to duplicate textures and mineral compositions observed in type IIA chondrules. Since plagioclase has not been observed in type IIA chondrules, defining the conditions that produce plagioclase within an FeO-rich melt will determine a lower limit on the cooling rates of type II chondrules.

Analytical Methods: For our experiments we used a bulk composition based on the average bulk composition of type IIA chondrules in the LL3.0 chondrite Semarkona [6]. The major element composition is given in Table 1: we also added trace elements including 500 ppm each of the REE yttrium, samarium, europium, dysprosium, and ytterbium, for use in determining partition coefficients at a later date.

An oxide powder was prepared, ground to provide a homogeneous mix, and pressed into pellets. The pellets were suspended in a Deltech one-atmosphere gas-mixing furnace on Re wire. Charges were initially

heated to a peak temperature of 1600 °C for 12 to 18 minutes at $fO_2 = IW$. We performed several quench experiments from this temperature to determine the composition of the starting material. We also carried out experiments that were cooled to final temperatures

SiO ₂	44.5
TiO ₂	0.12
Al ₂ O ₃	2.37
Cr ₂ O ₃	0.51
FeO	16.2
MnO	0.40
MgO	32.2
CaO	1.79
Na ₂ O	1.43
K ₂ O	0.18
P ₂ O ₅	0.30
Total	100.0

between 750° and 900 °C, at cooling rates ranging from 1 to 30 °C/hr. Several charges were cooled in sequential stages, with slower cooling rates in each successive stage, to approximate the non-linear cooling rates that chondrules may have experienced. The experiments were not sealed, and sodium was lost during the runs. After quenching from the final temperatures, charges were cut, polished, and analyzed with an electron microprobe.

Results: Run products cooled at the same rate displayed similar textures. Over the range of cooling rates we have investigated so far, we have bracketed the conditions for plagioclase crystallization.

30 °C/hr. Charges cooled at a continuous rate of 30 °C/hr contain zoned subhedral olivine in a glassy mesostasis (Fig. 1). Small olivine phenocrysts 10 to 50 μm in size were concentrated at the bottom of the charge and larger phenocrysts, tens to hundreds of μm in size, were observed at the top. The olivine phenocrysts exhibit “ragged” edges which may represent overgrowth grown during quenching (Fig. 1).

30 - 5 - 1 °C/hr. The slowest cooling rate we have examined included a stage from 1600 °C to 1300 °C at 30 °C/hr, a stage from 1300 °C to 950 °C at 5 °C/hr, and a stage from 950 °C to 900 °C at 1 °C/hr. Run products contain zoned euhedral to subhedral olivine, low-Ca pyroxene, Ca-rich pyroxene, plagioclase, and very little glass (Fig. 2). Olivine and low-Ca pyroxene are intergrown, and Ca-rich pyroxene occurs as rims on low-Ca pyroxene. At the bottom of the charge, olivine and pyroxene have grain sizes of 25 to 50 μm, and no plagioclase is observed. At the top of the charge, olivine and pyroxene occur as larger grains, >100 μm, and plagioclase occurs as elongate grains, interstitial to olivine and pyroxene, with grain sizes from 50 to 100

μm in length. Small ($<20 \mu\text{m}$) grains of silica are associated with plagioclase.

We also observe small grains ($<20 \mu\text{m}$) of a REE-rich silicate phase, which occurs interstitially between pyroxene and plagioclase (Fig. 2). These grains appear to have grown from small pockets of residual melt that had become highly enriched in the incompatible REE. We are currently working to identify this phase.

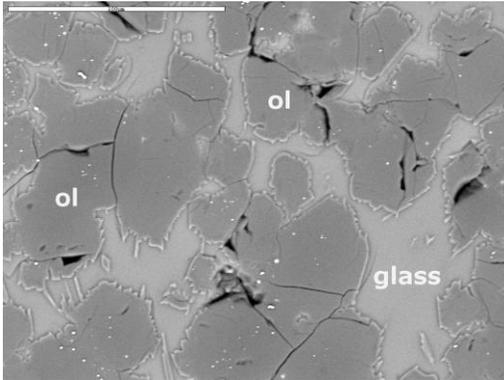


Fig. 1: Backscattered electron (BSE) image of texture characteristic of the $30 \text{ }^\circ\text{C/hr}$ cooling-rate experiments. Bright specks included in olivine (ol) are pieces of Re metal from the wire. Scale is $100 \mu\text{m}$.

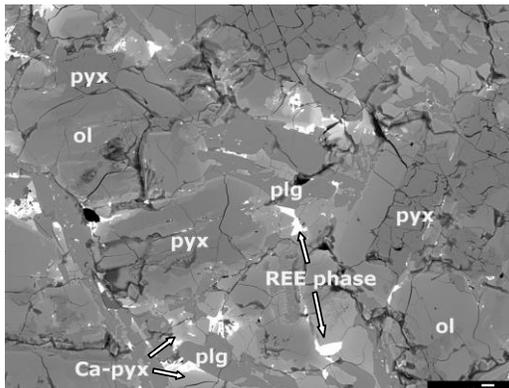


Fig. 2: BSE image of the slow-cooled plagioclase-bearing charge.

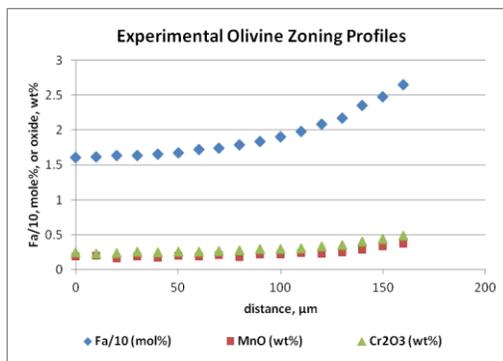


Fig. 3: Zoning profile from the core (left) to the rim (right) of an olivine grain, from an experimental charge cooled at $30 \text{ }^\circ\text{C/hr}$.

Mineral compositions. Olivine grains in the experimental charges have average compositions around Fa_{17} . Most olivine grains are zoned, for example from Fa_{16} at the core to Fa_{26} at the rim (Fig. 3). MnO and Cr_2O_3 contents are also zoned and correlated with fayalite contents (Fig. 3). These zoning profiles are similar to profiles in Semarkona type IIA chondrules [6]. The atomic Fe/Mn ratio of olivine in the experiments, 39-48, is similar to olivine in type IIA chondrules in ordinary chondrites ($\text{Fe/Mn} = 44$) [7]. The average composition of low-Ca pyroxene is $\text{En}_{80}\text{Fs}_{19}\text{Wo}_1$ and plagioclase in the slowest-cooled experiment has a composition of $\text{An}_{97}\text{Ab}_3$.

Discussion: Our experiments successfully reproduced Type II chondrule textures, as well as mineral compositions and zoning. Experiments at cooling rates of $30 \text{ }^\circ\text{C/hr}$ reproduced the PO textures of type IIA chondrules. The slowest-cooled experiments have significant amounts of pyroxene, and more closely resemble porphyritic olivine/pyroxene (POP) chondrules. The cooling rates we investigated are at the low end of the 10 to $1000 \text{ }^\circ\text{C/hr}$ range for porphyritic chondrules that has been proposed previously [1-3]. The experiments do not necessarily exclude faster cooling rates for type IIA chondrules, but they show that slow cooling rates are plausible.

In our experiments, plagioclase crystallized under very slow cooling conditions, with a final cooling stage of $1 \text{ }^\circ\text{C/hr}$, while run products cooled at $30 \text{ }^\circ\text{C/hr}$ did not contain any plagioclase. Hence, these conditions bracket the cooling rate at which plagioclase crystallization occurs, and indicate that a lower limit to the cooling rate of type II chondrules lies between the two sets of conditions. For type I chondrule analogs, plagioclase crystallization occurs under similar conditions to those we examined [5]. Since natural type IIA chondrules do not contain plagioclase, we can infer that natural type II chondrules did not experience very slow cooling rates, unlike some type I chondrules. We plan to conduct further experiments to better constrain the conditions under which plagioclase forms in type II chondrules.

References: [1] Hewins R. H. et al. (2005) *ASP* 341, 286-316. [2] Lofgren G. E. (1988) *Geochim. Cosmochim. Acta* 53, 461-470. [3] Jones R. H. & Lofgren G. E. (1993) *Meteorit.* 28, 213-221. [4] Radomsky P. M. & Hewins R. H. (1990) *Geochim. Cosmochim. Acta* 54, 3475-3490. [5] Wick M. J. & Jones R. H. (2012) *Geochim. Cosmochim. Acta* in review. [6] Jones R. H. (1990) *Geochim. Cosmochim. Acta* 54, 1785-1802 [7] Berlin J. et al. (2011) *Meteorit. Planet. Sci.* 46, 513-533.