

PORPHYRITIC OLIVINE CHONDRULE FORMATION AT EXTREMELY HIGH COOLING RATES: EXPERIMENTAL SYNTHESIS OF TYPE I AND II PO CHONDRULES. J. P. Greenwood¹, K. Abe¹, and W. Herbst², ¹Dept. of Earth & Environmental Sciences, Wesleyan University, Middletown, CT USA, ²Dept. of Astronomy, Wesleyan University, Middletown, CT USA.

Introduction: A recent review of chondrule thermal histories emphasized the number of studies in the last two decades that seemed to indicate extremely high cooling rates ($>3000^{\circ}\text{C/hr}$) near the liquidus [1], while a number of studies indicate very slow cooling near the solidus [1]. Previous experimental studies of chondrule formation reproduced the most common type of chondrules (FeO-poor porphyritic olivine (PO) chondrules) primarily at low cooling rates ($<100^{\circ}\text{C/hr}$). Experimental studies of FeO-rich PO chondrules (Type II) also suggested low cooling rates of $<500^{\circ}\text{C/hr}$ (only one experiment of [2] led to PO textures at 1000°C/hr).

Recent studies of chondrules have found intriguing zonation of Al and Ti in chondrule olivine grains [3-5]. We have recently reproduced this Al and Ti zonation in chondrule synthesis experiments at extremely high cooling rates [6] and apply these techniques to the formation of PO chondrules.

Methods: We have developed several techniques to allow us to conduct high temperature studies at extreme heating and cooling rates (dynamic crystallization experiments with non-linear heating and cooling rates). We have added a motorized sample assembly to precisely control the heating and cooling rates of experimental charges. We have also developed a sample technique that allows the majority of the experimental charge to not be in contact with the Pt container during the experimental run. While diffusion of Fe between the melt and container is

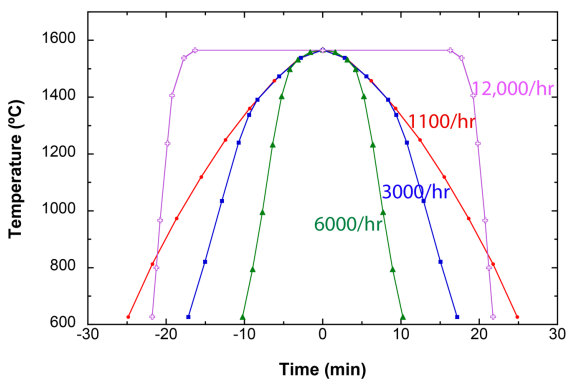


Fig. 1. Four different heating and cooling cycles for experiments from [13].

mitigated by pre-conditioning the Pt container, nucleation effects of the Pt container are minimized (lessened), as the charge is suspended between two Pt contact points.

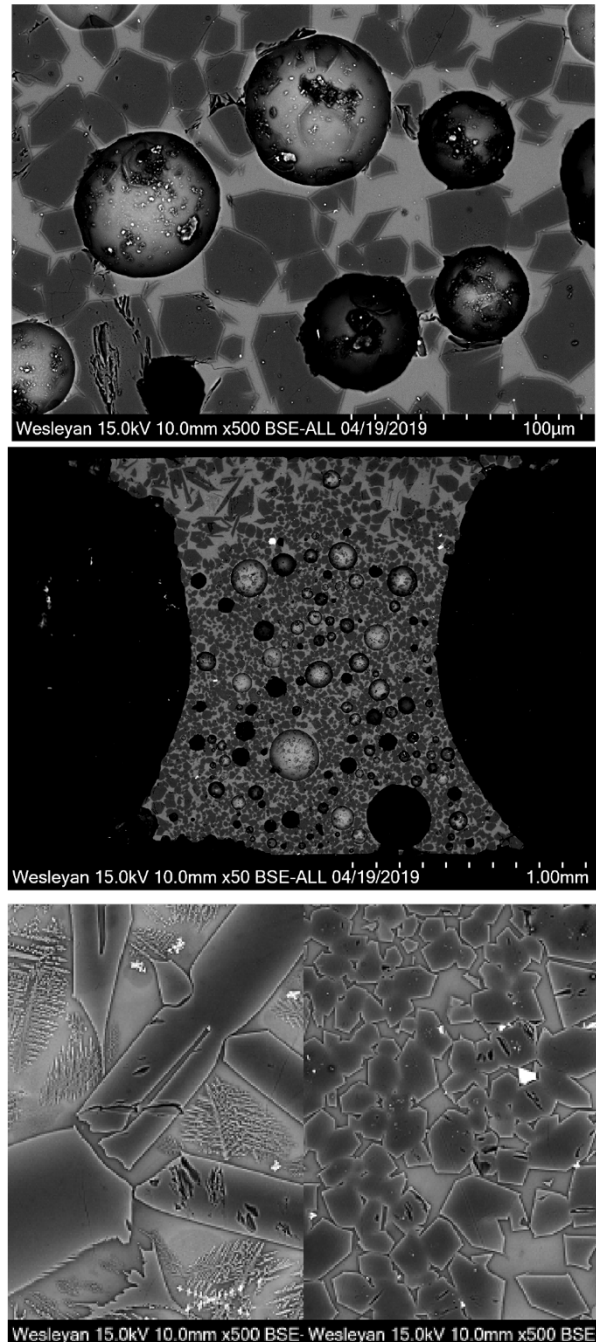


Fig. 2. (Top) BSE of Type IA PO experiment. (Middle) Same as Top, showing the experimental charge (contact points at top and bottom). (Bottom) BSE of Type IIA PO experiment. All experiments use the 6000°C/hr in Fig. 1.

For these experiments several starting compositions are used, corresponding to average Type I PO, POP, and Type II PO and POP [7-10]. For Type I PO we used a mixture of minerals ($<20\ \mu\text{m}$ Globe peridotite admixed with feldspar) and also a reagent grade oxide starting assemblage; for all others we used reagent grade oxides. Oxygen fugacity is controlled using $\text{CO}+\text{CO}_2$.

We employ heating and cooling curves developed for the close-passage of chondritic material to large differentiated planetesimals (LDP) in the early Solar System [11, 12]. These lead to heating and cooling rates in our experiments of $\sim 1100^\circ\text{C/hr}$ to $12,000^\circ\text{C/hr}$, if we linearize the curves between 1400°C and 1200°C . We employed a peak temperatures of 1565°C . The heating and cooling curves that we tried to emulate in the experiments are shown in Fig. 1.

Results: We were able to produce porphyritic textures at all cooling rates employed. As all five starting compositions used the same four heating curves (and same peak temperature), we can see important differences related to starting composition. Higher liquidus temperature compositions had porphyritic textures (IA and IIA) while more silica-rich compositions (IAB and IIAB) were dominated by barred and dendritic textures.

Type IA (PO). Our mineral mixture developed excellent PO textures, including Al and Ti zonation similar to chondrule olivines in the literature [3-5]. Cooling rates from 1100°C to $12,000^\circ\text{C/hr}$ were all successful at producing porphyritic textures (Fig. 2). Experiments at the highest cooling rate did not produce Al and Ti zonation similar to the literature [3-5] and were discussed previously [6]. The Type IA reagent grade oxide produced porphyritic olivine textures, but finer-grained than most chondrules.

Type IAB (POP). This composition did not produce very good chondrule analogues. This composition led to euhedral olivine grains enclosed in large pyroxene grains for the cooling rates between 1100°C and 6000°C . At $12,000^\circ\text{C/hr}$, a barred olivine texture develops.

Type IIA (PO). Experiments at cooling rates from 1100°C/hr to $12,000^\circ\text{C/hr}$ produced excellent porphyritic olivine textures (Fig. 2).

Type IIAB (POP). Experiments with this composition produced barred olivine chondrules. The width of the olivine bars decrease with increasing cooling rate in this set of experiments.

Discussion: *Porphyritic textures at extremely high cooling rates.* Porphyritic olivine textures were produced at all cooling rates employed for Type IA and IIA bulk compositions, from 1100°C/hr to $12,000^\circ\text{C/hr}$. Previous experimental studies only produced PO textures for Type I compositions at cooling rates of $10\text{--}500^\circ\text{C/hr}$ [1]. We find that short heating times (which result in

limited dissolution of relict grains [13]) are critical for the production of porphyritic olivine chondrule textures. Our Type IIA composition did not have any olivine starting material, yet still formed excellent porphyritic olivine textures. Some of the reagent grade oxides were high temperature minerals, and may have survived the heating cycle to act as heterogeneous nuclei for the olivine in Type II experiments.

Compositional dependence of texture. This experimental study is one of the first to employ non-linear heating and cooling rates for a range of chondrule bulk compositions [1]. All of the Type IAB experiments produced barred olivine textures. The three slowest cooling rate experiments (1100 , 3000 , and 6000°C/hr) produced an olivine-orthopyroxene texture, unlike that seen in chondrules. These results imply either that lower temperature compositions were heated to lower peak temperatures, or that Type IAB and IIAB are actually PO chondrules with pyroxene rims, that have been sectioned off-center, as suggested from 3-D study of chondrules [14].

Constraints on chondrule formation. This study shows that slow cooling ($<500^\circ\text{C/hr}$) is not necessary to form porphyritic olivine chondrules. When combined with constraints from experimental replication of oscillatory zoning of Al and Ti in chondrule olivine grains [6], cooling rates of $\sim 3000\text{--}6000^\circ\text{C/hr}$, above 1200°C , appear necessary.

Summary: We find that we can produce porphyritic olivine textures using starting materials with the average bulk composition of Type I PO and Type II PO from Semarkona [7,8] at extremely high cooling rates ($1100\text{--}12,000^\circ\text{C/hr}$). This extends the range of cooling rates that this most common type of chondrule can form from previous work of only $10\text{--}500^\circ\text{C/hr}$. We have also reproduced Al and Ti minor element zonation in olivine from porphyritic chondrules under these same conditions [6].

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