Experimental Reproduction of Olivine rich Type-I Chondrules

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ABSTRACT

Ordinary chondritic meteorites are an abundant type of stony meteorite characterized by the presence of chondrules. Chondrules are small spheres consisting of silicate, metal, and sulfide minerals that experienced melting in the nebula before incorporation into chondritic meteorite parent bodies. Therefore, chondrules record a variety of processes that occurred in the early solar nebula. Two common types of unequilibrated chondrules with porphyritic textures include FeO-poor (type I) and FeO-rich (type II) each subdivided into an A (SiO_2-poor) and B (SiO_2-rich) series. Type IA chondrules include those with high proportions of olivine phenocrysts (>80% olivine) and type IB chondrules include those with high proportions of pyroxene phenocrysts (<20% olivine). An intermediate composition, type IAB chondrules include those chondrules in which the proportion of olivine phenocrysts is between 20-80%. We conducted high-temperature laboratory experiments (melting at 1550° C) to produce type I chondrules from average unequilibrated ordinary chondrite (UOC) material mixed with small amounts of additional olivine. The experiments were conducted by adding forsteritic rich olivine (San Carlos olivine, Fo 91) to UOC material (GRO 95544) in a 30/70 ratio, respectively. Results of these high temperature experiments suggest that we have replicated type IA chondrule textures and compositions with dynamic crystallization experiments in which a heterogeneous mixture of UOC (GRO 95544) and olivine (San Carlos olivine) were melted at 1550°C for 1 hr. and cooled at 5-1000°C/hr using graphite crucibles in evacuated silica tubes to provide a reducing environment.

INTRODUCTION

Chondritic meteorites are the oldest and most primitive rocks in the solar system (Brearley and Jones, 1998). Additionally, chondrites are the hosts for interstellar grains that predate solar system formation and survived processing in the protoplanetary disk (solar nebula) environment (Brearley and Jones, 1998). The abundance of chondrules in chondrites implies that melting of small particles was a common phenomenon in the early solar system (Hewins, 1997). Therefore, chondrites offer planetary scientists the opportunity to study the earliest history of formation of our solar system.

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Type I chondrules have a distinctive chemical composition (Lofgren and Le, 2002) that is largely devoid of oxidized iron (Jones and Scott, 1989; and Jones, 1994). The silicate phases usually contain less than 5 wt. % FeO and metallic Fe is usually abundant (Lofgren and Le, 2002). Type I chondrules display a wide range of textures from barred to porphyritic to partially melted aggregates (Jones and Scott, 1989; Jones, 1994; and Lofgren and Le, 2000). Because of the reduced nature of the chondrules, experimental duplication of their crystallization histories is difficult (Lofgren and Le, 2002). Experiments conducted in silica tubes with the sample in graphite crucibles provides for a reducing environment, but also sets an upper limit on the temperature of the experiments. This limit of 1550°C is well below the melting temperatures required, but does allow testing of the hypothesis that many type I chondrules experienced a partial melting history that does not involve large amounts of melting (Lofgren and Le, 2002). The starting materials used in these experiments are unequilibrated ordinary chondrites (UOC) of the L petrologic type (i.e., low total Fe content). The bulk composition of these chondrites when reduced approaches the composition of the type IAB and IA chondrules. The experiments suggest that such a partial melting history is consistent with the observed textures and mineral chemistries in many type IAB and IA chondrules.

EXPERIMENTAL TECHNIQUES

Experiments were conducted in evacuated silica tubes with the sample in a graphite crucible using techniques similar to McCoy et al. (1999). The experimental configuration produces a reducing environment in which the oxygen partial pressure (f_{O2} or oxygen fugacity) is 3 to 5 orders of magnitude below the Iron-Wüstite (IW) buffer in the temperature range 800 to 1550°C, respectively. This f_{O2} is most likely lower than for type I chondrules, but does provide a lower limit. The starting meteorite material, collected from the Grosvenor Mountains, Antarctica, was comprised of fragments of the unequilibrated ordinary chondrite (UOC) GRO 95544 (L3.1) that were ground to an average grain size of approximately 50µm (<10 to 100 µm) and then mixed with San Carlos olivine (Fo91) in the ratio of 70/30, respectively. Starting materials differed principally in the grain size of the olivine. Heterogeneous aliquots (70/30 ratio, i.e., UOC/SC olivine) ranging between 145 and 155 mg were then pressed into pellets that were then placed in a graphite crucible. Each graphite crucible was sealed in an evacuated silica tube and placed in a furnace. Dynamic crystallization experiments (i.e., controlled cooling conditions) were brought to1550°C for 1 hour and then cooled at rates from 5-1000°C/hr. Each sample was quenched by removing the silica tube from the furnace and placing it in a stream of compressed air.

Polished microprobe mounts were prepared for textural and chemical analyses. Backscatter (BSE) images and mineral analyses were collected on the JEOL JSM-5910 LV SEM and the Cameca SX-100 microprobe, respectively at the NASA-JSC. BSE images and microprobe analyses of minerals were collected using an accelerating potential of 15 Kv, and 15 Kv and a beam current of 20 nA, respectively. Natural minerals were used as standards for the microprobe analyses.

RESULTS

All the experimental charges show evidence of partial melting in a reducing environment. The degree of silicate partial melting ranges from approximately 10-15 % to near 70 %. All of the silica phases crystallized from the melt plus the glassy mesostasis contain less than 1 wt. % FeO and metallic Fe occurs as large rounded blebs and as abundant, small blebs (<1µm) of exsolved Fe-metal in the olivine. Some zoned "relict" olivine however, show Fe contents that range from 8.3 to 1.4 wt. %. Olivine and pyroxene grains crystallized from the melt have uniform compositions with no obvious chemical zoning. Additionally, the metal blebs show a tendency to migrate to the outer edge of the experimental charges. All dynamic cooling experiments have elliptical to rounded shapes with large to small vesicles.

The experiment with the best developed type I characteristics is GRO-295. It was melted at 1550°C for 1 hour and cooled at 5°C/hr to 800°C. Figure 1 shows a type IA chondrule from QUE 97008 and compared with experiment GRO-295. GRO-295 has a well developed type IA texture (Figure 1D) in which the olivine is in contact with a clinopyroxene (cpx) set in a glassy mesostasis. Typical compositions of the phases analyzed in GRO-295 are given in Table 1. The olivine and orthopyroxene are relatively homogeneous and consistent in composition. Clinopyroxene has a variable composition relative to Ca and Al. The glassy mesostasis shows the greatest compositional variation,

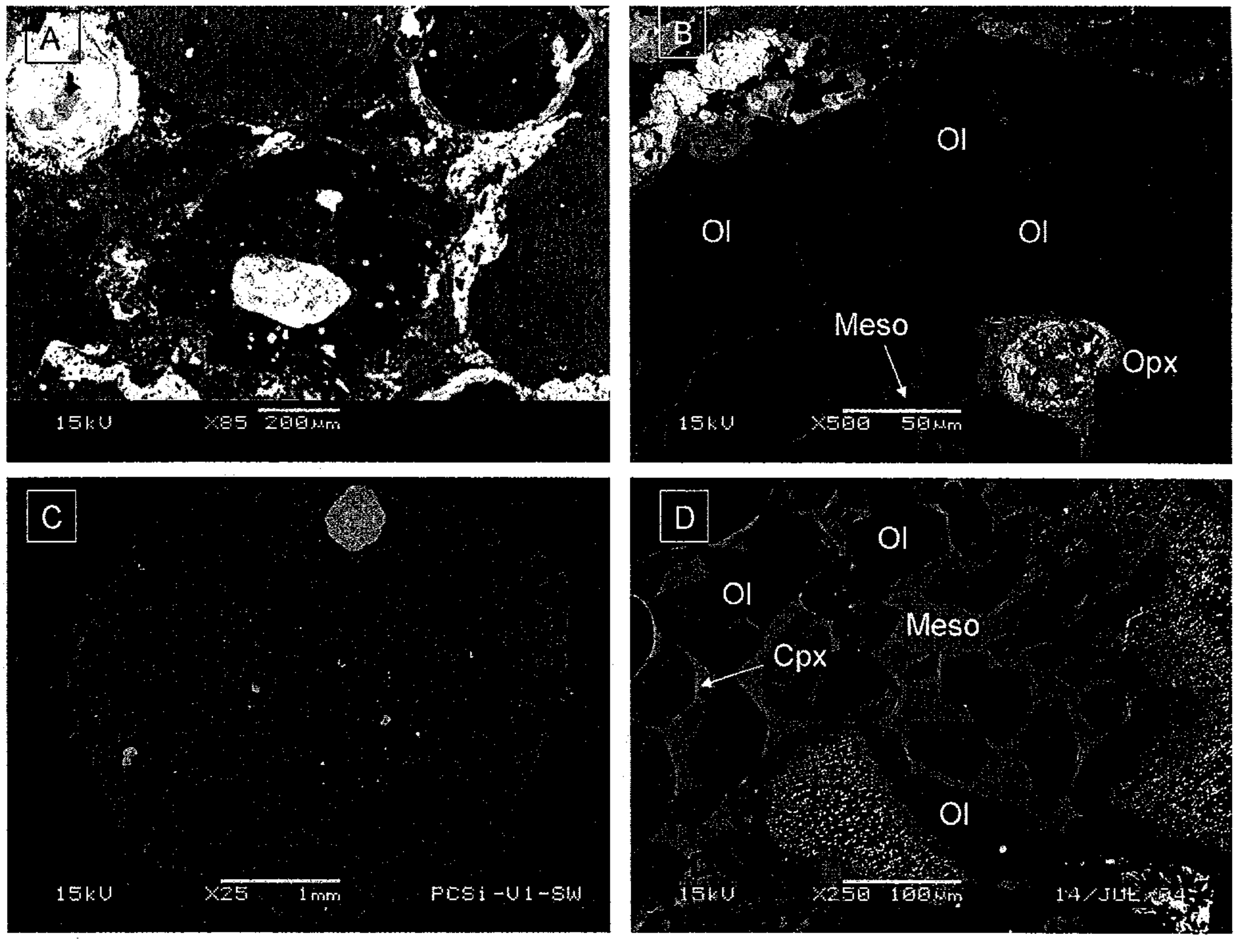

Figure 1. SEM backscatter images showing a comparison of an experimentally produced type IA chondrule (photo C) with a natural type IA chondrule from QUE 97008, lower center of photo A. A) Type IA chondrule. Olivine-orthopyroxene (dark grains) and metal (white). B) BSE image of QUE 97008-6, 500x. Ol = olivine (dark grains), Opx = orthopyroxene (medium gray grains), and Meso = glassy mesostasis (light gray). C) Experimental charge GRO-295 melted at 1550°C for 1 hour and cooled at 5°C/hr. Chondrule is circular in shape with numerous vesicles. Olivine (dark grains), orthopyroxene (medium gray grains), and glassy mesostasis (light gray). D) BSE image of experimental charge GRO-295 shown in photo C at 250x. Ol = olivine (dark grains), Cpx = clinopyroxene (light gray), and Meso = glassy mesostasis (medium gray). "Relict", more Fe-rich olivine shows partial melting with exsolving Fe metal blebs and heterogeneous nucleation and growth of more Mg-rich olivine rims. Smaller, equant, euhedral to anhedral crystals of Mg-rich olivine (dark) that nucleated and grew from the melt during cooling are present. Orthopyroxene has then nucleated and rims some olivine crystals (not seen in this BSE image). The texture and mineral proportions between photos B and C are similar, but more glassy mesostasis exists in the experimental charge relative to the natural chondrule.

Table 1.Typical compositions of olivine, orthopyroxene, clinopyroxene, and glassy mesostasis in experiment GRO-295, all in oxide wt. %.

Oxide	Olivine	Orthopyroxene	Clinopyroxene	Mesostasis
SiO_2	42.95	59.12	50.35	54.69
TiO_2	0.01	0.22	1.09	0.23
Al_2O_3	0.03	1.44	9.54	24.32
Cr_2O_3	0.06	0.11	0.17	0.03
FeO	0.69	0.37	0.33	0.47
MnO	0.05	0.02	0.07	0.06
MgO	56.61	38.90	18.08	5.97
CaO	0.13	0.46	21.01	14.72
Na_2O	0.00	0.00	0.00	0.03
K_2O	0.00	0.00	0.00	0.00
P_2O_5	0.00	0.00	0.15	0.10
Total	100.54	100.65	100.78	100.61

but is dependent on the amount of crystallization of the experimental charge. Sodium (Na) in experiment GRO-295 is very low, reflecting the long duration of the cooling event.

DISCUSSION

Type IA chondrules are characterized by highly forsteritic olivine and En (enstatite) rich pyroxenes (Jones and Scott, 1989). Additionally, type IA chondrule mesostasis varies from 100% glass to partly microcrystalline, occupying 5-15 volume % of the chondrule (Jones and Scott, 1989). The mineralogy in GRO-295 experiment shows all silicate phases (olivine and pyroxene) to meet the definition of a type IA chondrule, i.e., olivines are forsteritic and the pyroxenes are magnesium-rich. However, because the experimental starting material is heterogeneous modal percentages of the silicate minerals and mesostasis vary from one area to another within the experimental charge. Therefore, experimental preliminary results suggest that the formation of type I chondrules by reduction of ordinary chondrite debris in the solar nebula is a viable mechanism. The consensus is that most chondrules are crystallized melt droplets from the near total melting of crystalline precursor material (Lofgren ,1996; Lofgren and Le, 2002). The process proposed here, however is one of partial melting (<70% melting). The reduction and partial melting would take place at temperatures equal to or less than 1550°C

CONCLUSIONS

In this study we have reproduced type I chondrules by the reduction of UOC material (GRO 95544) mixed with olivine (San Carlos olivine, Fo 91) in the ratio 70/30, during dynamic crystallization experiments. The heterogeneous powdered UOC-olivine mixture used as starting material in the experiments simulates crystalline chondrule precursors in the solar nebula. These chondrules vary in silicate mineral modes and texture depending on the degree of melting of the precursor UOC-olivine mixture and the ultimate cooling rate after the melting-crystallization event.

REFERENCES CITED

Brearley, A.J., and Jones, R., 1998, Chondritic meteorites. Reviews in Mineralogy, vol. 36, Planetary Materials; Mineralogical Society of America, p. 3-1 to 3-398.

Hewins, R.H., 1997, Chondrules. Annual Review of Earth and Planetary Sciences, vol. 25, p. 61-83.

Jones, R. H., 1994, Petrology of FeO-poor, porphyritic pyroxene chondrules in the Semarkona chondrite. Geochimica Cosmochimica Acta, vol. 58, p. 5325-5353.

Jones, R. H., and Scott, E. R. D., 1989, Petrology and thermal history of type IA chondrules in the Semarkona (LL3.0) chondrite. Proc. 19th Lunar and Planetary Science Conference, p. 523-536.

Lofgren, G.E., 1996, A dynamic crystallization model for chodrule melts. In Chondrules and the Protoplanetary Disk, editors, R.H. Hewins, R.H. Jones, and E.R.D. Scott, p. 187-196.

Lofgren. G. E., and Le, L., 2000, Experimental evidence for a partial melting origin for most porphyritic chondrules. In Lunar and Planetary Science XXXI, Abstract #1809, Lunar and Planetary Institute, Houston, Texas (CD-ROM).

Lofgren, G. E., and Le, L., 2002, Experimental reproduction of Type-1B chondrules. In Lunar and Planetary Science XXXIII, Abstract #1612, Lunar and Planetary Institute, Houston, Texas (CD-ROM).

McCoy, T.J., Dickinson, T.L., and Lofgren, G.E., 1999, Partial melting of the Indarch (EH4) meteorite: A textural, chemical, and phase relations view of melting and melt migration. Meteoritics & Planetary Science, vol. 34, p. 735-746.