Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 211 (2017) 256–279

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Secondary melting events in Semarkona chondrules revealed by compositional zoning in low-Ca pyroxene

Bastian Baecker[a,1], Alan E. Rubin[a], John T. Wasson[a,b,*]

[a] *Institute of Geophysics and Planetary Physics and Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA*

[b] *Department of Chemistry and Biochemistry, University of California, Los Angeles, CA 90095-1567, USA*

Received 14 November 2016; accepted in revised form 11 May 2017; Available online 17 May 2017

Abstract

It is well established that many chondrules contain relict grains formed in previous generations of chondrules. We here describe evidence that chondrules experienced multiple mesostasis melting events while remaining closed systems. Spheroidal chondrule shapes resulted from surface-tension effects following a primary heating event that caused substantial melting ($\gtrsim$ 40%) of the precursor assemblages. In some high-FeO chondrules in LL3.00 Semarkona, low-Ca pyroxene phenocrysts show multiple overgrowth layers produced by secondary melting events. We characterized these layers with the electron microprobe in terms of Fe, Ca and Cr in two Semarkona chondrules.

The first low-Ca pyroxene overgrowth that forms after a minor heating/melting event has low Ca and Fe; concentrations of these incompatibles gradually increase over the next 8 ± 4 μm until falling temperatures and slowing diffusion caused growth to stop. The next melting event remelts and mixes the local mesostasis; cooling causes growth of a normal igneously zoned layer. In the simplest cases, the Ca concentrations at the minima gradually increase towards the edge of the phenocryst. Heat deposition during heating events varied over a wide range; the weakest events produced recognizable changes in slopes (that we call "inflections" rather than minima). Large fractions of the individual phenocrysts were formed by the process that produced the overgrowth layers. It appears that overgrowth formation stopped when the Ca content of the mesostasis became high enough to make high-Ca pyroxene a liquidus phase.

Both Semarkona chondrules include olivine phenocrysts similar in size and modal abundance to the low-Ca pyroxene phenocrysts. Olivine compositional profiles show symmetrical, apparently normal zoning except for asymmetries attributable to the presence of relict grains. Surface compositions of different olivine phenocrysts in the same chondrule are very similar to one another, consistent with growth from mesostasis in the present chondrule. Hence, these olivines must have experienced the same heating events as the pyroxenes with overgrowths.

As argued in earlier papers, the fraction of chondrules heated to low temperatures (sufficient to melt only mesostasis) during nebular heating and melting processes is much larger than the fraction heated sufficiently to melt half or more of the mafic minerals. Melting is expected to result from flash heating in which heat is transported into the chondrule by radiation.

Keywords: Chondrule heating events; Semarkona chondrule; Pyroxene overgrowths in chondrules; Oscillatory zoning

* Corresponding author at: Institute of Geophysics and Planetary Physics and Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA.

E-mail address: jtwasson@ucla.edu (J.T. Wasson).

[1] Now at NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

http://dx.doi.org/10.1016/j.gca.2017.05.013

0016-7037/

1. INTRODUCTION

It has long been recognized that different components of chondrules such as relict grains, igneous rims, and secondary members of compound chondrules provide strong evidence that chondrules record successive melting events (e.g., Jones, 1996a; Rubin, 2010; Wasson et al., 1995). In this study we characterize features on low-Ca pyroxene phenocrysts that we interpret as recording evidence of repeated heating events that occurred inside the primary (spheroidal, extensively melted) chondrule under closed-system conditions.

There is a widespread view that coarse chondrule phenocrysts formed almost entirely via fractional crystallization during cooling following the primary heating event, i.e., the event that led to extensive melting and the characteristic spheroidal shapes of chondrules (e.g., Lofgren, 1989; Jones, 1990, 1994). An alternative is that mafic silicate phenocrysts grew incrementally, i.e., that most growth layers following melting events are small, $\lesssim 15$ μm in thickness (this study). To test these views, we have studied chondrules in the Semarkona LL3.00 chondrite; this highly primitive meteorite provides a well-preserved record of the nebular processes that formed chondrules.

Wasson et al. (2014) reported that a low-Ca pyroxene phenocryst in a Semarkona chondrule exhibits numerous dark-light zones evident in back-scattered electron (BSE) images. We interpret the compositional profiles across these bands as stacked overgrowth layers (e.g., Baecker et al., 2015); a cartoon of ideal profiles is shown in Fig. 1. Similar overgrowths on low-Ca pyroxene had been reported earlier by Watanabe et al. (1986), Jones (1996b) and Wasson et al. (2003). These studies stimulated us to obtain more-detailed data and compare the observed compositional profiles to those predicted by a simple overgrowth model. We also compared the low-Ca pyroxene profiles to those of olivine phenocrysts in the same chondrules.

Estimated cooling rates recorded in chondrules are rapid; at crystallization temperatures, these estimates range from $\sim 10^2$ K s^{-1} (Wasson and Rubin, 2003) to 10^{-1} K s^{-1} (e.g., Hewins et al., 2005; Jones, 1996b). There have been suggestions (e.g., Jones, 1996b) that the observed overgrowth layers on the pyroxene phenocrysts formed by a process analogous to the one that produced "oscillatory zoning" in some igneous rocks (i.e., where the concentrations of specific elements rhythmically increase and decrease across the grains).

2. EXPERIMENTAL PROCEDURES

Thin section AMNH 4128-2 of the Semarkona meteorite (surface area of 125 mm^2) from the American Museum of Natural History was examined microscopically in transmitted and reflected light and by back-scattered electron (BSE) imaging. We superimposed a millimeter grid on a BSE mosaic image of the section; the image is shown in the online materials (Fig. O-1). Chondrules were assigned names based on their location. An upper-case letter and number give the grid square coordinates and a lower-case letter shows the position on a 5×5 subgrid within the square where the upper row begins with **a** and ends with **e**. Each chondrule was described as low- or high-FeO; we defined high FeO to be Fa ≥ 4 mol% in olivine; if olivine was rare or absent, we used the same criterion for Fs in low-Ca pyroxene. Apparent chondrule diameters were defined to be the mean of the long axis and the largest dimension perpendicular to the long axis.

We identified a total of 73 porphyritic chondrules (8 porphyritic pyroxene—PP, 22 porphyritic olivine—PO, 43 porphyritic olivine-pyroxene—POP) larger than 350 μm in apparent diameter in the Semarkona thin section. Five high-FeO chondrules (i.e., ~10% of PP and POP chondrules) contain pyroxene phenocrysts that display prominent multiple overgrowth layers: B4v (PP), B7s (PP), D9v (POP), E3o (POP) and E4m (POP). Properties of these five chondrules are listed in Table 1.

Detailed BSE images of chondrules were made with a TESCAN VEGA 3 scanning electron microscope (SEM) using a 20 keV acceleration voltage and a working distance of ~17 mm as well as with a JEOL JXA-8200 electron microprobe (EMP) using an acceleration voltage of 15 keV and a working distance of ~11 mm (both instruments at UCLA).

Low-Ca pyroxene, Ca-pyroxene, olivine and mesostasis compositions were determined with the microprobe using natural and synthetic standards, an acceleration voltage of 15 keV, a 15 nA sample current, and counting times for Mg, Si and Cr ranging from 20 s in our initial work to 40 s in our later work. ZAF corrections were applied; Ca was analyzed using a high-efficiency PETH detector. Minerals were analyzed using a focused beam; to reduce alkali loss, mesostasis was analyzed with a 5-μm-diameter beam. Compositional zoning profiles across olivine and pyroxene grains were made with the microprobe using a 1-μm-diameter electron beam and spacings of 1.5–2 μm.

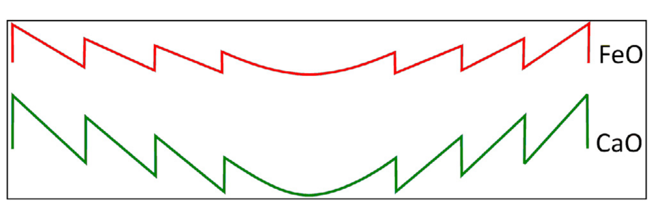

Fig. 1. Cartoon showing compositional trends expected in a series of overgrowth layers crystallizing away from a small central nucleus in low-Ca pyroxene. The amount of melt associated with each overgrowth layer is assumed to be approximately the same. The CaO gradients are higher than those for FeO.