IDENTIFICATION OF RELICT FORSTERITE GRAINS IN FORSTERITE-RICH CHONDRULES USING CATHODOLUMINESCENCE. R. H. Jones and E. R. Carey, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131. E-mail: rjones@unm.edu.

Introduction: Many chondrules clearly contain relict grains that result from incomplete melting of precursor material. Most discussions of relict grains have focused on grains that are easy to identify because they have compositions significantly different from their host chondrules, including forsterite in type II chondrules and dusty olivine in type I chondrules [1]. However, in order to fully understand the extent of chondrule recycling as well as the extent of melting during chondrule formation, it is necessary to be able to determine whether relict grains with compositions *similar* to those of the host chondrule are also present. Recent studies by Wasson and Rubin [2] have argued that such grains are common in type II chondrules, although this has been disputed [3]. Here we address the problem of how to identify relict forsterite grains in forsterite-rich chondrules. We report the results of a study of forsterite in type I chondrules in which we used cathodoluminescence (CL) to help identify grains that are distinguishable from host chondrule grains.

Technique: We studied eight chondrules that had been separated from the Mokoia CV3 chondrite [4]. All of these are type I porphyritic chondrules that contain olivine with Fa <1 mole%: higher Fa contents quench CL. We carried out CL surveys of each chondrule as well as electron microprobe analysis of selected grains. Our CL observations are limited to intensity variations; we have no spectral information.

Results: Before we can identify relicts we need to understand the nature of CL variations in all grains. The CL distribution in individual forsterite grains in type I chondrules varies significantly. CL intensity is largely controlled by the concentrations of Al and Ti, and essentially maps the Al, Ti distribution in individual grains [5,6]. Al and Ti are frequently decoupled from Ca.

Variations in CL distribution. We interpret CL distribution patterns as follows [7]: 1) homogeneous CL intensity across a grain results from chemical equilibration during chondrule formation; 2) smooth decreases in CL intensity from cores to edges of grains, common in Al-rich chondrules, probably result from open system fractional condensation (OSFC) [6, 8]; 3) oscillations in CL intensity from cores to edges of grains can be the result of either disequilibrium during growth or episodic overgrowths onto relict grains; 4) heterogeneous CL distributions with randomly distributed patches of bright intensity are the result of disequilibrium growth from melts.

Within individual chondrules, most forsterite grains show similar types of CL distribution. Using CL mapping, we were able to identify grains that had significantly different CL properties from most other host chondrule grains.

Compositional variations. We measured compositional profiles across individual forsterite grains, including those grains that we considered to be potential relict grains (Fig. 1). Variation plots of CaO vs Al_2O_3 are useful for discriminating between the different CL distribution types.

An example of a chondrule with relict grains. We use chondrule 10C as an example to illustrate how we can identify relict grains (Fig. 2). Most forsterite grains in chondrule 10C show heterogeneous zoning that we attribute to disequilibrium growth (Fig. 2b). However, two grains have cores that are smoothly zoned, with CaO and Al_2O_3 decreasing away from the core. Both of these cores are overgrown with two successive zones, so that the entire grain shows oscillations in CL intensity that are concentric about the core (Fig. 2b). Chemical compositions of the cores show that they are similar to grains that formed by OSFC. On a CaO vs. Al_2O_3 plot (Fig. 1), the grains stand out as having significantly different characteristics to the heterogeneous grains. We infer that these grains are relicts. Their chemical compositions differ from each other sufficiently for us to be able to infer that they may have originated in separate chondrules before being incorporated into the precursor assemblage of their current chondrule host.

The relict grains identified in this way would not have been identified by examination of BSE images, or even random analyses of individual grains, because their chemical compositions are very similar to melt-grown grains in the host chondrule. Cathodoluminescence mapping was an essential tool to arrive at the conclusion that there appear to be two relict grains in the section of chondrule 10C that we examined.

Discussion: Using the technique outlined above, we examined eight chondrules in order to assess the abundance of relict grains with compositions similar to the host chondrules.

Two chondrules showed homogeneous CL intensity in every forsterite grain, with no evidence for relicts. These chondrules appear to be well equilibrated. A further two chondrules showed heterogeneous CL intensity in all grains, which we interpret as disequilibrium growth, and also no evidence for relicts. One chondrule, which is Al-rich, showed smoothly decreasing CL intensity in every forsterite grain, and no evidence for relicts.

Three chondrules (including 10C described above) showed heterogeneous zoning in most grains, but included grains that we infer to be relicts. Two to three relict grains are observed in the random sections through each of the chondrules we examined.

Wasson and Rubin [2] have proposed that chondrules are the product of multiple short heating episodes. Although we have identified several grains with oscillatory zoning, the grains in which we see evidence for episodic overgrowth onto a relict core are unusual. Fine-scale oscillatory zoning described by Steele [5] can be explained by disequilibrium growth and interface kinetics. Disequilibrium growth and chemical heterogeneity are common features of forsterite in type I chondrules. We do not see overwhelming evidence for multiple successive overgrowths that might arise from multiple episodes of chondrule heating.

Conclusion: Overall, our conclusion is that relict forsterite can indeed be identified in forsterite-rich chondrules. Relict forsterite grains are common in forsterite-rich type I chondrules, but not ubiquitous. Cathodoluminescence mapping was an important tool in our study that enabled us to map the Al distribution in forsterite grains. Al distribution is a sensitive indicator of the degree of equilibrium during chondrule cooling, and hence the thermal history of chondrule formation.

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References: [1] Jones R. H. (1996) In *Chondrules and the Protoplanetary Disk*, eds. Hewins et al., 163-172 . [2] Wasson J. T. and Rubin A. E. (2003) *GCA 67*, 2239-2250. [3] Hewins et al. (2005) In *Chondrites and the Protoplanetary Disk*, eds. Krot et al., 286-316. [4] Jones et al. (2004) *GCA 68*, 3423-3438. [5] Steele I. M. (1995) *Am. Min. 80*, 823-832. [6] Pack A. and Palme H. (2003) *MAPS 38*, 1263-1281. [7] Jones R. H. and Carey E. R. (2006) *Am. Min.*, in press. [8] Pack A. et al. (2004) *GCA 68*, 1135-1157.

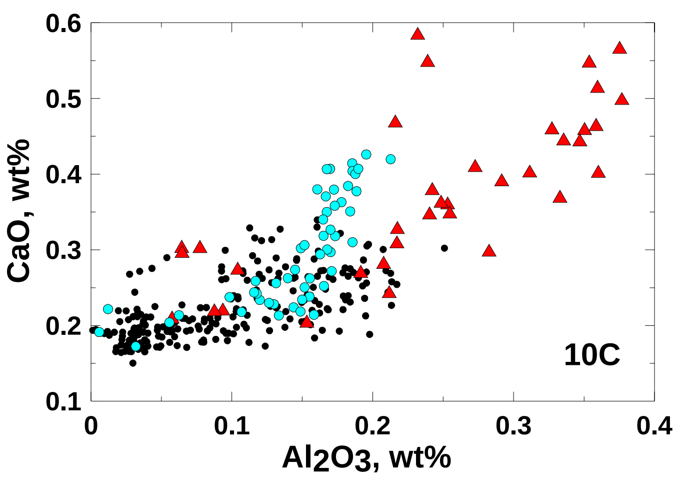

Fig. 1. Electron microprobe traverses from cores to edges of forsterite grains in chondrule 10C. Black dots are several grains that show heterogeneous CL distributions. CaO and Al_2O_3 contents are generally decoupled in these grains. Two relict grains are shown as blue circles and red triangles. Both of these grains have core regions in which CL intensity decreases smoothly away from the core, in which CaO and Al_2O_3 are strongly correlated.

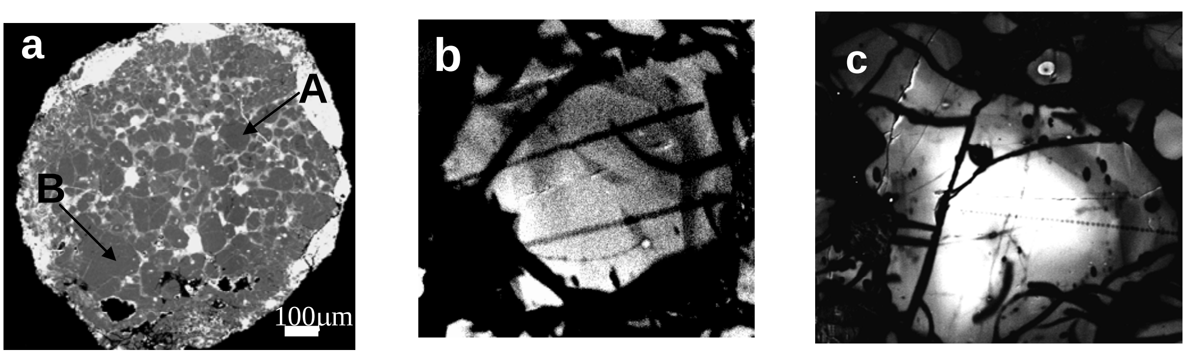

Fig. 2. CL variations in chondrule 10C. a) Back-scattered electron image of the PO chondrule. b) CL image of grain labeled A, which shows heterogeneous CL distribution. Most grains in the chondrule have similar CL. c) CL image of grain labeled B, which shows a smoothly zoned core region and concentric overgrowths. Compositions are shown with red triangles in Fig. 1. The core of this grain is interpreted to be a relict.