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Evidence for accretion of fine-grained rims in a turbulent nebula for CM Murchison

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A B S T R A C T

We use X-ray computed tomography (XCT) to examine the 3D morphology and spatial relationship of fine-grained rims (FGRs) of Type I chondrules in the CM carbonaceous chondrite Murchison to investigate the formation setting (nebular vs. parent body) of the FGRs. We quantify the sizes, shapes, and orientations of the chondrules and FGRs and develop a new algorithm to examine the 3D variation of FGR thickness around each chondrule. We find that the average proportion of chondrule volume contained in the rim for Murchison chondrules is 35.9%. The FGR volume in relation to the interior chondrule radius is well described by a power law function as proposed for accretion of FGRs in a weakly turbulent nebula by Cuzzi (2004). The power law exponent indicates that the rimmed chondrules behaved as Stokes number $St_\eta > 1$ nebular particles in Kolmogorov η scale turbulence. FGR composition as inferred from XCT number appears essentially uniform across interior chondrule types and compositions, making formation by chondrule alteration unlikely. We determine that the FGRs were compressed by the impact event(s) that deformed Murchison (Hanna et al., 2015), resulting in rims that are thicker in the plane of foliation but that still preserve their nebular morphological signature. Finally, we propose that the irregular shape of some chondrules in Murchison is a primary feature resulting from chondrule formation and that chondrules with a high degree of surface roughness accreted a relatively larger amount of nebular dust compared to smoother chondrules.

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1. Introduction

Fine-grained rims (FGRs) are dust-sized material that surrounds chondrules and refractory inclusions in chondritic meteorites and are usually distinguishable from the matrix in optical and scanning electron microscopy images on the basis of their differing texture and/or composition (Lauretta et al., 2006). Among the different chondrite groups FGR characteristics differ, most notably in that the carbonaceous chondrites have significantly thicker rims compared to the ordinary chondrites and contain hydrated phases (e.g., serpentines, smectites) (Metzler and Bischoff, 1996; Zolensky et al., 1993). Among the carbonaceous chondrites CMs contain the thickest, most visible FGRs and have been the most extensively studied (e.g., Metzler and Bischoff, 1996; Metzler et al., 1992; Trigo-Rodriguez et al., 2006). In some CM chondrites, FGRs surround all macroscopic components and dominate the proportion of fine-grained material in the rock with only minor interstitial matrix; chondrites with this texture have been termed "primary accretionary rock" (Metzler et al., 1992).

The origin of FGRs in CMs is debated and formation in both nebular (Brearley et al., 1999; Bunch and Chang, 1984; Greshake et al., 2005; Hua et al., 2002; Metzler et al., 1992; Zega and Buseck, 2003) and parent body (Sears et al., 1993; Takayama and Tomeoka, 2012; Trigo-Rodriguez et al., 2006) settings have been proposed (Fig. 1). Nebular FGR formation involves accretion of unequilibrated nebular dust to chondrule surfaces (e.g., Metzler et al., 1992). Mechanisms of FGR formation in a parent body setting include: 1) formation in the parent body regolith through attachment and/or compaction of fine-grained material onto the chondrule surface (Sears et al., 1993; Takayama and Tomeoka, 2012; Trigo-Rodriguez et al., 2006) and 2) formation via aqueous alteration of the chondrule (Sears et al., 1993; Takayama and Tomeoka, 2012). Evidence cited for nebular formation includes hydrated phases in the rim in direct contact with chondrule glass (Metzler et al., 1992) and sedimentary rim textures such as layering and grain-size coarsening (Brearley et al., 1999). Parent body formation evidence includes embayment textures along the chondrule/rim boundary indicating that areas of the rim formed through alteration of the chondrule (Takayama and Tomeoka, 2012) and low rim porosity compared to the matrix which may have arisen due

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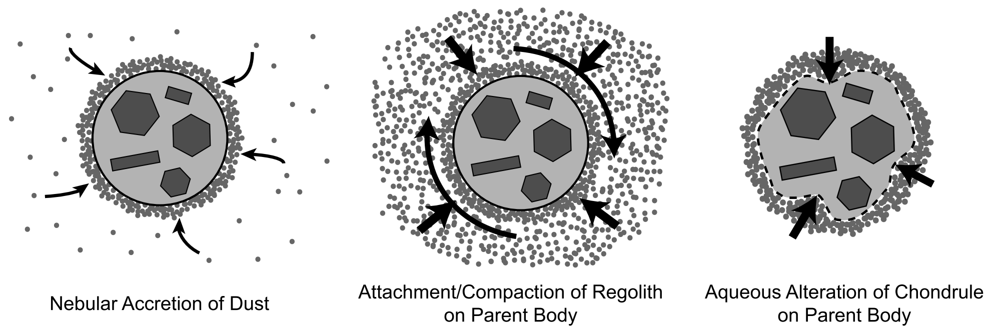

Fig. 1. Three proposed formation scenarios for FGRs in CM chondrites.

to preferential compaction of material next to the chondrules (Trigo-Rodriguez et al., 2006).

Another observation taken as evidence for nebular formation of FGRs in CMs is a positive correlation between rim thickness and the size of the interior chondrule (Greshake et al., 2005; Metzler et al., 1992). Conversely, Trigo-Rodriguez et al. (2006) did not find strong evidence for a such a correlation and argued that this was evidence against nebular formation and instead proposed parent body formation. All of these studies used uncorrected 2D thin section measurements, which give only apparent chondrule size and rim thickness unless the appropriate measurement corrections are applied (e.g., Sahagian and Proussevitch, 1998). Another complicating factor is that many CMs show evidence of deformation that has altered the shape of the chondrules and their rims (Hanna et al., 2015; Lindgren et al., 2015; Rubin, 2012; Zolensky et al., 1997). Although astrophysical arguments have been made for the positive linear correlation between rim thickness and interior chondrule radius (Morfill et al., 1998), subsequent refinements hypothesize that dust accretion around chondrules results in a power law relationship between the FGR volume and interior chondrule radius that in turn provides information on nebular turbulence conditions (Cuzzi, 2004; Cuzzi and Hogan, 2003).

Accurate measurement of FGR thickness and volume requires three-dimensional (3D) data of the chondrules and their rims. X-ray computed tomography (XCT) allows non-destructive measurement of textures and components in situ and preserves their 3D spatial context (e.g., Hanna and Ketcham, 2017; Ketcham and Carlson, 2001). This is particularly important for CM chondrites that have undergone deformation resulting in a petrofabric (e.g., Rubin, 2012). Previous XCT studies have found a moderately strong foliation and a weak lineation in Murchison due to impact(s) (Hanna et al., 2015; Lindgren et al., 2015), which also resulted in aqueous alteration of the chondrules (Hanna et al., 2015). If CM FGRs are produced via aqueous alteration on the parent body, we may see evidence for it in the form of greater FGR volume with increased degree of chondrule alteration.

This study examines the 3D morphology of FGRs in a sample of Murchison for which we have previously documented impact-induced deformation and aqueous alteration (Hanna et al., 2015). Using 3D measurement of the FGRs, we look for evidence of FGR deformation that may have occurred during the impact(s) such as compaction of the rims. In addition to documenting any post-accretional deformation, we determine if there is a positive correlation between the thickness or volume of the rim and the size of the interior chondrule as predicted for nebular FGR formation and whether the nebular environment was laminar or turbulent based on FGR/chondrule size relationships (Cuzzi, 2004; Morfill et al., 1998). We also look for evidence for parent body FGR formation via aqueous alteration that may have occurred after the chondrules accreted to the CM parent body.

2. Analytical methods

2.1. X-ray computed tomography

We imaged six small chips (0.143–3.63 g; some embedded in epoxy) from the Murchison USNM 5487 sample that was previously measured by Hanna et al. (2015) with X-ray computed tomography (XCT) at the University of Texas High-Resolution X-ray Computed Tomography Facility (UTCT) (Table 1). XCT produces a 3D data set of the X-ray attenuation of an object; values are referred to as XCT numbers and are mapped to grayscale values for viewing. Because X-ray attenuation is a function of a material's atomic number and density, the relative XCT numbers are a proxy for different compositions within the sample. In a typical XCT image, the lowest XCT numbers (darkest grayscales) represent the least X-ray attenuating materials while relatively higher XCT numbers (brighter grayscales) are materials that are relatively more attenuating.

Samples were imaged on two XCT systems at varying data resolutions (5.5 to 9.9 μm) to provide a statistically significant number of measurable chondrules at a range of sizes (Table 1). Relatively low energies (70–90 kV) were used to enhance the contrast between iron-bearing phases and helped to more clearly distinguish the rims that are lower in iron content than the surrounding matrix (Section 3.1). The first sample is an unlabeled chip of the USNM 5487 main mass scanned twice on an Xradia (now Zeiss) microXCT 400 system using a 0.35 mm SiO_2 filter to reduce beam-hardening artifacts. For the first scan (Chip A) the chip was imaged in two parts and the image stacks combined. The final reconstructed voxel size was 5.50 μm. The second scan (Chip A_HR) targeted a subvolume of the sample at higher resolution (3.00 μm) to investigate the different object types and their accompanying FGRs in more detail. To measure additional larger chondrules (≥300 μm in radius), two more individual scans of five larger-mass samples were done on the North Star Imaging (NSI) scanner, using a Fein-Focus FXE X-ray source with no filter and a Perkin Elmer 16" 2048 × 2048 detector. The first NSI scan imaged samples 5487-3-3 and 5487-3-6 with a voxel size of 9.49 μm (Chips 3-3 and 3-6) and the second imaged 5487-1, 5487-3-1, and 5487-3-5 at 9.99 μm resolution (Chips 1, 3-1, and 3-5).

2.2. XCT measurement of chondrules and FGRs

Chondrules within the six XCT datasets were manually segmented using Avizo™ software. Each chondrule was segmented twice, with and without FGR. Specifically, we used the brush tool to outline the exterior of the chondrule and then used the fill command to complete the segmentation. This was done for every other XCT slice across the chondrule in one orthogonal plane (segmentation plane varied across chondrules to minimize systematic measurement bias) and then the interpolate tool was used

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