METHODS FOR DIRECT MEASUREMENT OF CHONDRULE SIZE, MORPHOLOGY AND DENSITY.

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Introduction: How big are the chondrules in any particular meteorite or meteorite class? This has been an ongoing problem in meteoritics [1-2 and refs. therein; 3, 4]. Size, morphology and density information are all critical factors in describing aerodynamic sorting within a disk of dust and particles that eventually forms rocky bodies [5-9]. Of these physical parameters, size and density are most important [10], as is the shape of the chondrule size distribution curve [4, 11]. Furthermore, the packing of chondrules in ordinary chondrites may yield insights into the accretion process [12]. The physical properties of chondrules and their type distributions in particular meteorite classes allow constraints to be placed on chondrule-forming processes [13, 14], beyond those inferred from their chemical and isotopic compositions alone.

It is generally accepted that Semarkona chondrules are, on average, 1mm in diameter [1, 15-17]. Chondrule sizes have been primarily determined by 2D thin section analysis [e.g., 1, 18-21], or by physical measurement of separated chondrules [e.g., 1, 22-23]. However, the question remains: How accurately do 2D sections represent 3D size distributions? This has been addressed theoretically by [24-27], but such corrections are not consistently applied. Furthermore, preserving chondrules during meteorite disaggregation is only feasible for a few friable chondrites (e.g. Bjurbole and Saratov).

We seek to understand the true, three-dimensional size and morphology of chondrules in primitive ordinary chondrites and extend our understanding of successful techniques to other chondrites.

Data: Semarkona is an LL (low metal, low reduced metal), highly primitive (petrologic grade 3.00 [28]) ordinary chondrite. A parallelepiped sub-sample of Semarkona [29] was imaged by synchrotron x-ray microtomography (μCT). The outlined sub-volume (136 mm^3, 8 x 8.5 x 2 mm) consists of individual virtual slices 17μm thick, in 17x17 μm pixels. About 2.5 mm of the same 6 mm thick volume has been physically sliced (serially) with a 30 μm wire saw to reveal five surfaces that are subparallel to tomographic image planes. These thick sections were polished and mapped on both sides for element x-ray emission intensity (Mg, Ni, Ti, Al, Ca WDS; S, Si, Fe EDS) on an electron microprobe at 6 or 8 μm/pixel resolution.

Methods: Several methods are available for solving parts of the chondrule volume, morphology and density problem. These include:

Method #1: Whole rock CT imaging, segmentation of chondrules in images, and image analysis [e.g., 3, 29-31].

Method #2: Physical separation, CT or microscopic scanning of individual chondrules, and high-resolution mass determination.

Method #3: Surface (2D) mapping, 2D segmentation (outlining) of chondrules, and image analysis [e.g. 28; 32-35].

Each of these methods has drawbacks. We have discovered that method #1 is extremely laborious since individual chondrules have variable X-ray attenuations and therefore thresholding techniques used in separating metal grains in CT images of chondrites are not applicable [36]. Moreover, this method depends upon the development of image handling tools not yet available in any integrated software package. We are, therefore, developing these tools as we apply method #1 to the Semarkona data.

Method #2 requires independent imaging of each chondrule in a high resolution instrument (SEM, XR-CMT), followed by image analysis for size (volume) and morphology. Tomography allows volume determination to a high degree of accuracy, and also yields complete external morphology [12]. It also allows identification of adhering matrix in most cases. SEM imaging requires more complex image analysis to obtain accurate volume data. A high-precision microbalance is necessary to combine mass with volume data to obtain meaningful density measurements. Care must be taken that adhering matrix is removed from chondrules. Furthermore, size selectivity of disaggregation and survival may bias results toward more robust and/or larger chondrule types.

Method #3 is perhaps the most straightforward. This method is, however, dependent on the assumption that the distribution of chondrules follows a logarithmic or other model statistical pattern [27, 35], inherent in algorithms for the correction of 2D results for 3D effects due to non-equatorial sectioning [e.g., 25]. Furthermore, correction must also be made for oversampling of larger chondrules [25]. It is the latter effect that results in the common perception that LL chondrite chondrules average 1mm in diameter. Our

preliminary analysis of Semarkona using methods #1 and #3 does not accord with this perception.

We are pursuing methods #1 and #2 on the single piece of Semarkona described above. Preliminary results reveal more than 100 entire (complete) chondrules in a 2.0mm thick 'virtual' volume 8.5 x 8.0 mm (136 mm^3). These statistics will be compared with size distributions obtained using method #3, to test the applicability of 2D correction algorithms [25-27] for various segments of the same Semarkona sample.

Discussion: Method #1 will yield data useful for characterizing the packing efficiency of chondrules in Semarkona. Method #3 in combination with #1 allows verification in detail of the outlines created for each chondrule in the tomography data images that correspond most closely to the imaged 2D thick sections.

All three methods allow determination of chondrule density, but to different degrees of accuracy. The metal/silicate ratio in segmented tomography data (method #1), and in outlined 2D x-ray maps (method #3), can be tabulated for each chondrule using custom software and used to estimate chondrule mass. However, direct measurement of mass is clearly superior

Conclusion: Chondrules can be measured using method #1 by digitally outlining 2D slices of 3D tomography data and layering the vertical slices to makeup the third dimension. Although this technique is laborious, it yields 3D volume measurements of individual chondrules not dependent on correction models nor subjected to the hazards of disaggregation. Furthermore, the outlining process can be completed with no prior first-hand knowledge of the sample.

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