A 3-D Tomographic Survey of Compound Chondrules in Two Carbonaceous Chondrites: Acfer 139 and Renazzo

by

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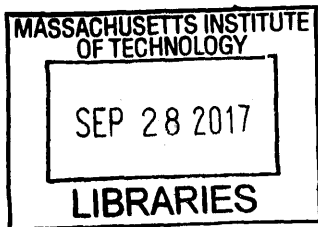
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ABSTRACT

Compound chondrules (CCs) are two or more chondrules fused or mechanically joined together. Studies of compound chondrules have been conducted in order to understand the chondrule formation process, including the environment and precursor materials. Chondrule formation is still not currently understood and much doubt still remains as to whether the chondrule formation process is nebular and/or planetary However, our evidence suggests that a primary and secondary process are responsible for CCs: (1) semi-molten collisions among individual (I) chondrules (Gooding and Keil, 1981) and (2) Parent-body impacts that cause jostling, fracturing and compaction (Wasson et al., 1995). By understanding chondrule collisions and impacts we can gain greater knowledge into what was happening during early solar system formation, including mean interparticle distances and velocities (Gooding and Keil, 1981).

This thesis introduces x-ray tomography as a new method of measuring and surveying CCs; and explores the advantages and limitations of this method. A 3-D tomographic study of two CR carbonaceous meteorites, Acfer139 and Renazzo, reveals a higher frequency of compound chondrules in CR chondrites than in ordinary chondrites. Previous two-dimensional studies of compound chondrules are reexamined and two new categories, touching and aggregate compounds, are also introduced. Our reexamination suggests a 9.6% frequency of compound chondrules (excluding the new categories), twice more than the value of 4% found by Gooding and Keil (1981) and almost 4 times the value of 2.4% found by Wasson et al. (1995) in their studies of ordinary chondrites. The implications of a higher compound chondrule frequency on chondrule formation are also examined.

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CONTENTS

1. INTRODUCTION

1.1.   Chondrules and Chondrites

Chondrules, which make up the bulk of meteoritic material, are small, spherical iron-magnesium silicate and/or iron-metal aggregates that are thought to be among the earliest formed solids in the solar system. Textural clues imply that chondrules were once molten droplets, which in turn led to the accretion of the inner planets. There are three main types of chondrule bearing meteorites (chondrites): ordinary (OCs, most common and mostly comprised of olivine and orthopyroxene.), enstatite (ECs, rarest and mostly iron-free pyroxene), and carbonaceous chondrites (CBCs, rare and mostly composed of olivine, serpentine, and carbon). Each category is subdivided into: H, L, and LL (OCs) based on their Fe percentage and metal content; EH and EL (ECs) based on their total Fe percentage; CI (Ivuna), CM (Murray), CV (Vigarano), CO (Ornans), CR (Renazzo), CK (Karoonda), and CH (High metal) (CBCs) based on different meteorite types.

The focus of this study was the CR (Renazzo-like) carbonaceous chondrites. According to Wiesberg (1992), the characteristics include: (1) large, multilayered, iron-nickel rich chondrules, (2) abundant matrix and dark inclusions, (3) serpentine- and chlorite-rich phyllosilicates and Ca-carbonates, (4) calcium-carbonate chondrule rims, (5) abundant iron, nickel metal, (6) rare refractory inclusions, (7) amoeboid olivine aggregates. In addition, CRs have (8) unique oxygen isotope compositions. For our study, features (1), (2), and (4) turned out to be very useful for identifying chondrules in our tomography data.

1.2. Models of Chondrule Formation.

The understanding of chondrule formation has eluded many. Currently no chondrule formation model is universally accepted because they all have aspects that make them a plausible model and aspects that preclude them from being a plausible model. With that said, three likely candidates for chondrule formation include (Boss, 1996):

(1) Lightning in the solar nebula: Large dustballs collide with smaller dust grains as they fall into the center of the nebula. This creates a large charge separation that induces lightning, which, in turn melts the dustballs. The drawbacks of this model include uncertainty in the physical feasibility of lightning in the solar nebula and short heating time scales.

(2) Shock waves in the solar nebula: Shock waves (front of hot, compressed gas) melt chondrules. Behind the shock wave, pressure density and temperature increase. Particles are heated through friction with the post-shock gas. Drawbacks of this model include short heating pulses and uncertainty around the method of shock production.

(3) X-winds associated with the young sun: Chondrules are heated by solar flares. Interactions between the nebular disk and the young sun produce X-winds that are actually observed. Material is then launched from the disk by the x-winds and melted by the sun. Drawbacks to the x-wind model include cooling rates that are too slow for chondrule formation and incapacity to explain multiple heating events.

2. PREVIOUS WORK

To date, there are only four extensive studies of compound chondrules- Gooding (1979), Lux et al. (1981), Gooding and Keil (1981), and Wasson et al. (1995), all of which were exclusively carried out using ordinary chondrites. Gooding (1979) separated 216 whole chondrules from type-3 and type-4, the least altered, ordinary chondrites and found that 4% of the chondrules were compound. Lux et al. (1981) analyzed 32 chondrules and determined that approximately 81% had similar textures and compositions. Gooding and Keil (1981) examined over 1600 chondrules and found that 1.4% of these were compound. Wasson et al. (1995) found eighty-three compound chondrules in his study of seventy-nine ordinary chondrite thin sections and found a value in accordance with Gooding and Keil of 1.4%. Incidentally, Wasson et al. (1995) suggested that further studies are warranted of "tiny adhesions [which] demonstrate that tiny chondrule-like bodies of melt (i.e. microchondrules) were produced in the chondrule-forming process". These "microchondrules" were examined further using x-ray tomography and found to be an important addition to compound chondrule types.

Extensive studies of compound chondrule have been primarily limited to two-dimensional thin sections. However, this reliable method precludes accuracy with regard to frequency and type. Given that the frequency of occurrence and the types of chondrules are important in various chondrule and early solar system formation models, it is important to get a better constraint on parameters such as diameter, frequency of occurrence, and textural classes. Three-dimensional tomographic analysis has proved to be a better tool for accurate measurements of these parameters.

3. METHODS

3.1. X-Ray Tomography (XRT)

X-ray tomographic images of two CR chondrite samples (Figure 1), Acfer139 (two 3 x 4 x 19 mm pieces) and Renazzo (two 5 x 6.5 x 11.5 mm pieces), were obtained using the Advanced Photon Source synchrotron radiation facility at the Argonne National Laboratory in Illinois. These images where supplied by Denton Ebel, a curator of meteorites at the American Museum of Natural History in New York.
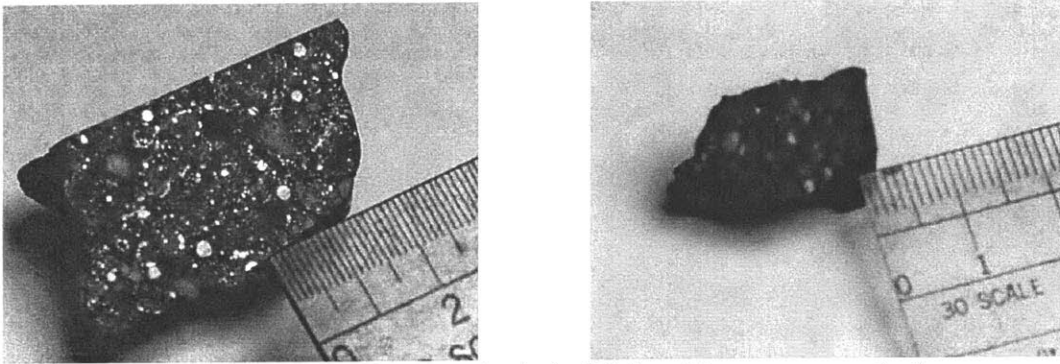

Figure 1: CR chondrite samples Acfer139-1 and Renazzo, respectively.

An XRT image is obtained by placing the sample in a synchrotron x-ray source beam while the sample is rotated through 180 degrees in 0.25-degree increments. Meanwhile, a photosensitive CCD camera detects the x-rays over a 16-bit range that corresponds to 65536 gray values (Figure 2). The image is similar to a CAT scan. The
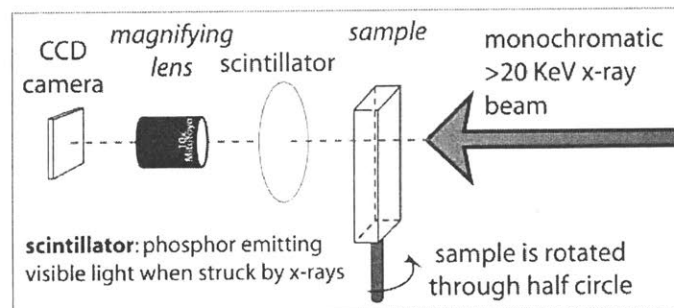

Figure 2: Schematic of a sample placed in the beam of a synchrotron x-ray source.

brightness correlates strongly with the mass density variation in the meteorite; the brightest objects are the densest (i.e. metals), and the darker objects are the least dense (i.e. chondrules). The gray area that comprises most of the image is called the matrix, which consists of very small mineral grains and fragments.

A Fast Fourier Transform algorithm is applied to reconstruct the density model of the sample. The result is a datafile that contains a 3-dimensional array of volume elements (voxels), each of which has a unique value that resembles the x-ray attenuation by that voxel. The resulting datafile is then converted into stacks of tiff images correlated to the x, y, and z directions (Figure 3) using IDL, visual data-analysis software.
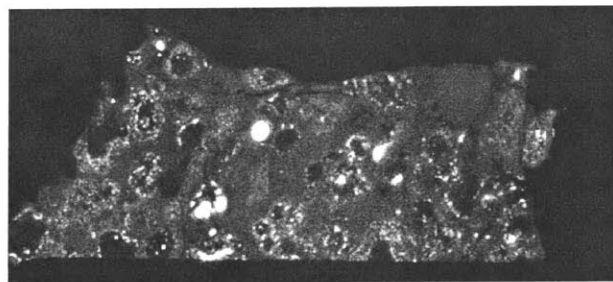

Figure 3: Tomographic image 300 out of 486 of Renazzo sample in the y-z-direction.

During tomographic sample preparation, the Acfer139 samples were cut adjacent to each other, while the Renazzo sample was not due to its irregular shape. The thick sections where cut prior to tomographic analysis in order to expose the maximum 3-D the surface area while remaining within the size restrictions of the synchrotron source.

3.2 Thick Section Analysis

Following tomographic analysis, each sample was mounted on a glass slide and cut into multiple slices (Figure 4a-b) using a 30-micron precision wire saw, which was

coated with boron carbide in an oil slurry. Each slice was then diamond polished to eliminate contamination. In total, four thick sections of Renazzo and five thick sections of Acfer139 were prepared approximately 0.5 mm thick. After preparation, each slice was analyzed using a 2-D technique with the Cameca SX-100 electron microprobe at the American Museum of Natural History (AMNH). Back-scattered electron (BSE) images were created at a resolution of 4 μm/px (5 μm/px for Acfer139-1B) using a current of 20 nA and high voltage of 20 kV (Figure 4b). Unlike XRT images, BSE images only provide 2-D analysis. However, they allow one to see textures and impact "breaks" or fractures within and around the chondrules.

Thick sections were created, analyzed and compared with 3-D analyzed tomographic images. BSE maps of these sections were used to locate chondrules and identify which ones were CCs. The corresponding tomographic images were then located in the stack of tiff images. In each case, the frequency of CCs was significantly lower in the BSE images than in the tomographic images and in accordance with Gooding and Keil's (1981) CC occurrence of 1.4%. Digital images were also taken of the thick section samples and analyzed in the same manner as the BSE images. The CC frequency matched the BSE image CC frequency.
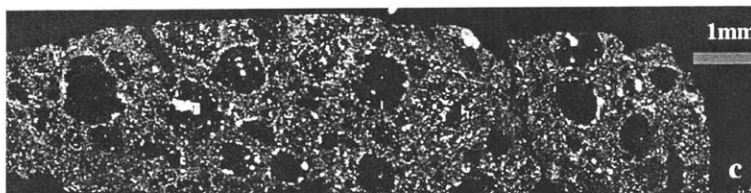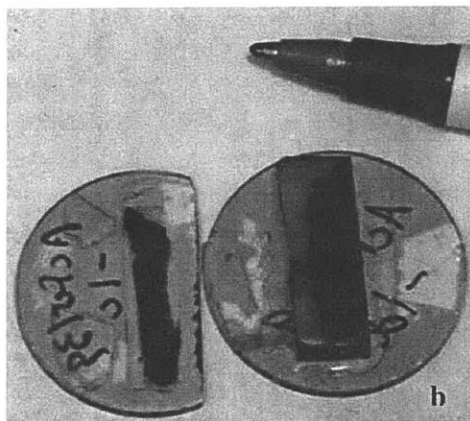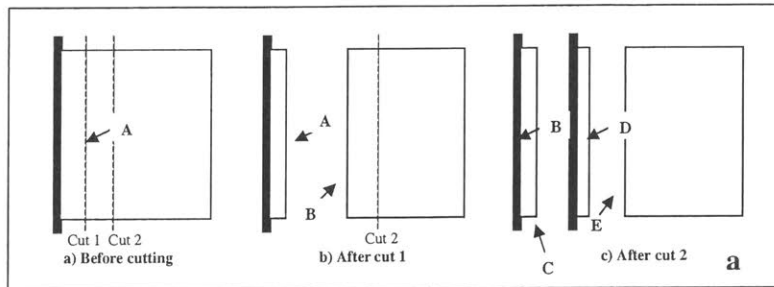
Figure 4: a) Sample thick section cutting method. Capital letters represent order of cutting and analysis. b) Carbon-coated polished thick sections of Acfer139-B and –C, on the left and right respectively. c) Back-scatted electron (BSE) image of Acfer139-2A.

3.3 Thin Section Analysis

To date, studies of compound chondrules have primarily been limited to two-dimensional thin sections. In 1981, Gooding and Keil examined over 1600 chondrules in thin sections and 216 whole chondrules removed from bulk meteorite samples. They found the frequency of compound chondrules to be 4%, based on an observed frequency

of 1.3%, multiplied by a factor of 3. This factor was used to correct for thin section bias, and was obtained by dividing the percent of whole compound chondrules found by the percent found in thin sections. In 1995, Wasson et al. surveyed over 10,000 chondrules in thin sections and found only 2.4% of their chondrules to be compound. This value was also obtained by multiplying the observed frequency by a correction factor of 3. It is assumed that the reason for this disparity lies in the fact that Wasson et al. (1995) included only whole chondrules in his calculation, and did not include chondrules less than 40 microns in diameter. Gooding and Keil (1981) included broken chondrules if they met the criteria for (1) being a chondrule and (2) had a boundary of more than 180 degrees of continuous arc (i.e. more than half of the chondrule was visible). In the 3-D tomographic data, our limiting size was 100 microns. Chondrules that were cut off, regardless of the degree of continuous arc, were not included in our study. Table 1 compares the result of two different chondrule studies. Wasson's study of chondrules is the most extensive to date and is the source of the accepted value for compound frequency.

Table 1: Comparison of thin section analysis

	Gooding & Keil (1981)	Wasson et al. (1995)
# of chondrules analyzed	>1600 in thin sections 216 whole chondrules	>10,000 in thin sections
Type	Ordinary	Ordinary
Factors	Included broken chondrules with >180 degrees in arc	Omitted chondrules less than 40 microns in diameter
Frequency of Compounds	4%	2.4%

3.4 *Classification of Chondrules*

3.4.1 *Chondrule Identification*

We worked with a stack of 8-bit tiff images normal to a particular axis of the tomography volume. In other words, we scanned though the third dimension and viewed the chondrite sample in 2-D. Each chondrule was assigned a number based on the order in which it was found and labeled on every tenth image (Figure 5). We used the program ImageJ for this work (http://rsb.info.nih.gov/ij/). We catalogued the chondrules in the 3D tomographic images for both sections of Acfer139 and both sections of Renazzo. Then, we developed the criteria for identifying chondrules in the images: (1) continuity of chondrule in two or more consecutive 2-D images, (2) a change in size over the two or more 2-D images, and (3) the presence of a distinct boundary between the dark chondrule interior and the background matrix. The reason for the first two criteria comes from the fact that there are minor flaws in the tomographic method. These lead to artefacts in the image, which don't change in size as we look through the 2-D slices and fail to appear in two or more consecutive images. Criterion # 3 was necessary because clear visibility was necessary for classification. Finally, we did not include any chondrules that were partially cut off in any image.
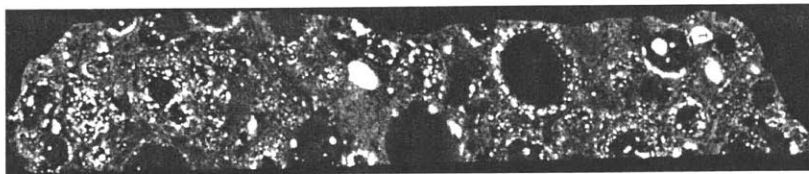

Figure 5: *Example of labeled tomography slice*

After identifying the chondrules, in ImageJ, an ellipse was visually fit to them where the chondrule appeared to have the largest area. From this fit we extracted the center of the

ellipse, its area, major and minor axes, and the angle between the major axis and the horizontal. For compound chondrules, we fit an ellipse to each component, if possible. For aggregate compound chondrules having more than four parts, we fit an ellipse to the entire aggregate.

3.4.2 Compound Chondrules (CCs)

The chondrules were separated into two main categories, individual (I) and compound. Individual chondrules are single chondrules that are not joined to any other chondrules nor compound with a chondrule that is cut off and therefore not included in our survey. Compound chondrules were then further divided into 4 subcategories— penetrating (P), touching (T), enveloping (E), and aggregates (A) (Figure 6).

a) P   b) T   c) E   d) A
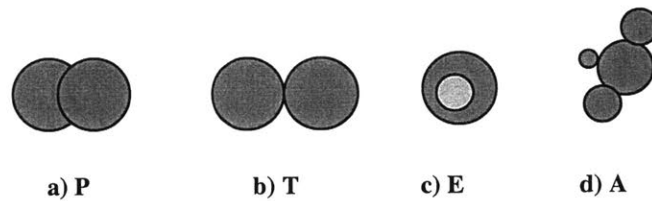
Figure 6: Compound types: a) Penetrating (P), b) Touching (T), c) Enveloping (E), d) Aggregates (A)

The latter two subcategories, penetrating and enveloping, are classified according to the published definition of Wasson et al. (1995). In this definition, penetrating compound chondrules consist of two or three chondrules joined together, where and one chondrule retains its original shape and the other conforms to the shape of the primary chondrule. Enveloping chondrules consist of one chondrule that is completely enclosed inside the other. However, Wasson et al. (1995) also divided penetrating compounds into 2 categories— adhering and consorting compounds. The two categories differ in that

consorting CCs consist of penetrating chondrules that are of similar size, while adhering

CCs differ widely in size. In our tomography data, and in polished thick sections, we

failed to find any instances of adhering CCs. Touching (50.9 % of all chondrules) and

aggregate (15.5% of all chondrules) CCs are new categories created after finding an

overwhelming number of examples in our tomography data. Touching CCs consist of two

or three chondrules mechanically joined together where each chondrule still appears to

retain its original shape. Aggregate CCs are deviants from touching CCs that consist of 4

or more chondrules mechanically joined together. Table 2 below shows the distribution

of compound chondrule types in our tomography data.

Table 2: Distribution of chondrule categories.

	Acfer139-1	Acfer139-2	Renazzo2	Total
T CCs	69	81	73	223
A CCs	28	24	16	68
P CCs	18	6	16	40
E CCs	2	0	0	2
I	25	32	48	105
Total	142	143	153	438

3.5.   *Exclusion of Touching and Aggregate Compounds*

We feel that there are several reasons that these types of compound chondrules

have been left out of previous studies. Gooding and Keil (1981) were primarily

concerned with chondrule types, and placed minimal focus on compound chondrules. It

does appear though, that their definition was broad enough to include touching CCs,

since they define CCs as those with attached or partially embedded chondrules. We assume this lower frequency of compounds to be a characteristic of ordinary chondrites. On the other hand, the exclusion of touching and aggregate CCs by Wasson et al. (1995) is very clear. Their criteria for CC identification are: (1) continuity of the shared border, (2) preservation of a circular arc on the primary chondrule, and (3) evidence that material was added subsequent to compound chondrule formation. Criterion (2) immediately excludes touching and aggregate CCs given that most of the points of contact are not circular arcs and most are flattened. Criterion (3) was added later after Wasson et al. (1995) believed they found instances of "ghost rims" or chondrules that appeared to be compound but were interpreted as remelted without the addition of mass. One section in Wasson et al.'s paper is of particular interest, however. Entitled **Distinguishing Compound Chondrules from Independent Chondrules which Share Congruent Surfaces,** this section mentions what we have identified as touching compounds. In this section, he also mentions findings by Holmen and Wood (1986) where they found cases of indenting (penetrating) chondrules separated by matrix. Though Wasson et al. (1995) did not find any examples of these types of penetrating chondrules, we found this to be the case more than 50% of the time in our tomography data. The omission of touching and aggregate CCs by Wasson et al. (1995) can also be explained by their assumption that chondrules were formed in the solar nebula by flash heating of chondrule precursors (shock model). An assumption regarding thee method of chondrule formation disqualify our new cateogories from being considered compound chondrules.

4. MODELS OF COMPOUND CHONDRULE FORMATION

4.1.   Penetrating and Enveloping Compounds

Gooding and Keil (1981) presented what is now considered the more popular view of compound chondrule formation. In their model, individual chondrules collided while at least one of the chondrules was still molten. Wassson et al. (1995) felt that the Gooding and Keil (1981) random collision model was implausible and proposed a "relic-chondrule" model that calls for the primary, or rigid, chondrule to be part of a porous aggregate that was then flash heated to form the secondary, or conformed, chondrule. The latter seems plausible since we found quite a few aggregates (15.5%) throughout our tomography data.

Another possibility consistent with accepted theories of compound chondrule formation is that of hot accretion suggested by Holmen and Wood (1986). According to their interpretation of penetrating CCs with different textural and chemical compositions and separated by matrix, some important conclusions can be drawn:

(1) Accretion began immediately after thermal processing

(2) Matrix and chondrules were a product of the same thermal event.

Though our data is limited to physical interpretation, we did find several instances of penetrating chondrules separated by matrix material that enveloped the chondrule interface. Given the high frequency of matrix between the CC interface (> 50%), conclusions (1) and (2) imply that the primary mechanism for chondrule formation is a nebular process.

4.2.   Touching and Aggregate Compounds

The new categories, touching and aggregates, garnered the most interest because they could not be explained by previous theories that were used to account for

interpenetrating compound chondrules. We interpreted the physical evidence to correlate to two possible processes, parent body and nebular, and came up with two very different but equally plausible processes that would be able to produce these types of compounds.

(1) Impacts onto parent body regolith caused compaction and flattening that sorted and mechanically joined the chondrules together. The jostling and fracturing during parent body compaction allowed some chondrules to fit together like jigsaw puzzle pieces (Wasson et al. 1995).

(2) Semi-molten objects are colliding in space and are mechanically joining together.

The existence of these types of compounds warrants future study due to its evidence for secondary parent-body processes. Confirmation can be seen in BSE and Scanning Electron Microscope (SEM) images, where adjacent chondrules are clearly separated by matrix material and distance yet appear to be two connecting pieces of a jigsaw puzzle. Touching and aggregate CCs look as if they have initially undergone process (2) then, secondarily,. process (1). Nebular and parent-body processes must be considered in conjunction when considering the models of compound chondrule formation due to the strong evidence that suggests both happen in succession.

5. CONCLUSIONS

Based on a 3-D tomographic study of chondrules in CR chondrites, the following conclusions are made:

(1) Compound chondrules occur more frequently in CR chondrites than in ordinary chondrites.

(2) Compound chondrule study, including textural, thin section, and chemical

analysis, should be expanded to include touching and aggregate compounds.

(3) Compound chondrules constitute more than 9.6% of all chondrules in the

traditional sense and comprise more than 75% of all chondrules with the

addition of the new categories in CR chondrites.

(4) The high frequency of these new compound categories suggests additional

processes may be involved in the compound chondrule formation.

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