Investigations of Meteorites by Tomography

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Introduction

Chondritic meteorites record the earliest stages of the formation of the solar system. Abundant free-floating spherical chondrules (once partially molten), along with larger refractory inclusions (calcium aluminum inclusions or CAIs) and hydrated matrix silicates, accreted to form the chondrite parent bodies. The early history of the condensation, agglomeration, partial melting, and evaporation of dust is thus recorded in the chemical and isotopic compositions and textures of the smallest components of chondrites. Chondrules average slightly less than 1 mm in diameter, while CAIs can be much larger (*d* of >1 cm) in some meteorites.

Many models of the formation of these molten droplets in various gaseous environments in the solar nebula have been proposed. Most of these models depend on accurate descriptions of representative CAI and chondrule textures for their input data and to test their validity (e.g., see Ref. 1).

Most of our knowledge of the textures and chemical compositions of meteorites and their components comes from petrography on thin sections (30-µm thick) of these very heterogeneous objects. Such 2-D methods are, however, unsatisfactory for detailed modeling of spherical objects that are not radially symmetric. Are two "isolated" grains connected in the third dimension? How close is an "interior" portion of a presumably spherical object to the "edge"? Is the modal proportion of metal grains in a slice of a chondrule an accurate representation of the modal proportion in its entire volume? Many studies are questionable or obviously inconclusive because the particular thin section cannot be related to the whole of the sample. This is the rationale for studying meteorites and their components in a 3-D context.

Methods and Materials

We are using the x-ray computed microtomography (XR-CMT) apparatus at the GSECARS sector at the APS. The methods are explained elsewhere.

We work with bulk samples of chondrite meteorites from the AMNH collection, ~0.8 cm^3 analyzed at 12- to 17-µm/pixel resolution. Individual CAIs and chondrules are separated from these meteorites and analyzed at resolutions of 2- to 10-µm/pixel. We also work on smaller pieces cut from the larger chondrite samples to obtain *in situ* high-resolution images of particular CAIs and chondrules (clasts) that we identified from the initial low-resolution images. These samples are cut with a low-waste 20- to 50-µm kerf wire saw into tetragonal prisms with a cross section of <2 mm for analyses at 2- to 5-µm/pixel resolution. A single analysis averages ~2 hours, including setup time.

After data were collected at the APS, their interpretation and use required extensive use of image-processing software at AMNH. We used the open source code ImageJ in conjunction with the commercial code Imaris and scripts written in IDL to quantify phase abundances in chondrules and CAIs [2, 3]. We are exploring existing techniques of thresholding and segmentation, so we can extract more quantitative information from the tomographic data without "reinventing the wheel."

Tomography is only the very first step in learning about these extraterrestrial materials. We are using the 3-D data we have in hand to optimize further cutting and 2-D studies of particularly interesting samples that use optical and microbeam instruments, such as the scanning electron microscope (SEM) and electron microprobe (EMP). We have learned how to obtain serial sections of the chondrules and CAIs and are currently working on registering the 3-D tomographic data with 2-D elemental composition maps obtained from using SEM and EMP.

Results

Our microtomographic work with meteoritic material began very late in 2001 and continued with three data collection dates in 2002. This work is covered in a previous report. We have spent a lot of effort in learning the best ways to obtain images of meteoritic materials, prepare samples, and handle the resulting data. We have learned how to prepare very small samples for tomography and have developed techniques for fiducial marking of samples before further cutting and 2-D analysis. We are also exploring ways to manipulate the very large (300-800 MB) tomographic data files and couple them with backscattered electron and energy-dispersive spectroscopic maps of selected elements obtained on the SEM and EMP. These operational results are important because this is a new technique in meteorite studies.

So far, we have concentrated on specific questions that are addressed best by using 3-D tomographic data. We found that we could quantify the abundance of void space and the abundance of metal in the silicate chondrules and CAIs with relative ease. Metal grains and void spaces have very high contrast with regard to the silicate minerals that dominate these objects. This has allowed us to show that for an important class of highly primitive meteorites (the CR chondrites), traditional 2-D methods do not allow for an accurate determination of the metal abundances in chondrules [4, 3]. Some of these results are illustrated in Fig. 1. We suspect but have not yet collected the data to prove that the same is true for other chondrites.

In samples from the Allende (CV3) meteorite, we have demonstrated that void spaces of different types are unambiguously present at higher abundances than hitherto recognized [2]. One object of study is shown in Fig. 2. This result is due directly to the 3-D technique, because the extent of void spaces has always been ambiguous as a result of the plucking of material by the abrasives commonly used to prepare traditional petrographic thin sections.

All these results have been published as extended abstracts [2-4] and presented at international meetings. They are now being combined with results from further work for submission to peer-reviewed journals.

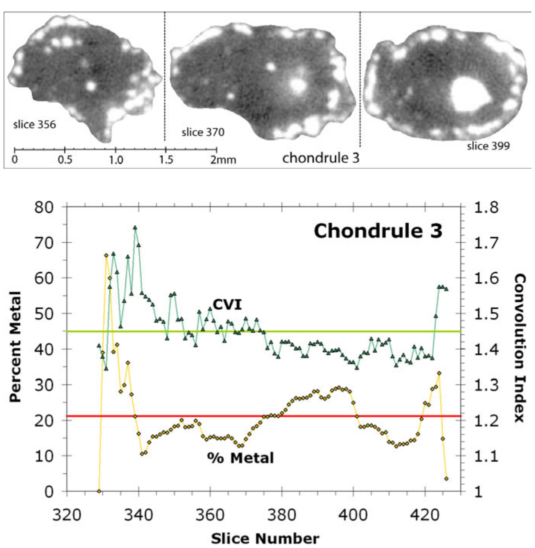

FIG. 1. Chondrule heterogeneity revealed by tomography [3]. Three tomographic images (of ~100) through a single chondrule have been cropped so only that chondrule is shown. Note gross variations in the cross section's shape and the metal abundance (metal = bright, silicate = dark). Corresponding modal data for metal and the convolution index (i.e., CVI = perimeter length/ circumference of circle with equal area) were calculated for all slices. These and other data illustrate the utility of 3-D observations for accurately measuring chondrule properties [3].

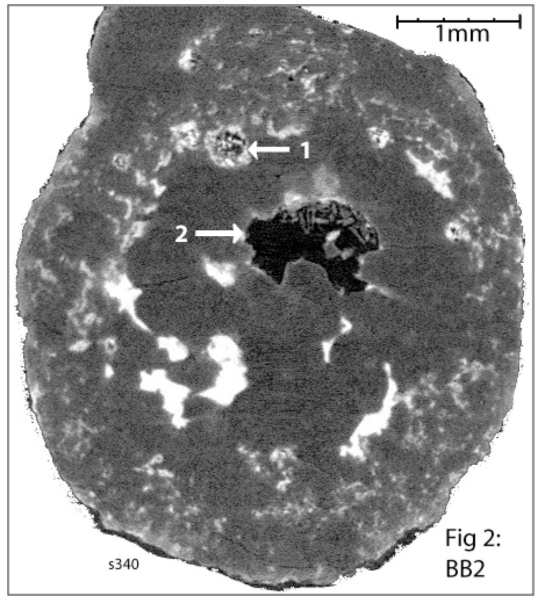

FIG. 2. Tomographic slice showing two types of void space in an Allende chondrule. Several explanations for these and other types of void spaces have been proposed [3]. The existence of voids was verified by cutting the chondrule.

Education and Outreach

The AMNH completed a total renovation of its Arthur Ross Hall of Meteorites in October 2003. This hall includes a theater in which an x-ray tomographic "fly-through" of a chondritic meteorite is a prominent part. As lead curator for this hall, D. Ebel has had numerous opportunities to showcase the tomographic work on meteorites to audiences including high-school students, teachers, and the interested public.

In 2002, Ebel worked with J. Murray (then a senior concentrating in geology at Colgate) to produce an abstract that was presented as a poster at the 2003 Lunar and Planetary Science Conference in Houston, Texas [2]. Murray went on to become full-time exhibition coordinator for the Hall of Meteorites project and is now involved in geology and astronomy education at both AMNH and Kingsborough College of The City University of New York (CUNY).

At the same conference, Ebel presented an abstract of work done with J. Hertz, then a high school senior in New York [3]. Hertz, now a freshman at Columbia, is continuing to collaborate on a paper incorporating further image analysis work chondrules in CR chondrites.

Discussion

The ability to "see" different mineral grains nondestructively in 3-D is fundamentally new in the field of meteoritics. The learning curve for instrumentation is not as steep as that for extracting quantitative information from the results. The work of J. Hertz [3] is the best we have done so far with regard to the quantitative treatment of the tomographic data. We are also making good progress in connecting the detailed chemistry of 2-D sections with the 3-D density maps of chondrules and CAIs through serial sectioning and chemical mapping. We now have 64-bit hardware and applications at AMNH that allow the handling of large tomographic data sets in their entirety at full resolution. This has enabled the identification of more interesting chondrules and CAIs in existing samples and the targeting of these objects for future high-resolution tomography at APS.

Further work using tomography data collected in 2002 is in progress. For example, a large, unmelted CAI from Allende was imaged in early 2002 in a bulk sample, then cut out as a smaller piece for reanalysis at higher resolution. We have now physically sliced this object, revealing eight surfaces suitable for SEM and EMP analysis. Working with colleagues, we have begun a complete 3-D analysis of this object by using the ion microprobe and laser-ablation ion-coupled mass spectrometry.

A grant application has been submitted to the National Aeronautics and Space Administration (NASA), proposing to use tomographic data collected in 2002 to quantify the size ranges, types, and other textural characteristics of chondrules in several classes of meteorites. This goal is directly coupled with the development and testing of models for astrophysical processes models of processes in the early solar nebula.

Acknowledgments

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