Three-dimensional Chemical Petrography of Chondrites by Using X-ray Microtomography

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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, accreted along with larger refractory inclusions (CAIs), and they hydrated matrix silicates to form the chondrite parent bodies. The early history of condensation, agglomeration, and 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 a millimeter in diameter, while CAIs can be much larger (d > 1cm) in some meteorites.

Many CAIs show evidence of having once been molten, and the melilite crystals in them are zoned, chemically, from core to rim. Recent models describe the evaporation of such molten droplets in various gaseous environments, the crystallization of zoned melilite from such evaporating liquids, and also the diffusion of Mg and Si through the melt [1-3]. Similar models are being developed for chondrules [4]. Other models use chondrule textures to constrain the astrophysical setting of their origins [5]. Such models depend upon accurate descriptions of representative CAIs and chondrules for their input data and to test their validity.

Most of our knowledge of meteorites and their components comes from petrography on 30-µm thin-section and chemical analysis of small portions of these very heterogeneous objects. None of these methods is satisfactory for detailed modeling of chondrule or CAI formation. For example, the bulk compositions of CAIs are not at all well constrained by these techniques [6], nor are the details of mineral zoning. Many studies are questioned or obviously inconclusive because the particular thin section cannot be related to the whole of the sample. Are two “isolated” grains connected in the third dimension? How close is an “interior” portion of a presumably spherical object to the “edge”? Many questions would be better answered if meteorites and their components were studied in a 3-D context. This project will produce an extremely well-characterized suite of samples curated by the AMNH and available to the research community. We intend that the chemical and textural data from thin-section analysis will be referenced to the 3-D tomographic maps, allowing interpolation between sections. It should be noted that synchrotron x-ray tomographic studies of CAIs and chondrules are proceeding elsewhere in the world [7], but the project described here is the only one we know of active in the U.S.A.

Methods and Materials

We are using the x-ray computed microtomography (XR-CMT) apparatus at the GeoSoilEnviro Consortium for Advanced Radiation Sources (GSECARS) sector of the APS. These methods are explained elsewhere.

Our first suite of samples were bulk samples (~0.8 cm^3 in size) of a group of chondrite meteorites from the AMNH collection, analyzed at a resolution of 15 to 25 µm per pixel. Individual CAIs and chondrules separated from these meteorites constituted a second suite. Presently, we are starting work on smaller pieces cut from the larger chondrite samples to obtain high-resolution images of particular CAIs and chondrules (clasts) *in situ*. These particular clasts were identified from the initial low-resolution images. The large samples are cut with a 50-µm kerf wire saw so the clasts are encased in tetragonal prisms with cross sections of <2 mm, for analyses at a resolution of 2 to 5 µm per pixel. The time for these analyses averages about 2 h each.

We are learning to cut smaller samples with finer wires and addressing issues of data registration and data storage. We are also exploring ways to manipulate the very large (300-800 MB) tomography data files and couple them with back-scattered electron and energy-dispersive spectroscopic maps of selected elements obtained on the field-emission scanning electron microscope and electron microprobe at AMNH.

Results

Much of what we have done in our first year of work has been learning — how to obtain the best images of meteoritic materials, best prepare the samples, and handle the resulting data. These operational results are important because this is a new technique in meteorite studies. Our results fall into several categories.

Petrologic-Tomographic Survey of Meteorites

We tomographically imaged bulk samples of more than 10 carbonaceous and ordinary chondrites. We identified and cut prisms of individual chondrules and CAIs in some of these. In our second run at APS, we examined these prisms and the individual objects in them at high resolution. We also located irregularly shaped, small (<1-mm cross section) CAIs in the Allende sample for our next round of analysis. Our continuing work involves closer examination of particular components of all these samples, at higher spatial resolutions.

One large CAI ($4 \times 5 \times 11$ mm) separated from the Allende meteorite (imaged at 15 µm per pixel) has been cut to smaller dimensions to resolve tiny spinel grains at 3 to 5 µm per pixel in our next run. From the first set of images, we learned to distinguish between several mineral types and found unexpected void spaces or cavities in the interior of this CAI and what look like impact craters on its surface. We are preparing an abstract on this object.

Public Education about Meteorites

The AMNH intends to renovate its Ross Hall of Meteorites in 2003. X-ray tomographic images of the small objects that formed in the early solar nebula will likely be included in at least one media display element. These images provide raw material for dynamic ways to connect the microscopic features of chondritic meteorites, where the crucial clues to our origins lie, to the macroscopic meteorite samples. The collaboration of GSECARS and the APS will be fully acknowledged in any such display.

Study of Metal in the CR Chondrites

The CR chondrites are widely considered to be among the most primitive chondrite groups despite various degrees of hydration alteration suffered by their constituent components. One intriguing component in the CR chondrites is the metal. It constitutes up to 7.5 vol % of CRs [9] and has a solar Ni-Co ratio, consistent with an origin by nebular condensation [9, 10]. However, petrologic and trace element data suggest formation of CR metal by reduction during chondrule formation [11] or devolatilization of iron sulfides [12]. On the basis of trace siderophile elements, formation of CR metal by direct nebular condensation has been excluded [13]. Metal in chondrule rims may have formed by vaporization of interior metal followed by recondensation onto the rim [11]. To better understand metal formation, we combined computed x-ray microtomography and petrology to study metal abundances in chondrules in the Renazzo CR chondrite fall.

We generated tomographs of a $12 \times 6 \times 6$-mm sample of Renazzo by using the GSECARS beamline at the APS. From the tomographs, we studied three chondrules that could be viewed in entirety. Two of these are silicate-rich chondrules containing large (~600 µm) metal globules in their cores and smaller metal globules in the rims. The third one is an isolated ~800-µm metal sphere in the matrix. We determined modal abundances (vol %) of metal in the cores and rims of the two silicate chondrules. Their cores contain up to 18 vol % metal, and the rim metal constitutes an additional 5 vol % of the chondrule. Also, we studied metal in thin sections of several CR chondrites. We found large metal chondrules similar in size to the silicate chondrules, and we identified small (2- to 3-µm) metal grains in amoeboid olivine aggregates (AOAs). These AOAs consist of forsterite surrounding nodules of anorthite, diopside, and Mg-Al spinel. In some cases, AOA metal appears to be included within the olivine.

Model(s) for the formation of CR metal must account for the high abundance of metal in the chondrules, the occurrence of large metallic chondrules, and the presence of metal in refractory inclusions. The formation of some metal by reduction of FeO in silicates requires that the chondrule precursors be highly oxidized and contain a high abundance of Fe. Some large, isolated metal chondrules may have formed by centrifugal ejection of metal from chondrule cores [12]. However, this may require unusually large parent chondrules, which have not been observed in the CR chondrites. Some metallic chondrules may have formed by melting of metal precursors that condensed from the nebula. If CR metal formed by devolatilization of sulfides, chondrule precursors must have included high abundances of FeS. The AOAs that contain metal are aggregates of olivine and refractory nodules and do not appear to have ever been molten. The formation of metal in the AOAs by reduction would require that the olivine was initially FeO-bearing. Another possibility is that the metal in the olivine is condensate that acted as nuclei for olivine growth. We conclude that the origin of metal in the CR chondrites is not completely understood and may require a variety of processes, including reduction, vaporization, and recondensation, and nebular condensation cannot be entirely excluded.

What's Next?

So far, we are very pleased with our results. The ability to "see" different mineral grains in three dimensions, nondestructively, is fundamentally new in our field. These images and movies impress our colleagues and stimulate excellent discussions, but the question remains: What is the scientific payoff? The payoff will come when we are able to connect the detailed chemistry with the 3-D maps. This is, in no small part, a problem in data handling or "informatics." We have improved the tools used to do this work: computer power and image analysis software. It is increasingly clear, however, that handling the large tomographic data sets in their entirety at full resolution will require 64-bit hardware and applications that will, fortunately, be available in a year or two, according to our sources in the industry.

We have therefore front-loaded this project with the acquisition of tomographic data. We have been able to find, isolate, and obtain high-resolution images of a few individual CAIs and chondrules. For those objects, the tomography phase is finished, and we are proceeding to the stage of serial sectioning and chemical mapping. High-resolution tomography on more individual CAIs, chondrules, and other primordial rocky objects from other meteorites is our next task at the APS.

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