Reports

Computed Tomographic Analysis of Meteorite Inclusions

Abstract. *The discovery of isotopic anomalies in the calcium- and aluminum-rich inclusions of the Allende meteorite has improved our knowledge of the origin of the solar system. Inability to find more inclusions without destroying the meteorite has hampered further study. By using a fourth-generation computed tomographic scanner with modifications to the software only, the interior of heterogeneous materials such as Allende can be nondestructively probed. The regions of material with high and low atomic numbers are displayed quickly. The object can then be cut to obtain for analysis just the areas of interest.*

Our understanding of nucleosynthesis and the origin of the solar system has been transformed by the discovery in the meteorite Allende of isotopic anomalies dating back to, and probably before, the origin of the solar system (*1*). The findings have stimulated intensive isotopic studies of inclusions in meteorites, especially carbonaceous chondrites. These studies have mainly been done on a few inclusions in Allende ranging in size from 3 mm to 1 cm (*2*). Progress has been retarded by the necessity of crushing each meteorite specimen to expose candidate inclusions.

We have developed a method of locating inclusions in intact specimens to facilitate sample selection. In this technique, which is generally applicable to rocky materials—terrestrial, lunar, or meteoritic—with significant internal structure, a standard medical fourth-generation computed tomographic (CT) scanner is used. The only modifications are to the user-accessible software constants.

Two whole specimens of Allende were used. One (818-4) weighed 458.5 g and was about 80 mm in length and 20 mm in diameter. The other (818-5) weighed 585.5 g and was about 95 mm in length and 30 mm in diameter.

The CT scanner (Deltascan 2020, Technicare) consists of a circular array of 720 solid-state detectors and an x-ray tube that rotates just over 360° on a concentric path. The x-ray beam width can be varied from 2 to 10 mm along the axis of rotation. The x-rays have a peak kilovoltage of 80 to 140 (three-phase). The calculation of a 512 by 512 matrix of picture elements (pixels) is accomplished by a minicomputer with an array processor. Normally calibrated for use on tissues with a density only slightly greater than that of water, the CT software has the flexibility to be used for scanning meteorites with a density of about 3.8 g/cm^3, though attenuation of the x-ray beam limits the size of a specimen that can be scanned at the maximum energy and power of the x-ray tube.

To allow CT scans of rocks to be made, software parameters used in correction for beam hardening were increased to account for the higher density and atomic number (*Z*) of the samples, and further adjusted by trial and error for each specimen to produce a relatively uniform density distribution across it. Specimen size and length of the path of the x-ray beam in high-Z material affected beam hardening and the calculated x-ray absorption coefficients. For these first trials, as with early clinical scanning, it was necessary to surround the meteorite sample with water to achieve satisfactory uniformity of image density. Absolute density values differed from those used clinically, since rocklike materials exceeded the density scale of the machine. Water, usually normalized to zero in Hounsfield units, was given a value of about −750. Calibration at the density levels of interest was first achieved by scanning terrestrial rocks,

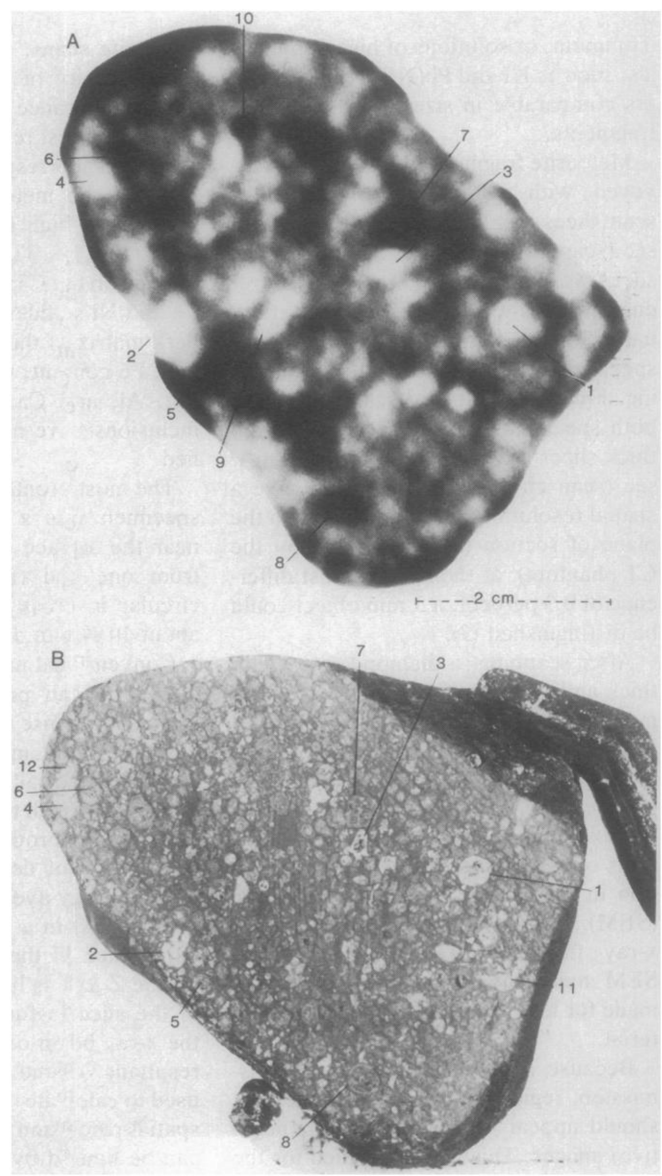

Fig. 1. Two views of the interior of Allende 818-5. (A) Positive-image reconstruction of x-ray data. (B) Photograph of the cut face of the sample. The x-ray reconstruction depicts information of a 4-mm-thick slab through the meteorite. Therefore, there is not a perfect match between the reconstructed image and the cut face. Areas 1 through 4 have both low x-ray absorption and low iron content. Areas 5 through 8 have high x-ray absorption and high iron content. Areas 9 and 10 of the reconstructed image do not seem to have counterparts on the cut face, while areas 11 and 12 do not seem to show up in the x-ray reconstruction.

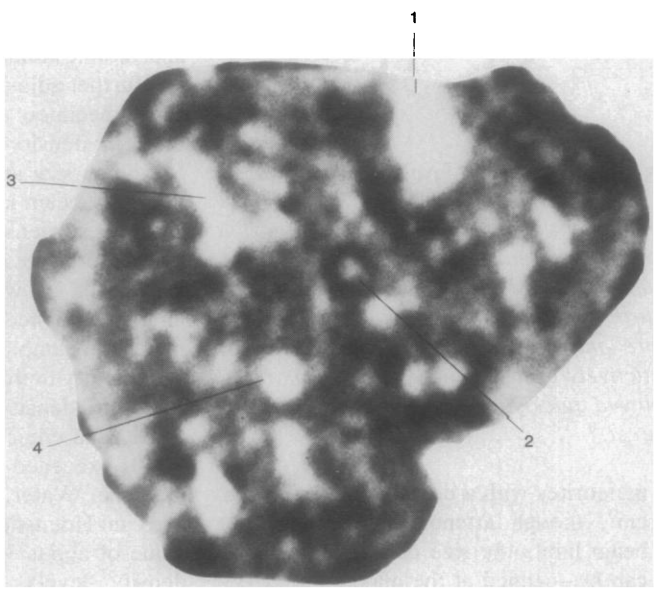

Fig. 2. Positive reconstruction of x-ray data, showing several of the most interesting features found. Area 1 is a feature of low x-ray absorption almost 15 mm in depth and just below the surface of the fusion crust of the meteorite. (The crust does not show in the image.) The feature appears on each of the frames that bracket this view, indicating that it is at least 12 mm long. Area 2 is a chondrule with a shell that absorbs x-rays more strongly than its center. Area 3 is an irregular feature of low x-ray absorption. Area 4 is a smaller chondrule-like feature (about 5 mm in diameter).

aluminum, or solutions of high-Z materials, such as KI and $Pb(NO_3)_2$, in containers comparable in size to the meteorite fragments.

Meteorite fragment 818-4 was first surveyed with consecutive 10-mm-thick scan slices at 120 kV peak and 800 mA/sec (scan circle, 25 cm). Selected 2-mm slices were made at 800 mA/sec. Lower energy scans were attempted, but attenuation of the x-ray beam by the dense specimen precluded satisfactory imaging. Finally, end-to-end scan surveys of both specimens were made with 4-mm-thick slices at 120 kV peak and 400 mA/sec (scan circle, 12.5 cm). This gave a spatial resolution better than 1 mm in the plane of section (as determined by the CT phantom): at the low-contrast difference of 0.3 percent, a 3-mm object could be distinguished (*3*).

After scanning, a diamond saw 1 mm thick and 15 cm in diameter was used to make cuts corresponding to selected scan slices. Approximately 2 mm of material was lost in this process. Samples of exposed inclusions and the meteorite matrix were scraped with stainless steel tools onto aluminum stubs for examination in a scanning electron microscope (SEM). Elemental analysis was done by x-ray fluorescence in a Hildebrande SEM and scanning micrographs were made for identification of crystalline material.

Because of their greater x-ray transmission, regions low in high-Z materials should appear dark on standard (negative) images. This was confirmed for the meteorite scans, which showed marked heterogeneity of density, matching the gross appearance of the specimens (Fig. 1). The darkest regions on the CT reconstructions corresponded to light inclusions in the meteorite; scrapings from these were high in Ca, Mg, Al, and Si and low in Fe, Ti, and Ni. The brightest regions on the CT scans corresponded to Fe and Ni sulfides in the meteorite. The dark matrix of the meteorite had a fairly high Fe content, with lesser amounts of Mg, Al, and Ca. The minerals in the inclusions have not been further identified.

The most promising inclusion in either specimen was a low-Z region located near the surface of 818-5 about 24 mm from one end (Fig. 2). It is roughly circular in cross section and measures about 10 mm in diameter.

Conventional medical or industrial radiography can produce high-resolution images of dense or metallic materials, but each point in the image represents the average of all the density variations on a line through the material. Computed tomography produces a display of the distribution of density (more precisely, of the energy-averaged x-ray absorption coefficients) in a cross section or transverse slice of the structure. Resolution on the Z axis is limited by the thickness of the slice, a function of the width of the x-ray beam or its detectors, and the resultant volume of the element (voxel) used to calculate density. In an image the spatial resolution in the plane of section can be limited by the size of the matrix used in the computer reconstruction: this determines the size of the pixel. In terms of information content, this resolution is actually limited by the number of discrete angular positions of the x-ray beam and by the spacing of the detectors. Contrast resolution is limited by the number of x-ray photons available. Compared to conventional radiography, CT has poorer spatial resolution but far superior contrast resolution (*4*).

We have shown the feasibility of obtaining a cross-sectional display of a heterogeneous but very dense specimen in a nondestructive manner. Regions of high- and low-Z material are readily distinguished on a millimeter scale. It is relatively simple to find the larger light inclusions in Allende samples without destroying the whole specimen. This method can be readily applied to other inhomogeneous dense materials, such as drilling cores, or other rocks with inclusions, voids, or internal structure.

Further improvements in software can be envisioned that would facilitate optimizing parameters for dense specimens. Different kinds of low-Z inclusions cannot yet be distinguished on the CT scans; correction of the CT numbers to correspond to actual x-ray absorption coefficients may be possible in the future. If x-ray beams of sufficient photon energy and number can be provided, additional information may be provided by scanning at more than one energy level and calculating Compton and photoelectric x-ray absorption coefficients separately (*5*).

J. R. Arnold
J. P. Testa, Jr.

Department of Chemistry,
University of California,
San Diego, La Jolla 92093

P. J. Friedman

Department of Radiology,
School of Medicine,
University of California, San Diego

G. X. Kambic

Technicare Corporation,
Cleveland, Ohio 44101

References and Notes

1. F. Begemann, *Rep. Prog. Phys.* **43**, 1309 (1980).
2. G. J. Wasserburg, T. D. Lee, D. A. Papanastassiou, *Geophys. Res. Lett.* **4**, 299 (1977).
3. *Phantoms for Performance Evaluation and Quality Assurance of CT Scanners* (American Association of Physicists in Medicine, Chicago, 1977). N. A. Baily provided the phantom materials.
4. G. N. Hounsfield, *Science* **210**, 22 (1980).
5. R. E. Alvarez, and A. Macovski, *Phys. Med. Biol.* **1**, 733 (1976).
6. We are indebted to N. Fong for technical assistance and C. Moore for making the Allende samples available. Supported in part by NASA grant NGL 05-009-148 and the San Diego Radiology Research Foundation. We also thank K. Marti and G. Lugmair for helpful discussions.

6 April 1982