X-Ray Microscopy in 3-D

Microtomography resolves micron-sized structures inside solid objects

By DIETRICK E. THOMSEN

Ever since the days of Wilhelm Roentgen and Henri Becquerel, just before the turn of the century, people have been using X-rays to find out about the insides of opaque solid objects. The standard X-ray picture is a shadowgraph. It shows that somewhere in the object a certain amount of energy was removed from the X-ray beam, but it doesn't tell at what depth in the object the removal took place.

Medical doctors have been able to use the ordinary X-ray pictures because often their previous knowledge of anatomy enables them to tell which structures inside the body were imaged by the shadows; they already know the depth in the body at which, for example, the spine or the ribs usually lie. But for an object about which there is no previous knowledge — say, an unidentified piece of mineral — such reconstructive reasoning doesn't apply. In general, the lack of depth information severely limits the information other kinds of scientists can get from X-ray pictures. And even the medical people were happy to see the development of X-ray tomography, which gives three-dimensional information about the structures inside a body.

Now a group of scientists has taken tomography into the microscopic range, developing what they consider a three-dimensional form of X-ray microscopy. The technique is called X-ray microtomography. Whereas the usual medical tomography, commonly known as a CAT (computer-assisted tomography) scan, images anatomical structures down to the level of millimeters, microtomography can resolve details as small as microns, about 1,000 times as fine.

The group includes Brian Flannery and Harry Deckman of the Exxon Research and Engineering Company in Clinton, N.J., and Wayne Roberge, formerly of Exxon, now of Rennselaer Polytechnic Institute in Troy, N.Y. So far, they have been using microtomography to study mineral samples, such as pieces of coal or rocks from the rim of the Grand Canyon, which, like most such rocks, happen to be of interest to Exxon.

They feel, however, that the method should be useful wherever detailed information about the interior structures of small, solid samples is desired. It could even be used for biological specimens, they say, provided the specimens are dead. The intensity of X-rays needed for the micron resolution is so high that if a biological specimen isn't dead at the beginning of the procedure, it will be at the end of it. Therefore microtomography can't be used to scan living patients.

Conventional tomography gets three-dimensional information basically by coming at the subject from all directions. An X-ray source swings around the patient — usually it's a patient — sending X-ray beams through the body from a series of different angles. Taking into account the amount of absorption in each beam, the direction from which the beam came and the locations and angles at which it intersected with other beams, the computation method known as a back-projection algorithm can reveal where in the depth of the body different amounts of absorption took place. Each such picture gives a two-dimensional slice of the body. Stacking a series of such slices gives a three-dimensional map.

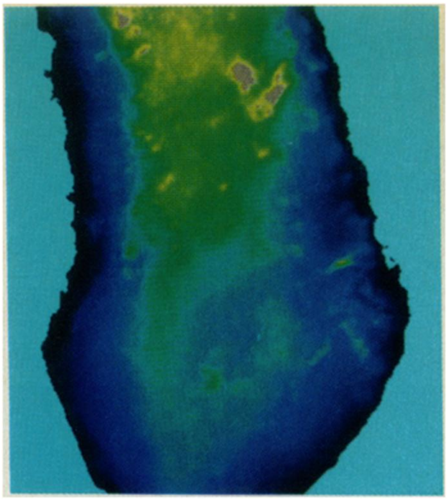
However, the X-ray sources in the usual CAT scanners are not intense enough to get the micron resolution the Exxon group wanted for its mineral studies and other purposes. As Roberge describes it, the X-ray energy needed to make a 3-D image of a given object is inversely proportional to the pixel size raised to the fourth power. To get micron resolution, the pixels — the tiny, basic elements of the picture — have to be 1,000 times smaller than they do for millimeter resolution. That means the amount of X-rays used for micron resolution must be 1,000 to the fourth power or a trillion (10^{12}) times that sufficient for ordinary tomography.

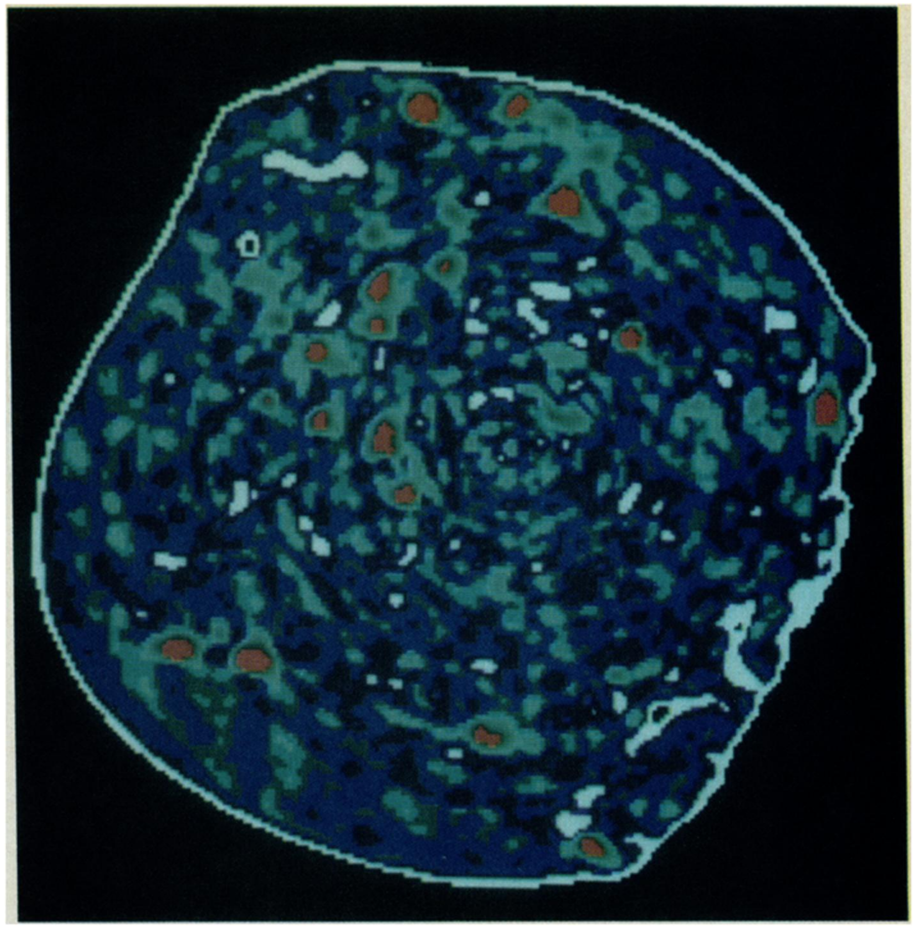
Ordinary X-ray sources were out of the question. However, Lee Grodzins of Massachusetts Institute of Technology suggested that a synchrotron, particularly one of the synchrotron light sources now being developed around the world, might do the job. The Exxon group used the Synchrotron light source at Brookhaven National Laboratory in Upton, N.Y., and they say their work confirms the feasibility of Grodzins's suggestion.

A synchrotron is an accelerator of subatomic particles — in the case of those used as X-ray and light sources, it is an accelerator of electrons. The electrons go around and around in a circle, and as they do, they emit intense and highly parallel beams of X-rays and related radiation. The X-rays from the synchrotron proved intense enough to form the micron-resolution images in reasonable amounts of time, but required changes in the geometry of the arrangement, the development of a new instrument for recording the X-rays, and a completely new computation algorithm.

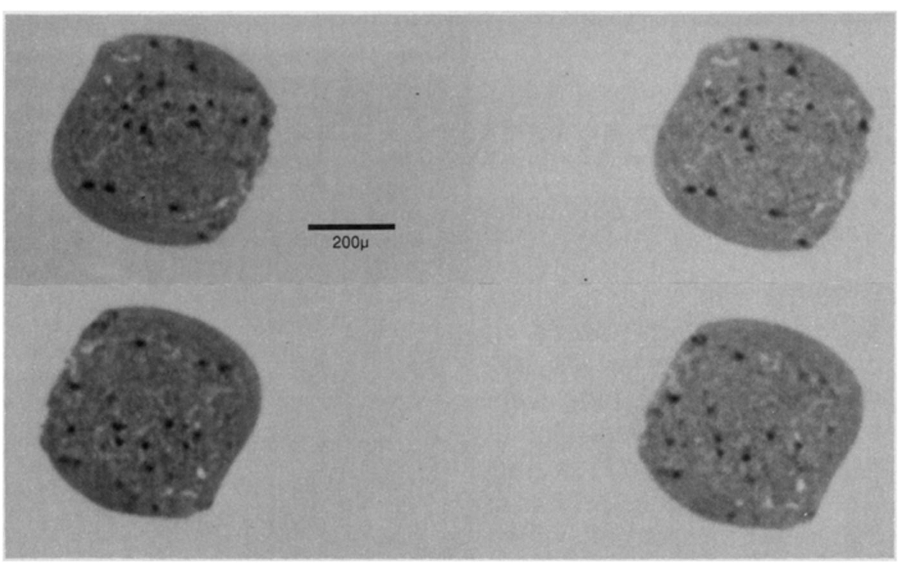
The synchrotron is not movable, so instead of moving the X-ray source around the sample, they rotate the sample on a turntable, while the radiation coming in an array of parallel rays passes through it. The X-rays then strike a phosphor that converts them to visible light, and a lens focuses the light on a charge-coupled device, an array of photoelectric sensors that sends digitized information directly to the computer.

The first phosphor arrangement they tried didn't work well for high-resolution images, Deckman told the recent meeting in New York of the American Physical Society, because light and photoelectrons leaked sideways in the phosphor and muddied the information. To remedy this they designed a cellular phosphor. Instead of a single plate, they made it into a pile of tiny cylindrical plugs, lying on their sides.





Views of a lump of coal by X-ray tomography. Above is a color-coded X-ray projection image showing variations in X-ray attenuation (increasing from blue through green to red) by different parts of the lump. At right is a tomographic reconstruction of a planar slice through the lump. Reddish spots are high-density inclusions; white indicates pores. Below are black-and-white images of four different planar cuts through the lump. Black spots are iron-rich mineral inclusions that appear and disappear as the sequence of cuts rises through different levels in the lump.



Photos: Corporate Research, Exxon Research and Engineering Co.

The face of each of these plugs represents a small part of the image, and the walls between the plugs are made so that light and photoelectrons can't leak through them. Thus the conversion of X-ray to light is kept separate for each piece of the image.

To get an image they take a very large number of different viewing angles, which leads to an astronomical number of X-rays and what Roberge calls "enormous amounts of data." One instance cited by Deckman involved 200 trillion (2×10^{14}) X-rays that were digitized into half a gigabyte of data per second.

The computation algorithm for ordinary medical tomography, which can reconstruct a medical image in a few minutes, is simply overwhelmed by such a data rate. Roberge writes that "to reconstruct just one of our 3-D *microscopic* images using the same methods would take about *two months.*" A supercomputer could do it in a few days, but supercomputer time is difficult to get; the synchrotron can scan several objects a day. So Flannery and Roberge developed a new algorithm. Stripped of the technical details, their method rearranges the steps in the old algorithm so that they go a lot faster. "By using these methods, it is now possible to reconstruct a 3-D microtomography image in just a few hours on an ordinary computer," Roberge writes in a popular abstract of his presentation at the American Physical Society meeting.

"While microtomography was developed for applications in the oil industry, we expect it to become a general-purpose research tool, like other forms of microscopy," Roberge writes. Deckman told the meeting that this is "a new form of microscopy, excellent for heterogeneous material." He feels "no sense of technical limitations" on its possible applications.

Among examples Deckman showed, the method has mapped the structure of pores in a piece of Coconino sandstone chipped from the edge of the Grand Canyon, pictured the fractures in a lump of coal and imaged the anatomy of an insect called a thrips. The method can also pick out different chemical elements. Different elements absorb different wavelengths of X-rays, and so by tuning the source to the wavelength of a given element, the scientists can map the locations of that particular element in some sample. Deckman also says the method makes images fast enough that some changes in minerals – leaching, for example – might be followed in real time. □