X-RAY TOMOGRAPHY: VISUALIZING IN THREE DIMENSIONS

I like to use the Toolkit as a platform to highlight technologies that are showing significant growth in their use by geoscientists or that strike me as having much unexplored potential. With its ten-fold growth in use by geoscientists over the past decade, the first laboratory method that comes to mind as fulfilling both of these characteristics is X-ray computed tomography (CT), a nondestructive method providing a 3-dimensional (3-D) visualization of nearly any solid material. Modern systems have been developed that specifically target mineralogical or petrological applications, often providing volume (or voxel) resolutions reaching the micron scale: hence, such technology is commonly referred to as micro-CT.

A micro-CT system consists of a finely focused X-ray source (Fig. 1) with a diameter typically around a few microns. Anisotropic X-rays are emitted from this quasi–point source, a process that can be visualized as a cone of achromatic photons being directed at the target material. As this cone of X-rays penetrates the specimen, some of the individual photons are absorbed whereas others penetrate through to the other side. In most systems, a 2-dimensional, low-noise photon detector records the X-Y coordinates of the individual photon arrivals. In order to expand the information beyond a simple 2-D radiograph, the specimen is rotated by tiny increments and successive images are recorded at each position. Key to producing a 3-D reconstruction of the material are powerful computer codes that can convert the flood of data into a volume representation; after this step, a variety of graphics packages can both manipulate and display the data.

Under normal conditions this technique does not give mineralogical information directly; rather it reveals the 3-D distribution of the density within the sample. The volume resolution is a function of a number of parameters, including how close the center of the sample can be brought to the X-ray source (hence, smaller samples generally provide better spatial resolution), the number of steps used during a single rotation, the pixel size of the photon detector, and the duration of a single exposure. Typical voxel resolutions are a few microns up to perhaps 20 µm, though submicron images have been reported. Commercial systems range in size from apparatus able to image centimeter-size rocks up to room-size devices used in industrial applications. Purchase prices start at 200,000–300,000 euros. At the heart of micro-CT technology are the computer codes that render the tens of gigabytes of raw data into a 3-D density model. Density differences of 5% are readily resolvable in most data sets, and under good conditions differences of down to 1% can be discerned. As this method is computing intensive, the power of the data-handling system is a key parameter, because a couple of hours of image acquisition can require a similar amount of computer time for rendering the data into a 3-D model. A significant hardware advance over the past few years has been the move away from large computer clusters and towards the use of the latest generation of graphics cards. Thanks here go to the global gaming "industry!"

The possibility of visualizing a rock specimen in 3-D obviously offers many exciting research opportunities in disciplines like mineralogy, rock mechanics, reservoir technology, and paleontology. Originally developed out of medical-imaging applications, one of the earliest applications of CT technology was in the hydrocarbon industry, which sought information on the porosity, permeability, and fracture patterns in drill core specimens (for a more detailed history, see Funk et al. 2011). From this early work in the mid-1980s—then seemingly a highly specialized niche domain—micro-CT has grown to become a key analytical discipline in both the oil and drilling industries (Fig. 2).

Over the past decade, micro-CT has also begun to interest mineralogists and petrologists. In a recent study, Mutina and Koroteev (2012) applied micro-CT technology to mixtures of coarse-grained mineral powders

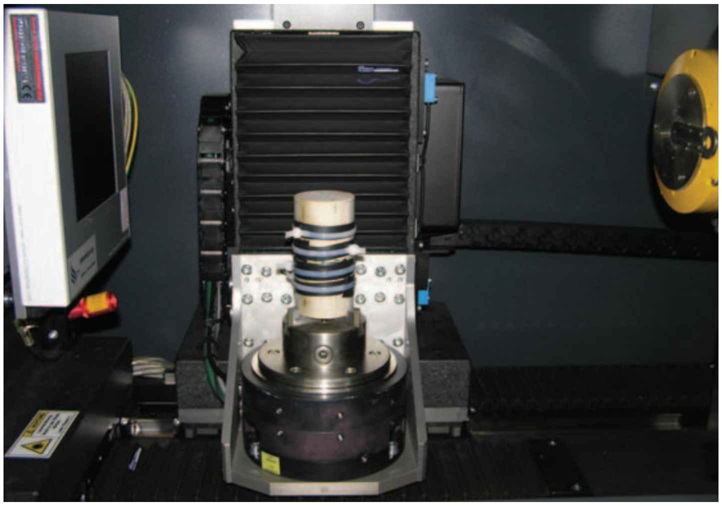

Figure 1 Photograph of the specimen chamber of the micro-CT system at the Helmholtz Zentrum Potsdam. Visible on the right is a beryllium window, which is the exit port for the photons being emitted by the X-ray generator. In the middle is a limestone specimen that has undergone a strain experiment, thus requiring the use of plastic cable ties to maintain its mechanical integrity. Visible on the left is the position-sensitive photon detector. Before beginning analysis, the sample will be raised up between the X-ray source and the detector, after which the chuck will slowly rotate, in steps of less than one degree, around the vertical axis. Note the quadratic reticule pattern that has been engraved into the top surface of the specimen. Image courtesy of the Helmholtz Zentrum Potsdam

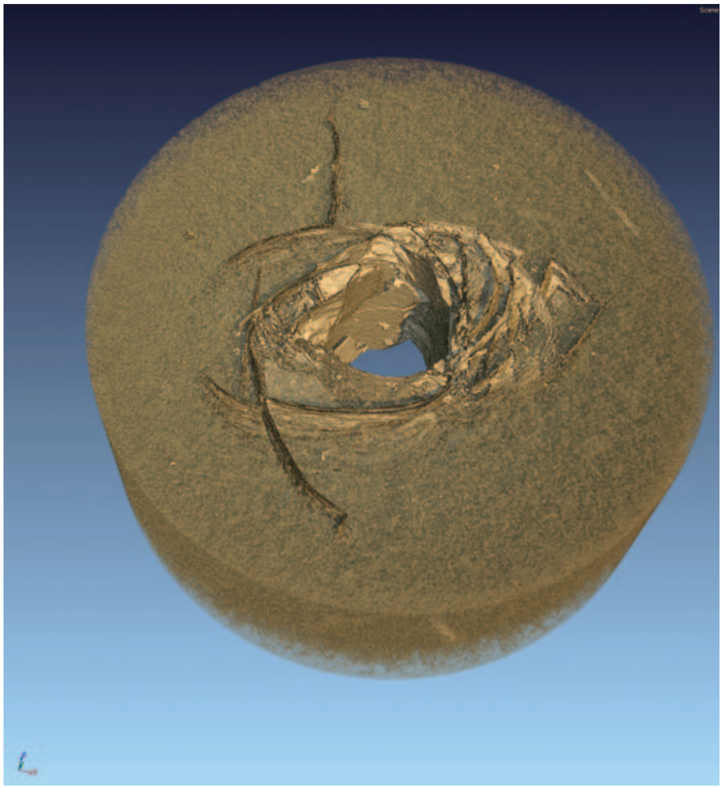

Figure 2 An example of a micro-CT image from a simulated bore hole breakout in shale. The outer diameter of the sample is 20 mm, and the fracture width is of the order of 50 µm. Image courtesy of the Helmholtz Zentrum Potsdam

employed as rock simulants. They found that quartz and calcite, though having similar densities, could be readily distinguished using their system. These authors were able to identify certain artefacts in their data set (for example, overlap in the greyscale distributions between phases and significant noise in the data) that could be addressed by an appropriate preprocessing of the data. A second mineralogy-oriented project, conducted here in Potsdam, examined mineral formation on a fracture surface in a sample of dense quartzite (Fig. 3). The goal was to understand the distribution of secondary mineralization along the fracture plane, and the resulting images were specifically enhanced to show the geometry of the newly formed phases.

One of the more exciting applications of micro-CT that I have read about is its use in paleontology, where the nondestructive nature of the technique makes micro-CT the method of choice for the study of unique fossil specimens. In order to get more information on this topic, I traveled to Berlin to visit its world-famous Natural History Museum, where the Leibniz Institute for Evolution and Biodiversity Research operates a micro-CT facility. There, I learned about amazing examples of the power of micro-CT as applied to the fossil record. Among their many projects, the Leibniz scientists are most proud of their study of a nearly complete specimen of the Eocene lizard *Cryptolacerta hassiaca* (Müller et al. 2011; Fig. 4), which they scanned in collaboration with the Helmholtz Centre Berlin. With perhaps a total of four weeks of work in the lab followed by several years of interpreting the resulting images, it was possible for scientists from the Leibniz Institute to unravel the history of this little fossil, along with that of lizards in general. Detailed microanatomical analyses of the skull, dentition, and postcranial elements of this ca 7 cm specimen allowed them to establish an evolutionary relationship between worm-like reptiles known as amphisbaenians and the four-legged, so-called lacertid lizards, refuting arguments that amphisbaenians share their ancestry with the quite similar-looking snakes. In view of the value of this specimen and the extensive physical deformation it underwent during the fossilization process, I cannot imagine such research without the micron-scale information provided by the CT process, which allowed a very exact anatomical reconstruction of this unique specimen.

Figure 3 A micro-CT image of secondary minerals that have formed on a fracture plane in a sample of low-porosity quartzite. After CT reconstruction, imaging software was employed to highlight the difference between the matrix quartz and the secondary mineralization; in the latter, a binning process was used that does not distinguish between differing phases in the mineralization. Furthermore, so as to enhance the visibility of the fracture plane, the data for the quartz matrix was removed from three-quarters of the total volume of the cylinder. Voxel size approximately 10 µm. Image courtesy of the Helmholtz Zentrum Potsdam

Figure 4 Two-dimensional projection of the 3-D reconstruction of a nearly complete specimen of *Cryptolacerta hassiaca*. This particular projection views the fossil from nearly straight above, although CT technology allows one to choose any perspective. Image courtesy of Prof. J. Müller, Berlin

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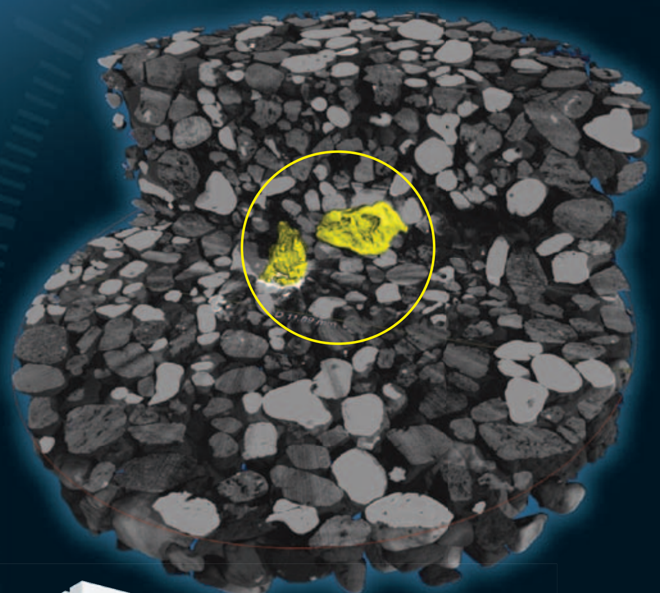

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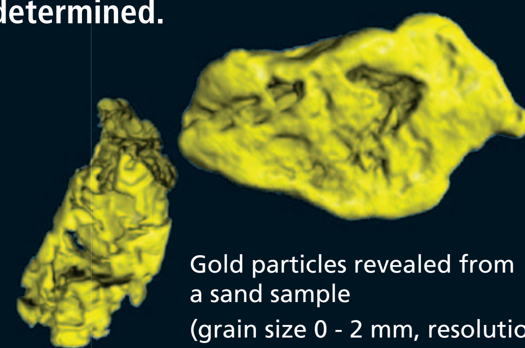

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