Microscale imaging of pore structure in hydrothermal sulfide chimneys using synchrotron x-ray computed tomography

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Introduction

The discovery of deep-sea hydrothermal vents 21 years ago opened a window into a largely unknown and unexplored biosphere. New discoveries from seafloor vents have fundamentally changed our beliefs about microbial metabolism and survivability, biological origins, and the physical and chemical limits to life. Because of the inaccessibility of deep ocean ridges, relatively few microbes have been isolated and characterized, and very little is known about the physical and chemical environment of microbial communities within sulfide structures on the micrometer-to-millimeter scale in which they live. As part of a large multidisciplinary study, we are currently designing and building laboratory flow-through reactors to recreate the temperature, pressure, fluid flow, and chemical conditions of seafloor hydrothermal chimneys in order to cultivate thermophile consortia under *in situ* conditions. Our laboratory systems require knowledge of the relationships among pore structure, permeability, fluid flow, and mineralogy within natural chimneys in order to design laboratory habitats in which thermophilic microorganisms will thrive. In order to characterize internal porosity at a scale relevant to porous flow and microbial communities, we carried out a feasibility study using synchrotron x-ray microcomputed tomography (μ-CT) at the Advanced Photon Source (APS). The goal was to image the internal micropore structure of vent chimney material recently recovered from the Juan de Fuca and East Pacific spreading ridges.

Methods and Materials

Ten black smoker chimney samples from two different seafloor sites [9 N° East Pacific Rise (EPR) and Juan de Fuca Ridge (JdFR)] were examined by μ-CT. Indurated samples were sectioned into cubic or rectangular pieces on the order of 0.5–3.0 mm in diameter. Friable samples were broken into small mm-sized pieces with a razor blade. The samples were mounted onto a metal sample stub with molding clay. Data was collected in September 1999 on the GeoSoilEnviroCARS (GSECARS) sector 13 bending magnet beamline (13-BM-D) with a Si(220) channel-cut monochromator. The monochromator was tuned to a high incident energy (≈40 keV) in order to penetrate the dense sulfide minerals of the samples. Visible light, generated by a phosphorescent screen downstream of the sample, was imaged with a Mitutoyo microscope onto a high-speed 12-bit CCD camera (Princeton Instruments Pentamax). The CCD readout was binned by a factor of two in each direction. Data were collected at two different pixel sizes (21.6 μm and 7.8 μm). Data was analyzed using IDL software and routines supplied by GSECARS on an SGI Origins computer.

Results

The samples examined in this study are dominated by sulfide minerals, mainly pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and sphalerite (ZnS), but they have variable amounts of amorphous silica or quartz (SiO_2), anhydrite ($CaSO_4$), and other secondary minerals. The samples differ significantly in the following ways. Samples from the EPR are relatively young (perhaps only weeks old), are dominated by sulfide minerals, and have very high microporosity. Samples from the JdFR are old (perhaps decades), are dominated by sulfides in their interiors, but have variable amounts of silica and anhydrite in their outer walls and have a more channeled porosity structure.

Reconstructed tomographic images of the smoker samples dramatically display the differences in age and mineralogy between the two sites. All samples show a range of porosities and permeabilities on different scales. The young EPR samples are very microporous, with visible pores ranging from about 50 μm to 1 mm. Pore structure is very irregular and nonchannelized with patterns suggesting diffuse flow of variable rates. Because the EPR samples are dominated by pyrite, mineral brightness is fairly uniform throughout the volume. The JdFR samples (more of which were studied) have less microporosity than the EPR samples, but have a large variation in pore size and connectivity. Samples collected from deep inside the chimney (presumably nearer to the central vent and of higher temperature) have no small pores. Visible channels are on the order of 300–500 μm in diameter. The high-temperature samples also contain bright minerals (≈100–200 μm in diameter) that we have tentatively identified as containing tungsten using electron microprobe. Moving outward from the interior of the chimney, most pores range from about 200–500 μm in diameter, with a few larger flow channels of ≈1–2 mm. The near-surface structures of the JdFR samples contain silica and anhydrite in addition to sulfide minerals. These samples had quite variable internal porosity, some with larger (1–2 mm) cavities that resemble dissolution features. Image contrasts are more variable in the outer-chimney samples, reflecting the different densities of sulfide, oxide, and sulfate minerals.

Discussion

Previous synchrotron CT work by Tivey and Singh [1] used the National Synchrotron Light Source (NSLS) to image a black smoker chimney, core material from a white smoker chimney, and a block of iron-rich sulfide. They were able to resolve flow channels within the structures on the scale of 1–3 mm. Other studies have used synchrotron μ-CT to investigate the porosity structure of sandstone in order to determine internal geometry on a scale of 10 μm, which was then used to calculate permeabilities (e.g., [2, 3]). Critical

comparisons between theoretical calculations from tomographic images and laboratory measurements of porosity, permeability, and resistivity in sandstones report good agreement for permeability calculations [4].

We are currently using the digitally reconstructed three-dimensional tomographic images to obtain a quantitative estimate of porosity within the chimney samples and to determine the size distribution of pores within different parts of the chimney structure. This will provide a first-order quantification of pore size distribution as a function of chimney age. We are in the process of collecting elemental maps of cross sections through the μ-CT samples using electron microprobe. Based on the chemical composition, we will attempt to correlate grayscale in the tomographic reconstructions to mineralogy, at least as far as distinguishing sulfide minerals (relatively dense) from oxide or sulfate minerals (relatively light). By mapping selected cross sections with electron microprobe, we can evaluate how well the mineralogy-grayscale correlation can be propagated through the three-dimensional volume. This will allow a quantitative estimate of mineral distribution in three dimensions as a function of chimney age and porosity structure. Taken together, these data will help guide the design and construction of laboratory reactor systems to recreate seafloor hydrothermal chimneys in the laboratory. Future studies will investigate how biofilms secreted by microorganisms might be imaged by synchrotron x-ray μ-CT in real and artificial black smoker samples.

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