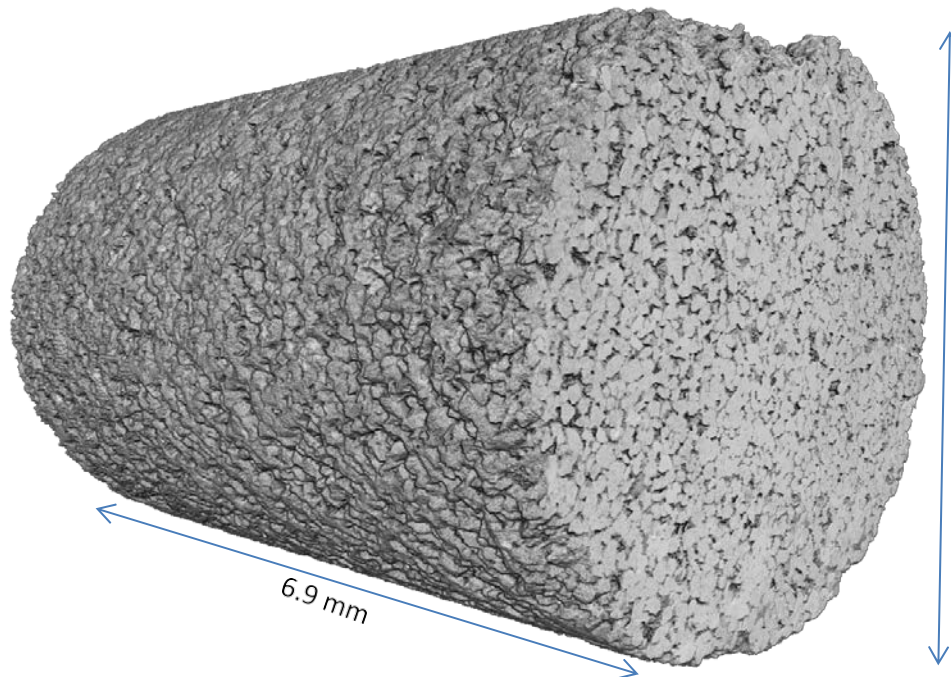


## Analyzing Full Micro-CT Image of a Berea Sandstone Mini Plug and the Associated Challenges

X-ray micro-CT imaging is becoming more prevalent in characterizing rock samples at pore- and grain- scale. By analyzing micro-CT data, one can gain an understanding about the micro-scale features in the rock sample. Challenges exist, however, in analyzing these data and obtaining properties based on images. Data size, accuracy of the results, and user bias are some of the issues associated with analyzing micro-CT images of rock samples. The PerGeos Digital Rock Analysis software has been developed to tackle these issues, and generate accurate and consistent results on large data. An example of micro-CT data analysis of a Berea sandstone sample using PerGeos is demonstrated in this article.

A Berea mini plug with a 6 mm diameter is scanned at a resolution of 2.5  $\mu\text{m}$  using the HeliScan micro- CT scanner. Figure 1 shows a volume rendering of the gray-scale image of the sample generated using PerGeos. The gray-scale intensities in X-ray CT images correlate with density. The low end of the histogram which represents the pore-space has been made transparent in Figure 1 to show the grain surfaces.



The micro-CT image shown in Figure 1 has, approximately, 2400 x 2400 x 2800 voxels, in x, y, and z directions, respectively. This is equal to over 30 GB of data on memory for the 16-bit gray-scale image. Analyzing a dataset of this size on a workstation can be challenging, especially if the amount of available memory is less than 5 times the size of data on memory. For this reason, a PerGeos recipe (i.e. a macro) and a block-processing script are used to analyze the whole data in a block-by-block fashion. The recipe is created based on a subset of data and has the set of instructions that are used to generate the end result. The script divides the dataset into a number of blocks defined by the user and applies the recipe on each block. The results from all the blocks are merged together to construct a whole analyzed image. The image processing steps used to segment and analyze the image are explained below.

Since the sample is not fully circular in cross-section, and in order to maximize the usable data from the scan, an irregular mask is created to cover the sample. A combination of multiple morphological operations of closing and filling is employed to create this mask. Figure 2 illustrates the cross-section of the image and the binary mask that is created to cover the irregularly-shaped sample cross-section. This mask is used in later steps during segmentation and analysis.

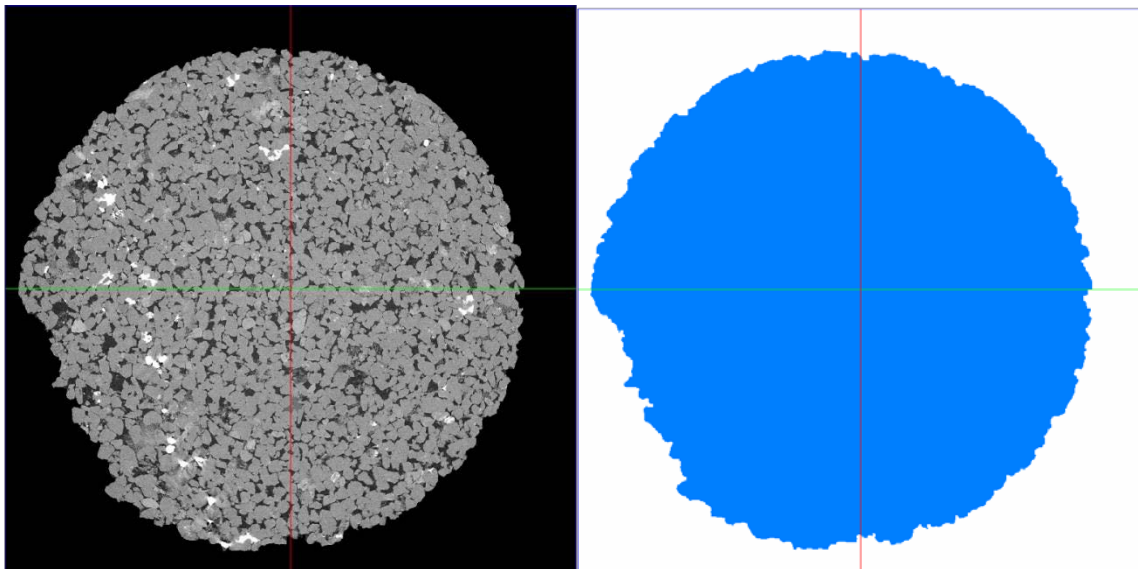
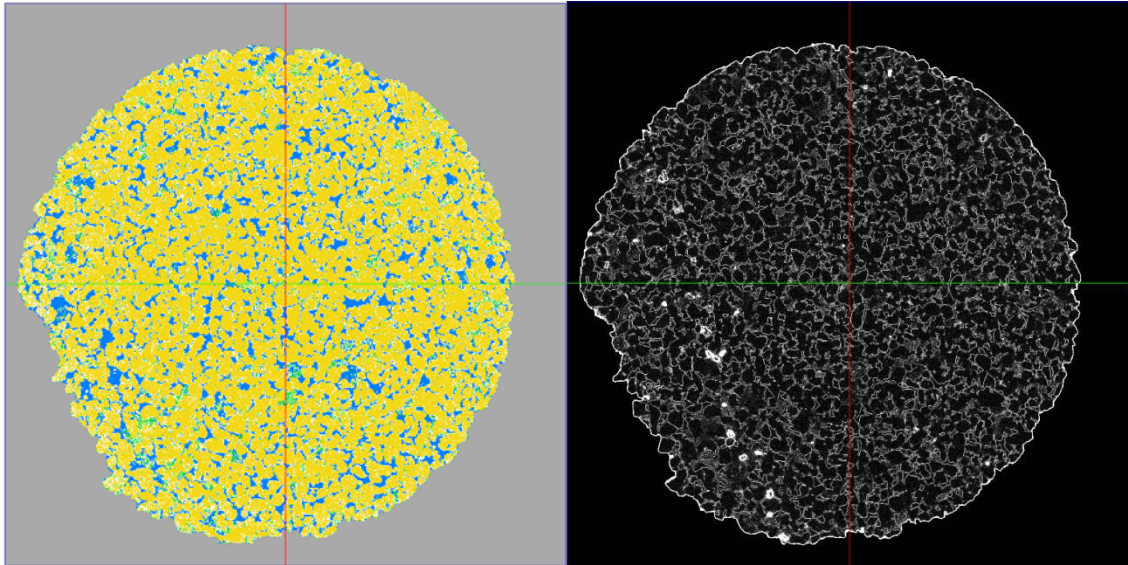


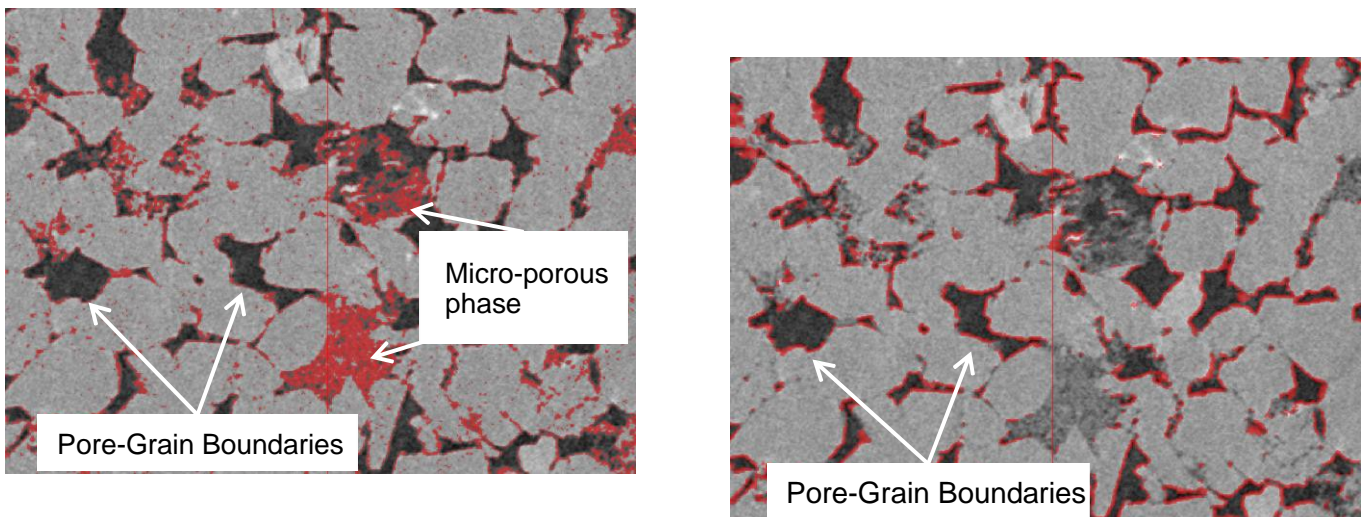
Figure 2. Cross-sectional views of the grays-scale image (left) and the binary mask (right) that covers the sample.

In order to remove user bias from the analysis, a semi-automated marker-based watershed technique is used for segmenting the gray-scale Berea image. In watershed segmentation, a seed image is used to flood an elevation map, which is a gray-scale image, and find the boundaries between different phases. The seed image is constructed by selecting areas with the highest certainty in the phases that are being segmented. The extents of the phases are then determined by the watershed transform, therefore removing user bias from labeling boundaries and low certainty regions. The elevation map is built by applying the Canny 3D gradient transform on the gray-scale CT image. In the resulting elevation map, the phase boundaries have higher intensities, whereas areas closer to the inner parts of the phases have lower values. Figure 3 shows cross-sectional views of the seeds image and the elevation map used in segmenting the Berea image. Three phases, namely, pore-space, micro-porous phase, and grains are seeded to be segmented, and are shown with blue, green, and yellow color, respectively.



**Figure 3.** Cross-sectional views of the seed image (left) and the elevation map, which is the gradient image (right).

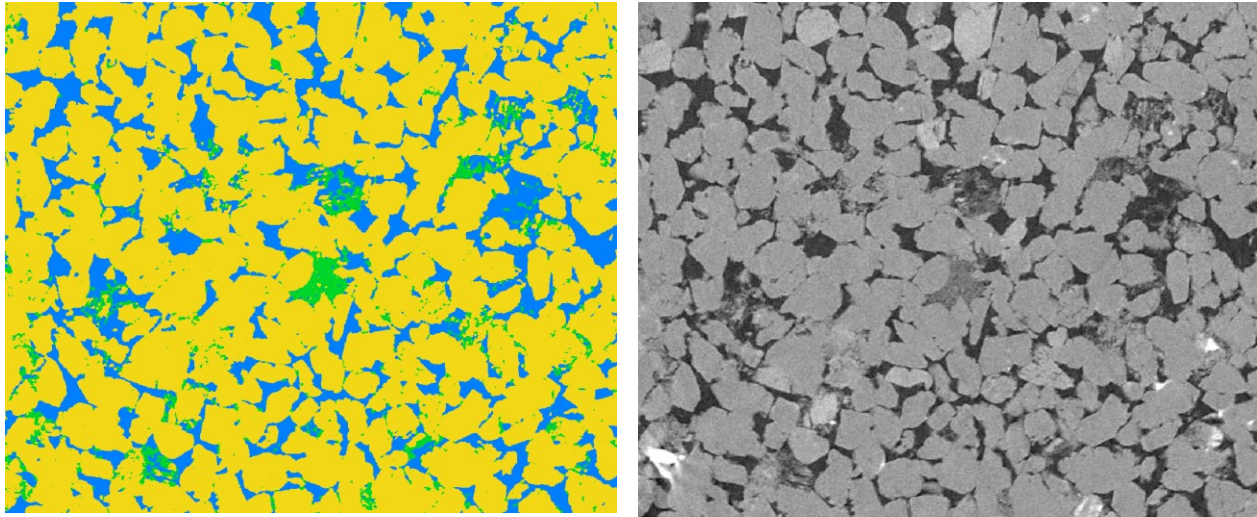
The micro-porous phase includes all the materials that have pores smaller than the resolution of the image, which is 2.5  $\mu\text{m}$ . This phase shows as intermediate gray-scale intensities in the micro-CT image. Because of the transition from low to high intensity values in the pore-grain boundaries, these areas may have similar intensities to the micro-porous phase. To obtain accurate results, it is important to differentiate between the pore-grain boundaries and the micro-porous phase during the seeding process. The gradient image, which is the elevation map for watershed segmentation, is used to select the boundaries and remove them from the seeds. Figure 4 shows an area of the sample where the intermediate gray-scale intensities (left) and the grain boundaries (right) are marked in red.



**Figure 4.** Intermediate gray-scale intensities, which represent the micro-porous phase and the boundaries (left). High-intensity gradient values, which represent the boundaries (right).



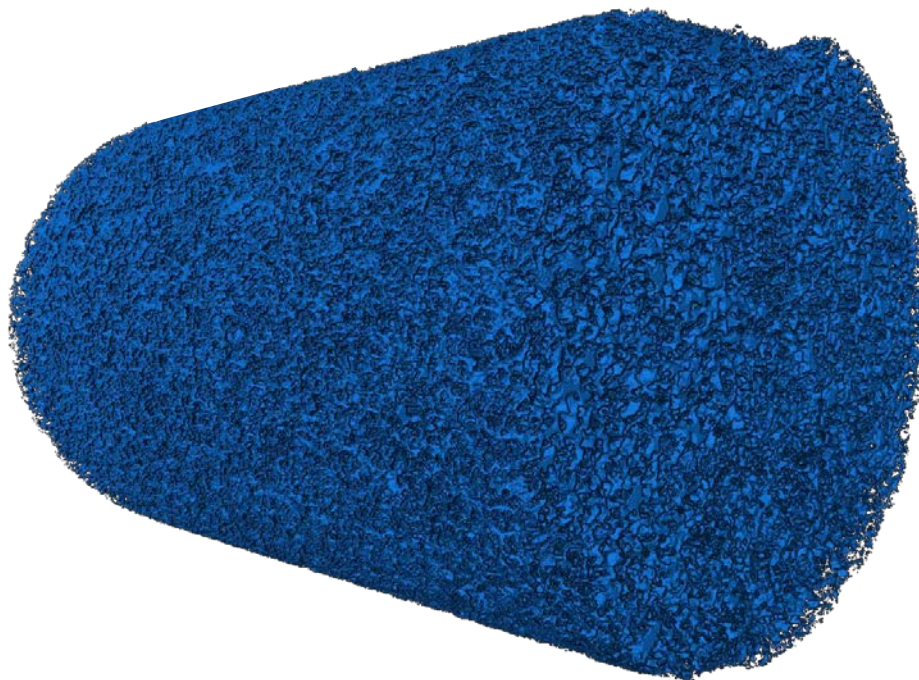
The watershed segmentation is run on the gradient image using the seeds image, after the removal of the boundaries. An area of the segmented image in a side-by-side comparison with the gray-scale image is shown in Figure 5. The volume fractions of the segmented phases are calculated and listed in Table 1. The total porosity is calculated to be 20.5 %, by assuming a 50 % porosity value in the micro-porous phase. Figures 6, 7, and 8 show 3D volume renderings of pore-space, micro-porous phase, and grains, respectively. The segmented image can be used for further analysis of any of the segmented phases, and also for model generation for simulation of physical phenomena.



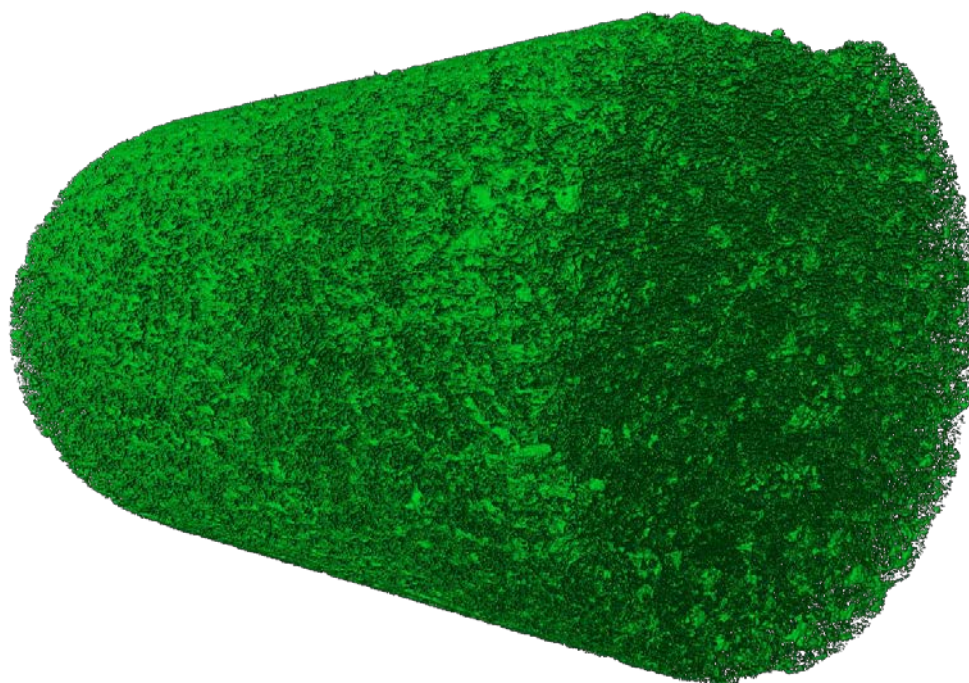
*Figure 5. Segmented Berea sample (left). Gray-scale CT image (right).*

**Table 1. Volume fractions of the segmented phases.**

Phase	Volume Fraction
Pore-Space	18.19 %
Micro-Porous Phase	4.65 %
Grains	77.16 %
Total Porosity	20.5 %

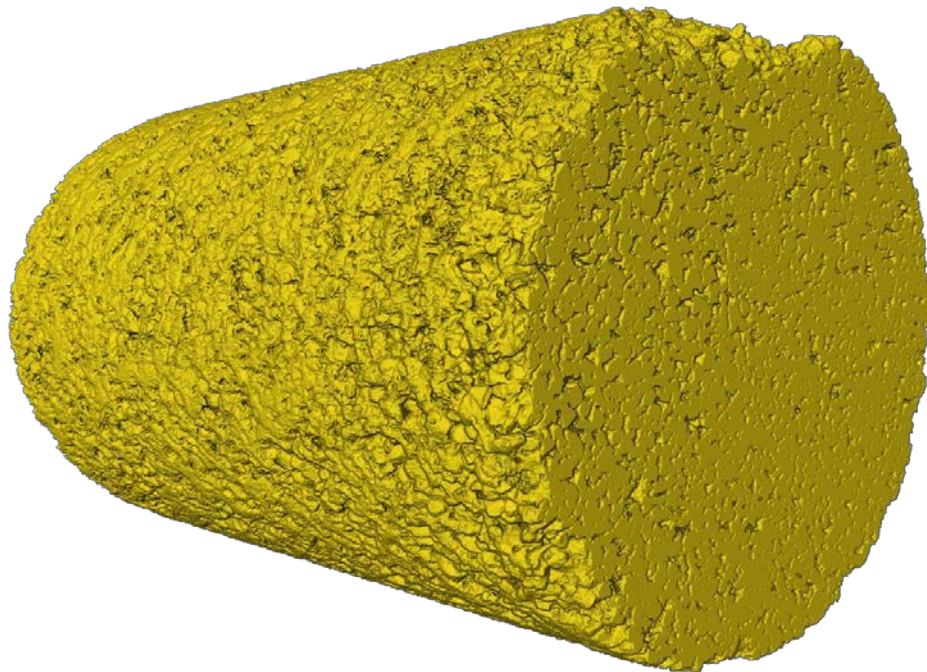


*Figure 6. Pore-space of Berea sandstone imaged and segmented at 2.5  $\mu\text{m}$  resolution.*



*Figure 7. Micro-porous phase of Berea sandstone imaged and segmented at 2.5  $\mu\text{m}$  resolution.*





*Figure 8. Grains of Berea sandstone imaged and segmented at 2.4  $\mu\text{m}$  resolution.*

X-ray micro-CT imaging is becoming an integral part of rock characterization processes. Large data size, user bias, and accuracy of the results are some of the challenges associated with analyzing micro-CT images of rock samples. In this article, the PerGeos Digital Rock Analysis software is demonstrated to analyze the full micro-CT dataset of a Berea sandstone mini plug. The analysis is done in blocks using a PerGeos recipe (i.e. a macro) and a block-processing script. The results are then merged together to form a whole analyzed image. To remove user bias from the analysis, the semi-automated watershed technique is used for segmentation. To improve the accuracy of the results the pore-grain boundaries are selected and removed from the seeds image before applying the watershed segmentation transform. The results of segmentation are demonstrated in the document. The porosity of the sample is calculated to be 20.5 %.

Keywords: #Berea Sandstone, #Micro-CT, #Watershed Segmentation, #Large Data Image Analysis,  
#Block-Processing, #PerGeos, #HeliScan, #Digital Rock Analysis