# DETERMINATION OF PHYSICAL PROPERTIES OF TIGHT POROUS MEDIA USING DIGITAL CORE PHYSICS/ANALYSIS

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## ABSTRACT

In this study we use pore-scale SEM images of tight porous media, and generate threholded binary images which are then used to reconstruct three-dimensional (3-D) pore structures. Computational physics is then employed in order to calculate the physical properties of the porous media, such as the porosity, permeability, electrical resistivity and formation factor, and the NMR spectra. This involves generating an unstructured 3-D grid in the pore space in which we solve the corresponding governing equations. The original thresholded images have high resolution which allows a more precise masking of the pore spaces. However, there is a high computational cost associated with the high resolution images. Reducing the resolution will reduce the mask precision in the pore areas and this will lead to a different numerical solution. Therefore, we much optimize between the computational cost and accuracy when performing the numerical simulation. The threshold values for the samples at hand were selected by trying to match porosity and permeability of a neighboring plug. The choice of threshold value has a profound effect on the porous medium properties. For the fluid flow calculations, we solve the velocity and pressure in the pore space by solving the Navier-Stokes equations and using the results to obtain the absolute permeability. The electrical resistivity is obtained by solving for the current density through Ohm's law, and for the NMR study we solve for the equations of molecular diffusion. This approach can be described as a version of digital core analysis (DCA) or digital core physics (DCP).

## INTRODUCTION

The main goal of this work is to characterize and determine the physical properties in tight porous media from actual pore samples of a tight formation. The method we employ is based on a computational physics approach where we discretize the 3-D structure into a computational mesh where the governing equations are then solved.

This study uses three scanning electron microscope (SEM) images of the tight sample as in Figure 1, and poses a method for numerically determining the physical properties of the reconstructed image, which includes the porosity, absolute permeability, electrical

resistivity and formation factor, and the NMR spectra. We then compare and validate the results to the experiment.
There are several challenges associated with this task. The main challenges include: the 3-D reconstruction of the sample with only three 2-D images, the effect of different threshold of the 2-D images on the calculation of the physical properties, and the computational cost involved in the solution to the 3-D heterogeneous (therefore noted as "upscaled") geometry.

The work here relies on 3-D reconstruction based on only three SEM images. Previous approaches of reconstruction include the work of Okabe and Blunt [1, 2] which reconstructed porous media based on only a single training image. A major assumption for them is that they assumed isotropy where the measured statistics on the XY plane is transformed to the XZ and YZ planes. We do not make such assumption in this work as several images were extracted directly from the given SEM images and used to recreate a 3-D digital porous media pattern.

The SEM images are 5120 × 3828 pixels (~ 637 × 476 microns) and are highly heterogeneous with large range of grain sizes. We provide a given tolerance for the different grain sizes into small, medium, and large. The smallest grains have bounding boxes ranging in size from 2×2 microns to 10×10 microns, the medium sized grains are from 10 × 10 microns to 50 × 50 microns, and the large grains have bounding boxes larger than 50 × 50 microns. The images are then decomposed into permeable domains and non-permeable domains, where the non-permeable domains include the large and medium sized grains. The permeable domains are at sub-pore scales where we extract from the original image to include the small grain sizes with tiny pores in between (Figure 2). We crop 33 of these images which are 256 × 256 pixels (or ~32 × 32 microns) from the three available SEM images. More images are required in order to reproduce a 3-D structure where we will perform pore-scale simulations. We do a spline interpolation between the greyscale of each 2-D image cropped images, in order to produce more 2-D images which we use to reconstruct the 3-D structure as show in Figure 3.a.

We perform pore-scale numerical simulations to calculate the permeability, resistivity and formation factor for the reconstructed geometry. The reconstruction, modeling and simulating process is an approach that is used in the areas of digital rock physics (see for example, [3, 4]) for understanding the macroscopic rock properties. Here we ignore the effects of adsorption, and assume that we are in the regime where the Navier-Stokes equations apply. For the permeability calculations we impose a simple pressure inlet condition and a 0 outlet condition, and solve the Stokes' equation to calculate average velocity of the flow within the pores as shown in Figure 3.b. Using the velocity and pressure profiles, we then back calculate the Darcy equation to obtain the permeability. We change the inlet and outlet, and calculate the permeability in different directions. Resistivity and formation factor calculations are obtained by solving for the current density using Ohm's law, see Figure 3.c. The calculated properties of the porous media are tabulated in Table 1. We also solve the equations of molecular diffusion and evaluate the NMR spectrum which is shown in Figure 3.d.

Following the pore-scale computations, we use the obtained values as properties of the permeable domain, while the grain properties are set to zero. We then solve for the fluid properties of the complex upscaled geometry. The upscaled geometry is constructed by using imageJ and tracing out the large and medium sized grains from the three SEM images, as seen in Figure 4.a. In order to represent the 3-D structure of the grains, we apply a dilation / erosion algorithm in several slices for both the medium and large sized grains as seen in Figure 4.b. The final set of images is then assembled by merging the medium and large grains together as shown in Figure 4.c. We then used these composite images in order to re-construct the upscaled representative geometry of the original image (see Figure 5.a) based on the three SEM images. In between the medium and large grains we assume a permeability of 3 μD in the z-direction as seen from Table 1. The porosity φ will be given by

$$\varphi = \begin{cases} 0 & \text{On medium and large grains} \\ \varphi_0 & \text{Everywhere else} \end{cases} \tag{1}$$

where $\varphi_0$= 0.09 from Table 1. The porosity of the upscaled geometry will then be the averaged porosity $\varphi_{av}$ over the entire volume $V$ given by

$$\varphi_{av} = \frac{\int \varphi \, dV}{\int dV} = \frac{2.015 \times 10^{-12} \ m^3}{2.8663 \times 10^{-11} \ m^3} \cong 0.07 \tag{2}$$

We assume Darcy flow where the permeability is given by

$$\kappa = \begin{cases} 0 & \text{On medium and large grains} \\ \kappa_0 & \text{Everywhere else} \end{cases} \tag{3}$$

where $k_0$ is the permeability of the cropped region (Figure 3.a). This resulting pressure and velocity profiles is then used to calculate the average permeability of the medium (Figure 5). Using Darcy's law, assuming incompressible fluid, we have

$$\nabla . \rho \boldsymbol{u} = 0 \, , \quad \mathbf{u} = - \frac{\kappa_0}{\mu} \nabla \mathrm{p}, \tag{4}$$

where $\mu$ is the viscosity of the fluid, and $\rho$ is the density. We inject a velocity of $1.0 \times 10^{-7} \ m/s$ at the inlet in the x-direction and a pressure of 0 Pa at the outlet. This will result in a $\Delta \mathrm{p} = 6818$ Pa (see Figure 5. b). The average permeability will then be given by

$$\kappa = \frac{u_p \, \mu \, \Delta L}{\Delta p}, \tag{5}$$

where $u_p = u \, \varphi_{av}$ is the Darcy velocity at inlet, which will lead to the result of 6.9 $\mu D$.

## CONCLUSION

A new approach of imaging and computing is presented in this paper for determining the petro-physical properties in tight formations using SEM images. SEM-CT images give higher resolution than micro-CT images and can handle smaller sized pores specifically in tight pores. This approach allows us to reconstruct the 3-D image based on only three SEM images and to numerically simulate various physical properties in this digital object such as permeability, porosity, electrical conductivity, and NMR.

The new component of the work relies firstly on the fact that images were not statistically created and we do not make any isotropy assumptions. Images are extracted directly from three SEM images provided. The only assumption is that the correlation length in the z-direction is the same as in the x and y directions.

Secondly, the reconstructed cropped images which are $256 \times 256 \times 256$ pixels lead to relatively high number of pores, approximately 10,000 – 15,000. At this number of pores the properties of the sample is same as what will be observed at much bigger sample. Therefore we performed the pore-scale simulations at the lower scales and then attempted early upscaling where we started describing the flow as Darcy flow.

We note that these results were based on a given threshold, and for very tight media we must have a very high resolution in order to be able to capture very low porosities without losing connected pores. Moreover, based on our grey scale, we assume pore regions which instead could have been organic material with nano sized pores. This would complicate gas flow simulations that would be necessary to take into account the effects of adsorption. This would in turn lead to different set of governing equations.

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**Table 1: Tabulated results from the pore-scale simulations**

| Porosity | Resistivity, Ω.m | Permeability, µD | | |
|---|---|---|---|---|
| | | $K_x$ | $K_y$ | $K_z$ |
| 0.09 | 145 | 3.0 | 2.3 | 9.2 |

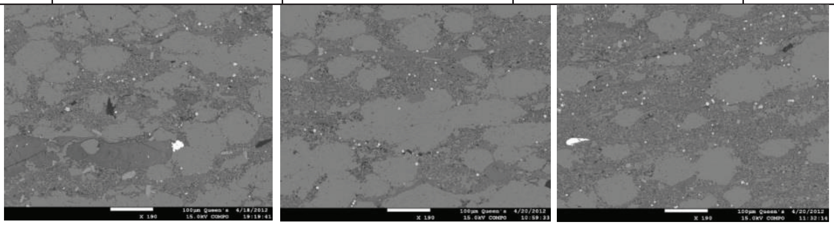


**Figure 1: Three SEM images of a tight formation**

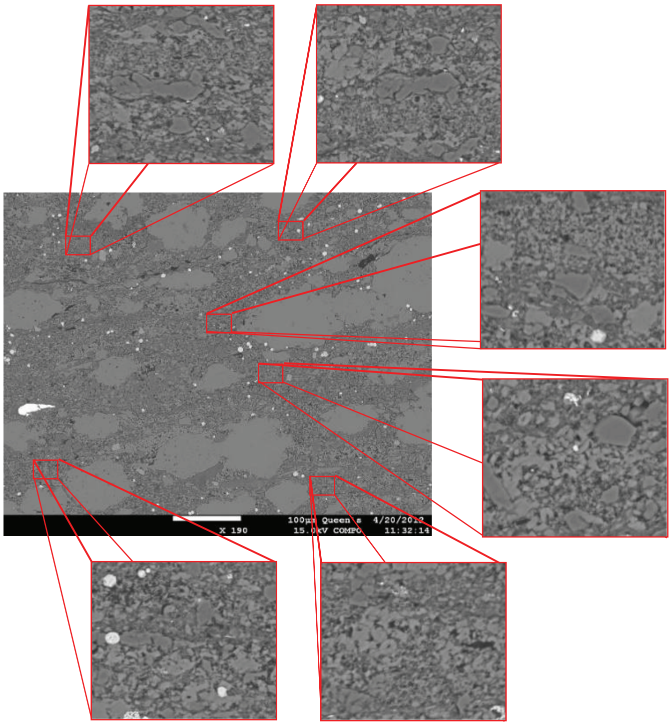
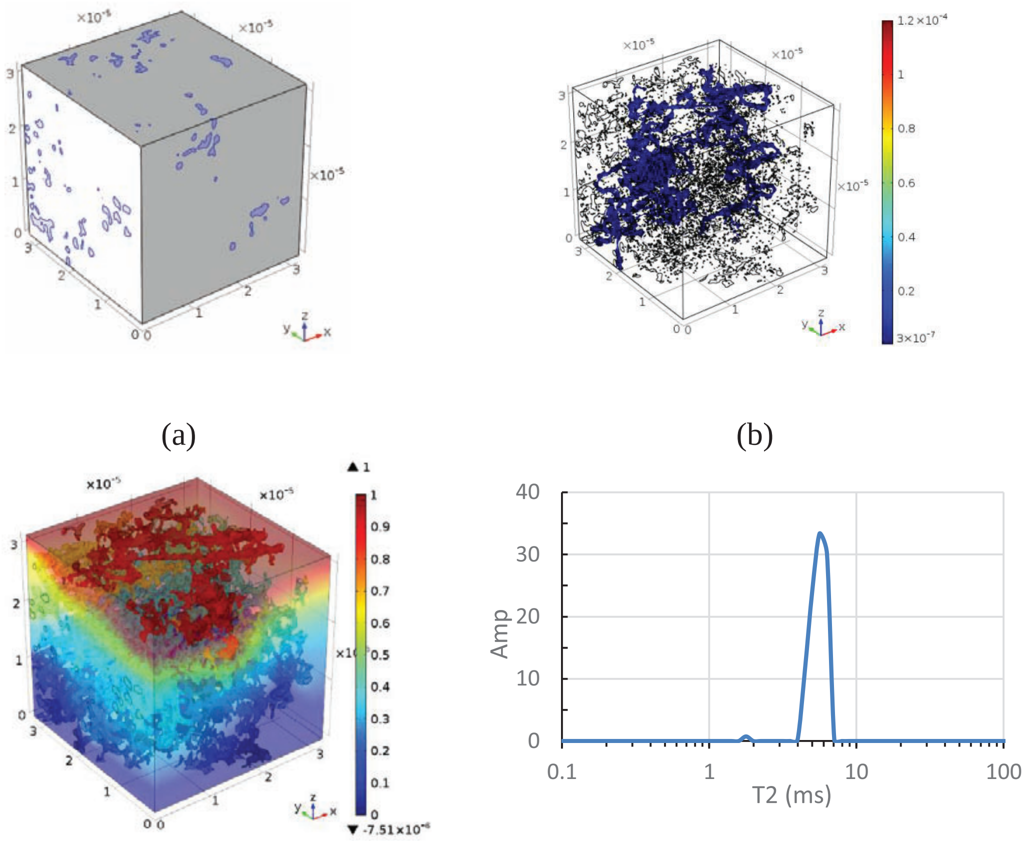


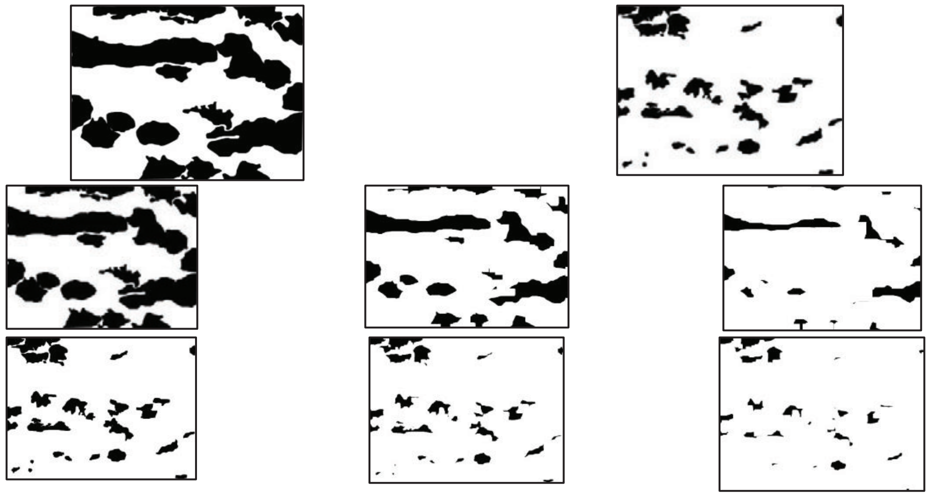
**Figure 2: Several Cropped images from SEM images**



(a) (b)

(c) (d)

**Figure 3: (a) computational domain (b) permeable regions, (c) current density (d) NMR spectra**



(a)

(b)

(c)

Figure 4: (a) large and medium sized grains, (b) dilation sequence (c) merging of the large and medium grains

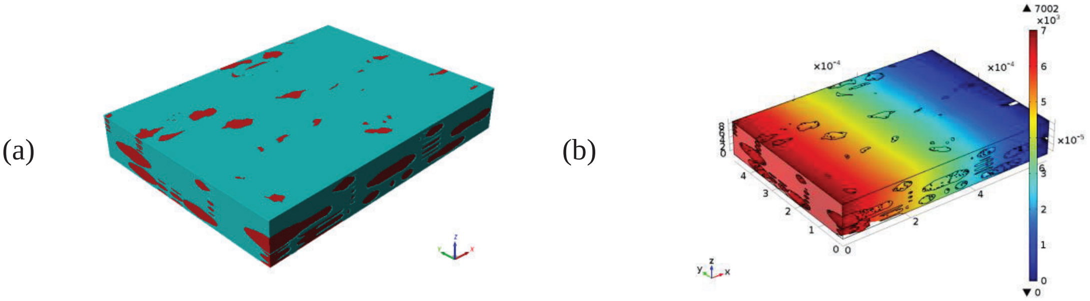


**Figure 5: a. Upscaled geometry with dimensions 637 $\mu m$ ×475 $\mu m$ ×96 $\mu m$, b. Surface pressure profile for the upscaled geometry**