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# COMPUTER-ENHANCED CORE ANALYSIS

M.A. Ioannidis, I. Chatzis and M.J. Kwiecien
Department of Chemical Engineering, University of Waterloo
Waterloo, Ontario N2L 3G1 Canada

## Abstract

A new approach for the prediction of petrophysical properties of rock samples has been developed by integrating statistical image analysis, 3-D stochastic pore structure reconstruction and characterization and network modeling techniques. Using statistical information (porosity, autocorrelation) extracted from segmented back-scatter SEM images of the pore space, software has been written which creates a 3-D stochastic realization of the pore structure. The result is a set of simulated serial sections through a model porous medium that honors the average statistical properties of the input images. Subsequent geometrical and topological characterization of this model is implemented to determine previously inaccessible information, namely the pore and throat size distributions and statistics of coordination number (number of throats connected to each pore). Knowledge of these parameters allows specification of the geometry and topology of network models which can be used to determine a variety of petrophysical and reservoir engineering properties (permeability, formation factor, resistivity index vs. water saturation relationship, capillary pressure curves). Comparison of model predictions with experimental data for a number of reservoir rock samples lends support to the new approach. Limited image resolution and unaccounted pore structure heterogeneity, are identified as the main factors responsible for observed deviations between model predictions and experimental data.

## Introduction

Determining the petrophysical properties of reservoir rock samples is the primary objective of core analysis. Although this objective is commonly achieved by laboratory testing, significant benefits may be expected from the availability of a computer-assisted method of analysis which requires a minimum of experimental information. Anticipated benefits include the ability to test a large number of samples at a fraction of the time and cost of experimental core analysis and the ability to estimate the petrophysical properties of samples not amenable to laboratory testing (drill cuttings, damaged core). This paper reports on the development and testing of a novel methodology which exploits 3-D pore structure information extracted from model porous media which honor the statistical properties of 2-D images of the void space (*i.e.* petrographic thin-section images).

Currently available methods based on image analysis[1-3] are limited by their inability to quantify the extent of 3-D connectivity of the pore space in reservoir rocks. The pore space is a complex continuum of interconnected channels with irregular geometry and can be conceptually described as a network of individual pores communicating through local constrictions (throats) in the pore space. Knowledge of the pore and throat size distributions and pore-to-pore connectivity is essential to the prediction of transport and capillary properties from first principles. Unfortunately, 2-D geometric or morphological analyses cannot lead to objective identification of individual pores and throats in sections through porous media. Alternatives, such as serial sectioning of pore casts[4] and non-destructive tomographic methods[5,6] (magnetic resonance and synchrotron emission tomography), have been recently employed in the study of pore structure in 3-D. These methods are either too laborious and expensive, or limited by resolution and thus not yet suitable for routine application.

An alternative to tomographic imaging and destructive serial sectioning is 3-D stochastic simulation[7,8]. This technique utilizes statistical information, obtained by analyzing binary images of sections through a sample, to create a stochastic reconstruction of the porous medium in three dimensions. The main principle of stochastic simulation is that the model and real microstructures must have identical statistical properties. The statistical properties used as input for the creation of simulated microstructures correspond to the first two moments of the binary phase function $Z(\vec{r})$, a function taking the value of unity if a point $\vec{r}$ in space belongs to the void phase or the value of zero otherwise. In this context, binary images of the pore space are nothing but discrete maps of the phase function $Z(\vec{r})$. Such images can be readily obtained by segmenting back-scatter scanning electron micrographs of petrographic thin sections. Only the first two moments of the phase function are used as input to stochastic simulation, namely the porosity, $\phi$, and the autocorrelation function, $R_Z(\vec{u})$, defined as the following statistical averages:

$$f = \left\langle Z(\vec{r}) \right\rangle \qquad (1)$$

$$R_Z(\vec{u}) = \frac{\left\langle \left[ Z(\vec{r}) - f \right] \cdot \left[ Z(\vec{r} + \vec{u}) - f \right] \right\rangle}{f - f^2} \qquad (2)$$

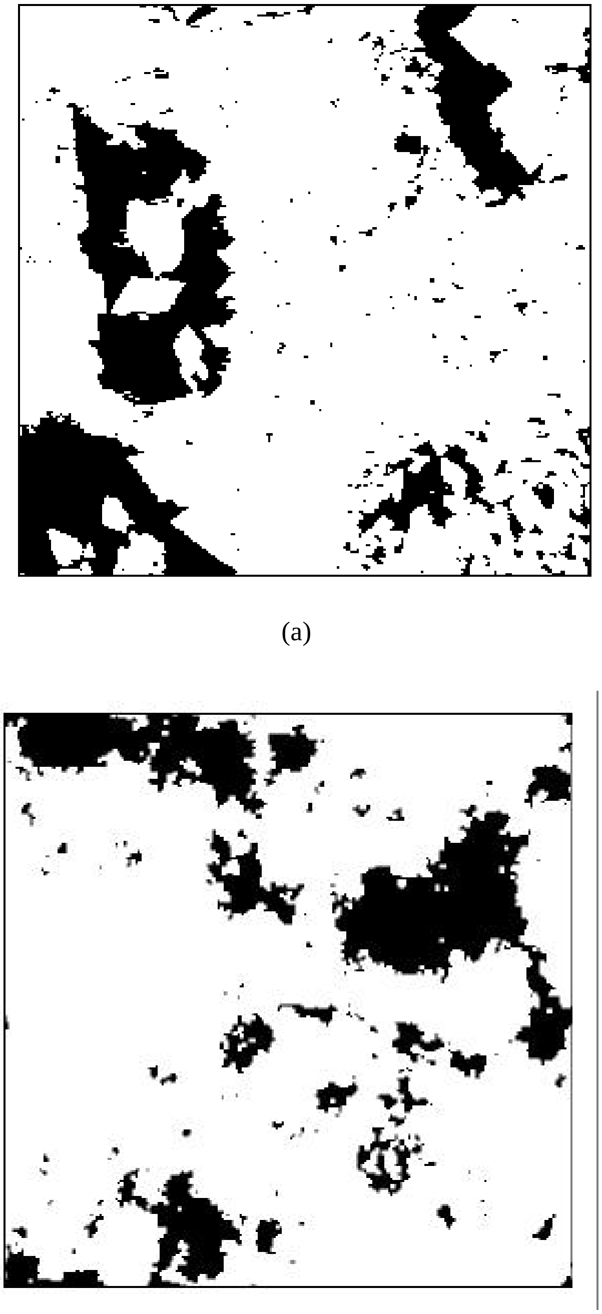
where $\vec{u}$ is a lag vector measuring the separation between two points in space. Stochastic simulation in 3-D provides a model pore structure which honors the statistical properties of its real counterpart. The extent to which stochastically simulated media reflect the microgeometry of real rocks has recently begun to be explored. Comparative analysis using serial sections through a Berea sandstone sample[9], however, confirms the validity of stochastic simulation.

In this paper we report on the use of 3-D stochastic methods to simulate the structure of a number of reservoir rock samples from statistical information (porosity and autocorrelation) obtained from back-scatter scanning electron micrographs of petrographic thin sections[10]. The geometry and topology of the resulting models is systematically characterized using computer software[11]. This software employs sectioning of the 3-D data set from nine orientations to determine local constrictions (throats) in the pore space and, thus, partition it into its constituent pores. In this manner, pore volume and throat area distributions, as well as coordination number statistics, are determined. This information is used as input to simulators which idealize the pore space as a network consisting of pores and throats of simple geometry[12]. The characteristic size of pores and throats and average connectivity of such networks are assigned in agreement with the results of 3-D characterization. Subsequent network analysis provides predictions of absolute permeability and formation factor, as well as predictions of the dependence of capillary pressure and electrical resistivity on fluid saturation for drainage-type displacements. These results are compared to standard laboratory tests in order to assess the strengths and weaknesses of the new approach for computer-enhanced core analysis.

## Results and Discussion

A total of 14 sandstone and dolomite samples were analyzed. Details pertaining to image statistical analysis and stochastic modeling methodology are provided elsewhere[10,13]. The resolution (voxel size) of all stochastically reconstructed samples was identical to the resolution of SEM images. This ensured that the smallest pore structure details revealed in the images were preserved. All stochastic realizations were created on a domain of $256^3$ voxels.

Figure 1 compares a typical binary SEM image from dolomite sample 58A to a cross-section through the corresponding 3-D model medium. A comparison of the average autocorrelation function of SEM images (input) and corresponding 3-D model (output) is given in Figure 2. Pore and throat size distributions and coordination number statistics, determined by analyzing a stochastic realization of sample 58A, are shown in Figures 3 and 4. Characteristic pore and throat sizes were computed from pore volume and throat area distributions by assuming cubic pores and rectangular throats. Figure 3 reveals relatively narrow pore and throat size distributions, a result typical of all simulated media in this study. This result is explained by considering that stochastic simulation is based on the assumption of statistical homogeneity (stationarity) and, for this reason, it creates model porous media with uniform statistical properties (porosity and autocorrelation). As shown in Figure 5, the porosity and autocorrelation of images taken from the same thin section show significant scatter. Stochastically simulated porous media reproduce the average statistical properties but do not reproduce the variability shown in Fig. 5. To capture this variability, one would have to analyze stochastic models conforming to individual image statistics and average the resulting pore



(a)

(b)

Figure 1. Sample 58A: (a) Segmented SEM image,
(b) Section through 3-D stochastic model.

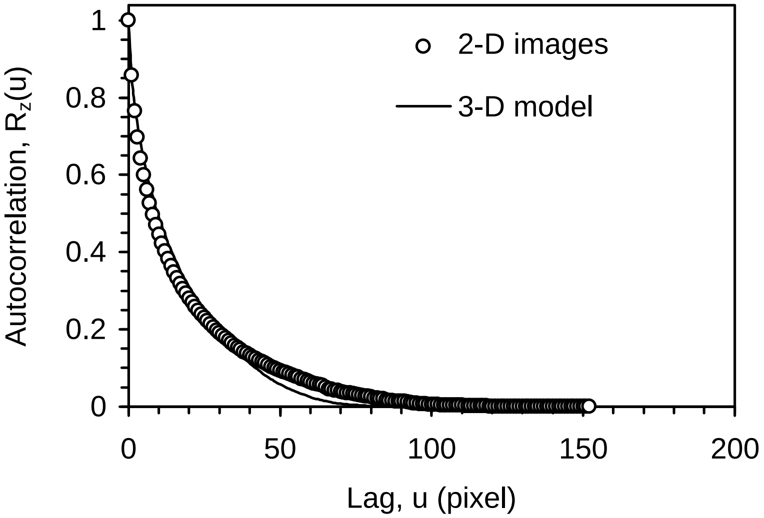


Figure 2. Average autocorrelation functions for input SEM images and 3-D model.

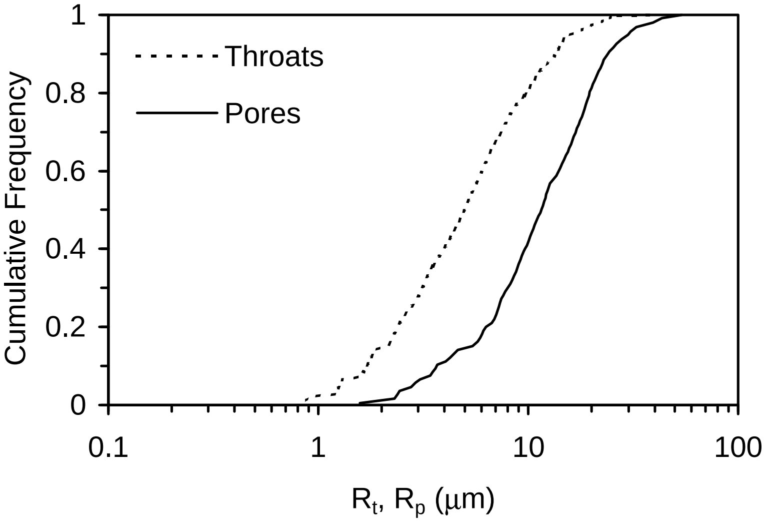


Figure 3. Pore and throat size distributions of stochastically reconstructed sample 58A.

and throat size distributions. The coordination number distributions reveal a large number of pores having a coordination number of two (see Figure 4). These pores arise from cross-sectional area variations along pore space channels and they do not contribute to the topological complexity of the pore network. If pores with coordination number of two are excluded from the statistics, stochastically simulated porous media are found to have an average coordination number approximately equal to four. Clearly, if throats are defined as local minima in the cross-section of pore space channels, the notion that every pore is a node (in a topological sense) must be abandoned.

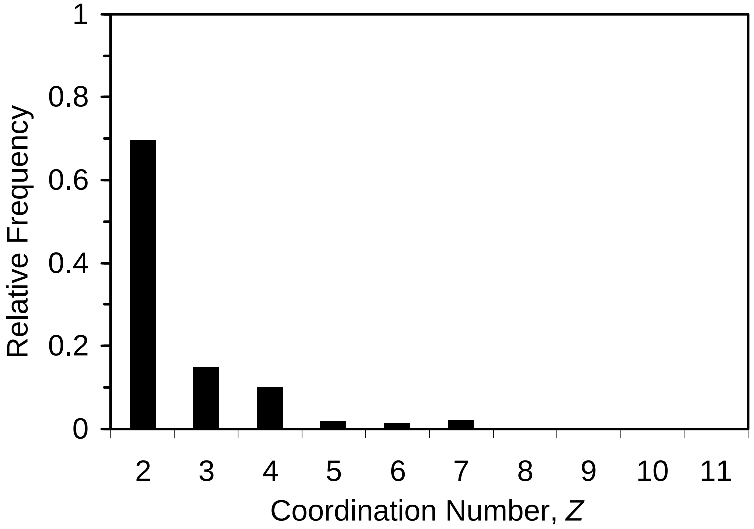


Figure 4. Coordination number distribution in stochastically reconstructed sample 58A.

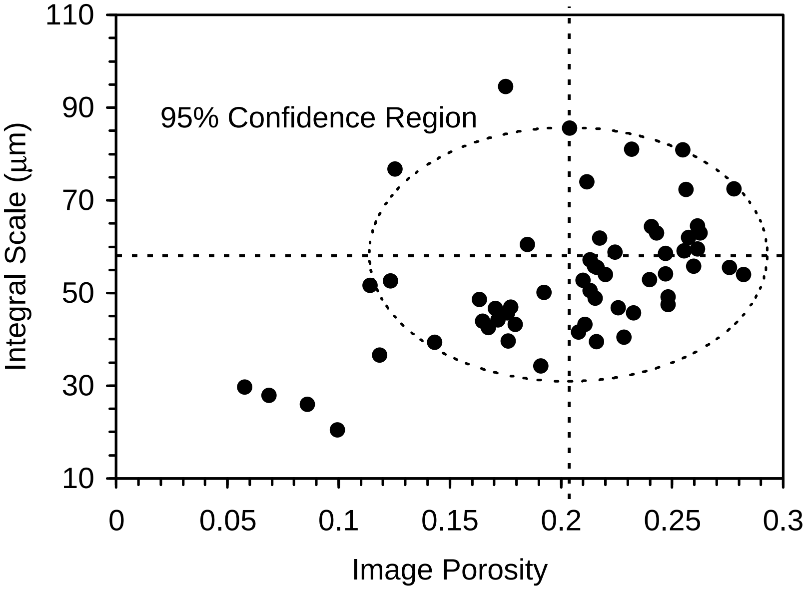


Figure 5. Cross-plot of integral scale (area under the autocorrelation curve) and porosity.

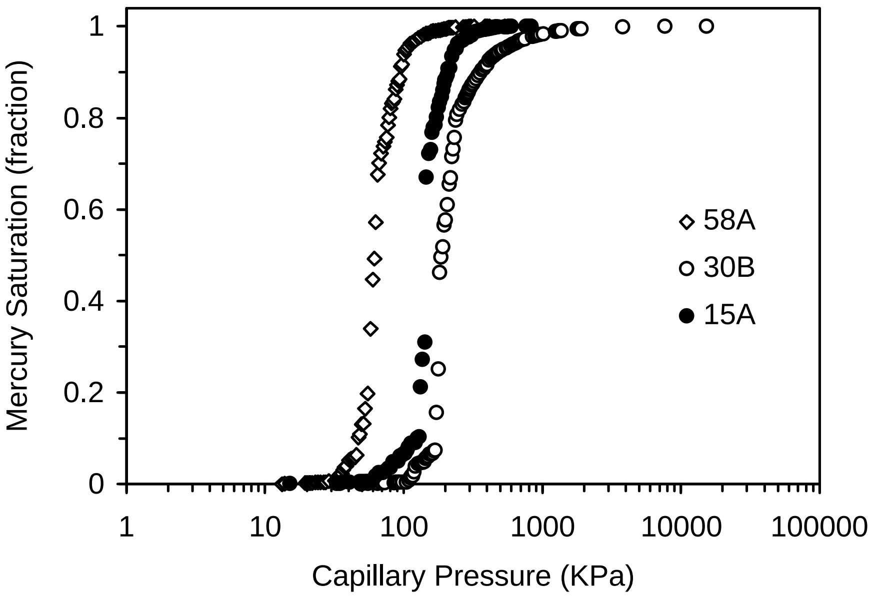


Figure 6. Simulated mercury intrusion porosimetry curves using geometrical and topological information from stochastic models of three different reservoir rocks.

Network simulation of a variety of petrophysical properties was accomplished using as input the results of 3-D geometrical and topological characterization. Figure 6 shows typical simulated mercury porosimetry curves for 3 different samples. These results reflect the narrow range of throat sizes found in the stochastically simulated media.

Figure 7 compares the prediction of resistivity index as a function of water saturation to experimental data obtained by the continuous injection method using n-decane as the displacing fluid. The agreement between the two sets of data is remarkably good considering that no adjustable parameters were involved in the prediction. Similar or better results were obtained for all of the samples examined.

Predictions of absolute permeability and formation factor are compared to experimental data in Table I. These results reveal a consistent over-prediction of the permeability of all samples below 10 mD. It is reminded that stochastic realizations of all media were created at a resolution equal to the resolution of the corresponding micrographs (see Table I). This value sets a limit for the smallest throat that can be detected in each simulated medium (*i.e.,* one voxel). The hypothesis that insufficient resolution is responsible for overestimating the permeability of low-permeability samples was further investigated. Since image data for the same sample were not available at two

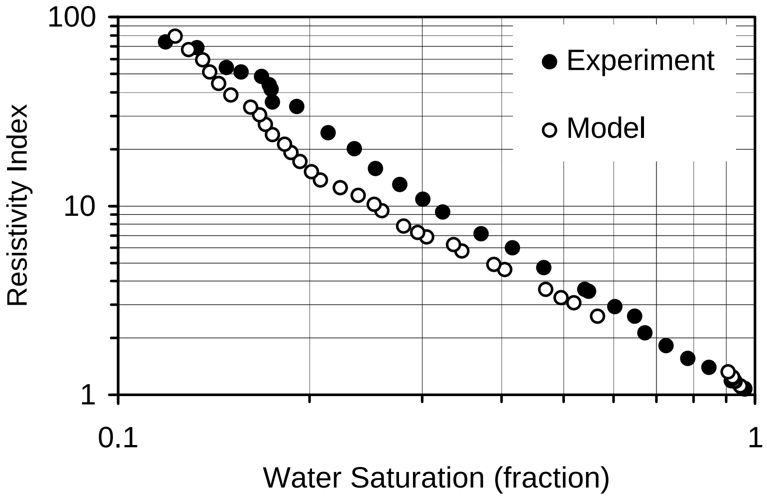


Figure 7. Resistivity index as a function of water saturation for sample 58A.

Table I. Measured and predicted properties of rock samples.

| Sample | Resolution (μm/pixel) | φ | k (mD) | | F | |
|---|---|---|---|---|---|---|
| | | Measured | Measured | Predicted | Measured | Predicted |
| 58A | 3.13 | 0.197 | 728.0 | 597.0 | 24.2 | 20 |
| 16 | 3.13 | 0.202 | 646.0 | 407.7 | - | 27 |
| 7 | 3.13 | 0.134 | 412.0 | 396.4 | 66.6 | 43 |
| 15A | 1.54 | 0.173 | 114.0 | 66.6 | 45.7 | 28 |
| 45B | 1.54 | 0.129 | 28.0 | 45.7 | 46.8 | 49 |
| 45A | 1.54 | 0.153 | 25.9 | 53.8 | 40.3 | 55 |
| 4A | 1.54 | 0.198 | 6.5 | 102.4 | - | 17 |
| 9B | 1.05 | 0.152 | 5.3 | 23.8 | 54.1 | 52 |
| 35B | 1.54 | 0.101 | 3.5 | 43.2 | - | 75 |
| 1 | 1.54 | 0.125 | 3.0 | 69.2 | - | 55 |
| 30B | 1.05 | 0.122 | 2.1 | 25.6 | 40.1 | 42 |
| 31B | 1.05 | 0.129 | 1.8 | 37.4 | - | 34 |
| 4B | 3.13 | 0.069 | 1.7 | 209.5 | 76.6 | 41 |
| 31A | 1.05 | 0.102 | 0.5 | 16.9 | - | 55 |

different magnifications, resolution effects were studied by analyzing the microstructure of a low-permeability sample (30B), reconstructed at twice the original resolution (2X). This was achieved by interpolating the original autocorrelation function. As shown in Figure 9, increasing the resolution does not only extend the range of throat sizes to smaller values, as expected, but also reduces the number fraction of throats of all other sizes. Similar effects on the pore size distribution were also observed. The shift in the throat size distribution results in a decrease of the throat size corresponding to the formation of a sample-spanning cluster of non-wetting phase through the simulated medium (percolation threshold), thus causing a significant reduction of permeability ($k_{2X}$ = 6.2 mD). The prediction of formation factor is also affected ($F_{2X}$ = 60.9), albeit to a lesser extent due to the weaker dependence of electrical conductivity on throat size. Resistivity index calculations were shown to be insensitive to pore space resolution.

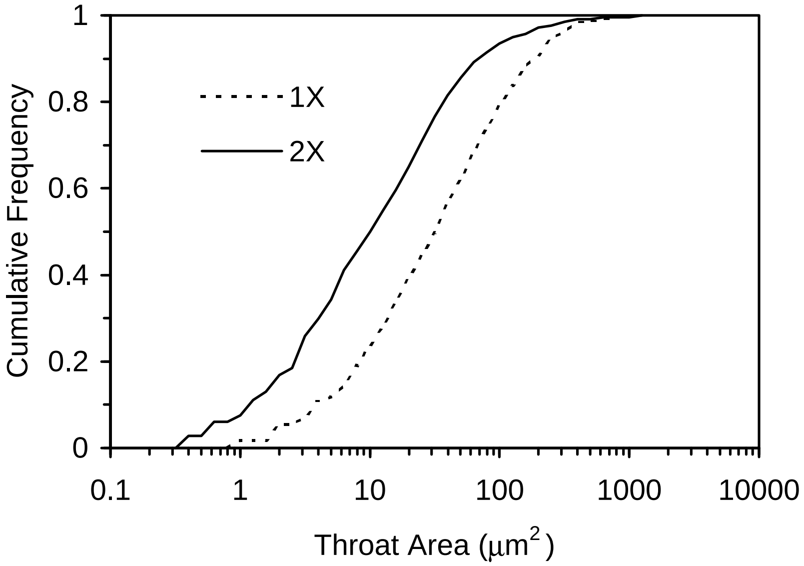


Figure 8. Effect of resolution of the stochastic reconstruction on throat area distribution.

## Conclusions

3-D stochastic simulation, geometric and topological characterization and network modeling were combined to create a new tool for the exploitation of 2-D micrographs of the pore space obtained from common petrographic thin sections. Predictions of the absolute permeability, formation factor and resistivity index-water saturation relationship were compared to laboratory data for a set of diverse reservoir samples. Although preliminary, this comparison is indicative of the potential of computer-enhanced core analysis to yield useful estimates of petrophysical properties. Image resolution was found to be an important factor in the estimation of pore and throat size distributions and was shown to affect network predictions of absolute permeability and formation factor.

Stochastic simulation based on the assumption of statistical homogeneity was also shown to produce model media with pore and throat size distributions much narrower than would be expected if the variability of image statistical properties had been taken into account. Further research is needed in order to overcome this limitation.

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