FINAL REPORT

DE-FG02-92ER14261

**PORE SCALE GEOMETRIC
AND FLUID DISTRIBUTION ANALYSIS**

W. Brent Lindquist

`lindquis@ams.sunysb.edu`

Department of Applied Mathematics and Statistics

SUNY at Stony Brook

Stony Brook, NY 11794-3600

January 21, 2005

Contents

1	Overview	2
2	Numerical Algorithms	2
3	Pore Space	4
4	Fluid Partitioning	7
5	Technology Transfer	15
6	Cited References	17
7	Publications Sponsored by this Grant	19
8	Theses Sponsored by this Grant	21
9	Appendix A	22

1 Overview

The elucidation of the relationship between pore scale structure and fluid flow in porous media is a fundamental problem of long standing interest. Incomplete characterization of medium properties continues to be a limiting factor in accurate field scale simulations. The accomplishments of this grant have kept us at the forefront in investigating the applicability of X-ray computed microtomography (XCMT) as a tool for contributing to the understanding of this relationship.

Specific accomplishments have been achieved in four areas:

1. development of numerical algorithms (largely in the field of computational geometry) to provide *automated* recognition of and measurements on features of interest in the pore space. These algorithms have been embodied in a software package, 3DMA-Rock.
2. application of these algorithms to extensive studies of the pore space of sandstones.
3. application of these algorithms to studies of fluid (oil/water) partitioning in the pore space of Berea sandstone and polyethylene models.
4. technology transfer.

2 Numerical Algorithms

The major algorithms in 3DMA-Rock [5] are: segmentation, medial axis construction and trimming, throat finding, pore-network construction, and medium geometry characterization. The complete characterization of these algorithms is addressed in [6, 7, 8, 9, 10, 15, 22, 25]; we summarize the major points here.

Segmentation, the phase identification of each voxel in the image is a vast area of investigation in computer science. We have contributed to this with the development [14, 15] of a segmentation algorithm designed for bi-phase media, such as rocks, which are described by an isotropic two-point correlation function.

The medial axis of the pore space provides a network of paths used to systematically search the pore space for features of interest. Crucial features of the medial axis are its faithfulness to the topology of the pore space, and its property of central placement with respect to the pore-grain surface. These two features, combined with a distance measure from medial axis voxels to the closest grain voxels also provide a direct means of characterizing some geometrical properties of the pore space. The susceptibility of the medial axis to details of the pore-grain surface (including digitization noise) produces dead end paths on the medial axis that are not meaningful descriptors of pore space geometry. We solve this problem by removing *all* dead end paths that terminate inside the imaged region. This leaves a medial axis “backbone” which captures the flow carrying pathways through the pore space.

A major contribution has been our development of two automated throat finding algorithms [7, 22, 25] which locate minimal cross sectional areas along the pore channels. The medial axis is employed as a search path in locating the throats. A throat is constructed as a triangulated surface; our algorithms have the feature that they do not presuppose the throat surface is planar. Fig. 1 shows four rotated views of a throat separating two pores in a polyethylene core. Side view (b) shows the intersection of the throat and pore-grain surfaces, demonstrating that the throat surface is non-planar. Construction of throats allows the void space to be divided into pores separated by

(a) throat view from first pore (0 degrees)

(b) side view (90 degrees)

(c) side view (135 degrees)

(d) view from second pore (180 degrees)

Figure 1: Views of a throat surface (white) between two pores. The pore-grain surface is brown, the voxels of the medial axis path connecting the two pores are green.

throat surfaces.¹

In addition to throat construction, we have implemented the marching cubes algorithm [1, 12] to determine the pore-grain surface for each individual pore. The pore-grain surface shown in Fig. 1 is generated via this algorithm.

With throats located, the pore space can be divided into a network of pores separated by throat surfaces. The pore network is subjected to geometric characterization. As rock properties are statistical, we characterize the spatial variation of any property by determining its distribution of values over the imaged region. Distributions are produced for: pore coordination number, pore volume, pore surface area, and throat surface area. For each pore, we also compute its center of mass, the diameters in each of the three principal directions (moment of inertial analysis), and an effective radius (determined from the sphere of volume equivalent to that of the pore body). For each throat we analogously determine its diameters in the two principal directions and an effective throat radius (determined from the circle of area equivalent to that of a throat surface). Finally cross correlations between pairs of variables, such as coordination number with pore volume or throat effective radius with pore effective radius, are computed.

3 Pore Space

We have applied 3DMA-Rock to an analysis of the pore space in Fontainebleau sandstone [7, 9, 10], Berea sandstone [16, 18], and to vesiculated basalts [9, 23, 24]. Our principal findings on the characterization of the pore space in Fontainebleau sandstones, for which we have the greatest porosity variation, are the following.

Coordination Number C . Over the range $3 \leq C \leq 9$, the coordination number distribution is well described by the exponential, $10^{-C/C_0}$ (Fig. 2(a)). C_0 increases linearly with porosity from 1.8 at 7.5% porosity to 3 at 22% porosity (Fig. 2(a) inset). This quantifies the expectation that the void space in higher porosity sandstones is more highly connected.

Channel Length L . We *define* a pore channel length as the medial axis path distance between two neighboring (connected) pores. This channel length distribution is Weibull-like, with a characteristic exponential decay, $10^{-L/L_0}$ (Fig. 2(b)). L_0 decreases linearly as porosity increases (Fig. 2(b) inset) indicating pores become closer together.

Throat Area. The throat area distribution (Fig. 2(c)) is suggestive of log-normal, though skewed to smaller throat area and with a strong exponential decay structure for areas above the mean value. The mean throat area increases linearly from $650 \mu\text{m}^2$ at 7.5% porosity to $1300 \mu\text{m}^2$ at 18% porosity. (Fig. 2(c) inset).

Pore Volume. The pore volume distribution is well described as log-normal (Fig. 2(d)) with mean pore volume *falling* slightly from $4 \cdot 10^{-4} \text{ mm}^3$ at 7.5% porosity to $2.7 \cdot 10^{-4} \text{ mm}^3$ at 22% porosity (Fig. 2(d) inset). In understanding this result it is important to emphasize that our pore network model is one of pores separated by throat surfaces, *i.e. all the void space volume is divided among the nodal pores.*² Thus at low porosity, the lower connectivity of the pores means the connecting “channels” between them must be longer, maintaining relatively high pore volume.

¹As opposed to pores connected by channels. For real rock, we know of no unique geometrical-based definition of where a pore terminates and a connecting channel begins.

²If considered from the perspective of pore-channel models, our pore-throat model includes channel volume as belonging to the pores.

Figure 2: Summary of measured distributions of geometrical characteristics obtained from an investigation of a suite of Fontainebleau sandstones, from 7.5% to 22% porosity. Voxel resolution is $5.7 \mu\text{m}$. In each case, the inset plot shows variation of the characteristic distribution parameter(s) with porosity. (a) Pore coordination number. (b) Channel length. (c) Throat surface area. (d) Pore volume. (e) Pore surface area. (f) Pore specific surface area.

Figure 3: (left) Distributions for pore principal axes diameters (D_1, D_2 and D_3), effective radius (R_{eff}), and diameter in an arbitrary direction (D_x). The diameter plots have been vertically offset from one another for clarity. The effective radius is plotted with the same vertical offset as D_3 to show the similarity of these two distributions. (right) Distributions for throat principal axes diameters (D_1 and D_2), and effective radius. The diameter plots have been vertically offset from one another for clarity. The effective radius is plotted with the same vertical offset as D_2 to show the similarity of these two distributions.

At high porosity, higher connectivity means shorter channels, with a net decline in average pore volume.

Pore Surface Area. The pore surface area distribution is log-normal with mean area of $\sim 4 \cdot 10^{-2} \text{mm}^2$ (Fig. 2(e)). As for pore volume, the mean surface area shows slight decrease with increasing porosity (Fig. 2(e) inset).

Specific Pore Surface Area. Based upon the previous two distributions, the specific surface area (defined as pore surface area divided by pore volume) must also be log-normal, as is verified in Fig. 2(f). The mean specific surface area increases by a factor of about two over the porosity range 7.5% to 22% (Fig. 2(f) inset).

Pore, Throat Diameters. There is remarkable similarity between the distributions for the *smallest principal diameter* and for the *effective radius* of a pore (Fig. 3(left)). (Recall, effective radius is defined from the sphere of equivalent volume.) This similarity is echoed (Fig. 3(right)) in the throat surface areas, where the distributions of smaller principal throat diameter and effective throat radius (defined from circle of equivalent area) are remarkably similar. We are currently trying to understand the implication of this observation.

Berea versus Fontainebleau. Our results for Berea sandstone ($\sim 20\%$ porosity) are similar to those of Fontainebleau.

These results provide a picture of how the pore space changes in Fontainebleau as the porosity decreases due to cementation and quartz overgrowth. The decrease in the characteristic coordination number C_0 implies decreasing connectivity between nodal pore sites. The strong increase in characteristic channel length L_0 combined with the continued maintenance of permeability above 5% porosity for Fontainebleau implies that a significant number of nodal pores remain open but are reduced in coordination number ultimately resulting in the geometric union of pairs of pores

into “longer” units. This process of pore “merging” with porosity reduction maintains a relatively constant average pore size. The more modest changes in average throat area indicate a universality of contraction of channels over all dimensional ranges in the cementation/overgrowth processes.

4 Fluid Partitioning

With the use of X-ray absorbing dopants (iodine and bromine) to increase X-ray contrast between fluids [16, 18, 19, 21] and careful tomographic registration to re-image *the same region*³ after fluid injection, we have examined 3D fluid distribution in pore space in Berea sandstone and a polyethylene rock model.

The algorithms described in §2 have been adapted [16] to the problem of differentiating (segmenting) two fluid phases residing in the (previously identified) pore space and analyzing the geometric partitioning of the fluid phases in the pore space. As XCMT imaging time (about 6 hours) is too long to visualize flow dynamics, the flow must be held static (fluid injection halted via cessation of driving pressure gradient) during the imaging procedure. We therefore concentrate on imaging at steady state conditions, either when one of the fluid phases is at residual conditions; or both phases have been simultaneously injected at a fixed volume ratio (fixed fractional flow conditions). In both cases, imaging occurs after many pore volumes of the injected fluid(s) have flowed through the core sample.

In collaboration with R. Seright (Petroleum Recovery Research Center, New Mexico Institute of Mining and Technology) we are tackling the problem of understanding the disproportionate permeability reduction induced by the emplacement of gels into the pore space. The filling of pore space with an aqueous-based polymeric gel can reduce permeability to subsequent water flow by a factor of 10^4 [20] compared with single phase permeability to water in the absence of gel. Gel placement in two phase flow situations causes analogous, though disproportionate, phase permeability reductions. In particular, consider the residual resistance factor to oil, F_{rro} , defined as the ratio of relative permeability to oil flow at residual water conditions before and after gel placement, and the residual resistance factor to water, F_{rrw} , defined as the ratio of relative permeability to water flow at residual oil conditions before and after gel placement. In Berea cores, $F_{rro} \approx 10$ while $F_{rrw} \approx 10^3$. In polyethylene, $F_{rro} \approx 25$ while $F_{rrw} \approx 2 \cdot 10^3$. During field treatments when, for example, production wells are treated with gelants, some zones have high water saturation and high fractional water flow and other zones have high hydrocarbon saturation and fractional flow. After gel placement, in the oil zones, oil is the first fluid to flow through gel zones and F_{rro} and the mechanism determining its values are field-relevant. In water zones, water is the first fluid through gel zones and the permeability reduction factor of $\approx 10^4$ for water through aqueous gel is relevant. However, active management of fields, with the potential for long term, induced changes in flow patterns make the study of the disproportionate value for F_{rrw} also of scientific interest.

Our typical study proceeds as follows. A 6.5 mm diameter, 35 mm length core sample is extracted from a larger Berea sample. The core is saturated with brine containing 1% NaCl and 0.1% CaCl_2 and imaged at the tomographic facility on the X2B beam line [3] at the National Synchrotron Light Source, Brookhaven National Lab. The central section along the length of the core is imaged, with image size being 1024^3 voxels at 4-5 μm voxel resolution. This region is successively imaged at residual fluid conditions that occur during a sequence of floods, the experimental apparatus [18] enabling both the flooding and imaging sequence to be performed

³Including alignment of voxels.

Figure 4: The same slice from a sequence of 3D XCMT images of a Berea core showing brine/oil distribution at residual fluid conditions before and after injection and emplacement of the water soluble gel, Cr(III)-acetate-HPAM. Image resolution is $4.93 \mu\text{m}$.

without removing the core from the mounting stage. A typical fluid injection sequence, shown in Fig. 4, is hexadecane; brine; aqueous gel; hexadecane; brine. Sufficient pore volumes of displacing fluid are injected at each stage to establish residual conditions in the core. (This is verified by simultaneous permeability measurements.) The gel is Cr(III)-acetate-HPAM (hydrolyzed polyacrylamide) consisting of (by weight) 0.5% Alcoflood 935 HPAM, 0.0417% Cr(III) acetate, 1% NaCl, and 0.1% CaCl_2 . The hexadecane is doped either with iodo- or bromohexadecane to improve X-ray attenuation contrast between the brine and oil phases. All experiments are performed at room temperature except following the gel injection stage, when the core is heated to $\sim 60^\circ\text{C}$ for 12 hours to effect gelation.

Permeability measurements are recorded as a function of pore volumes injected during each injection stage. Permeabilities used to compute F_{rro} and F_{rrw} are taken at the end of the sequence when residual conditions have been established. At the end of each injection stage, flow is halted

(release of pressure gradient) while tomographic imaging is performed. After each 3D image is acquired, the core is rotated to zero position to ensure voxel alignment between images.

The geometry of the pore space is analyzed from the image of the initial brine saturated core. In particular the location of grains and pore throat surfaces are determined from this image. The grain matrix is identified in the remaining images of the sequence from its location in the first image. In the remaining images, the fluid filled space is then subjected to segmentation using the kriging based algorithm to identify the oil and brine phases (the water-based gel is indistinguishable from brine phase). In addition to determining oil and brine saturations for the entire image, by inserting the identified throat surfaces into the pore space of the rest of the images, saturations can be determined on a pore-by-pore basis. Figs. 5 and 6 contrast measured saturation behavior at the pore level in a flooding sequence in a Berea core and in a polyethylene core.

Additionally the structure of each fluid phase is separately analyzed. We characterize the connectivity of each fluid phase by computing the number, location and size of the individual disconnected “blobs” of each phase. Figs. 7 and 8 contrast the measured blob size distributions for the flows in the Berea and polyethylene cores of Figs. 5 and 6. We are also interested in the “pore occupancy” of each phase [2], where the pore occupancy of a blob is defined as the number of pores it spans.

Our principal findings to date are the following.

Oil is largely immobile in small polyethylene pores, whereas pore size does not significantly influence water retention in Berea. In the polyethylene core, an expected “S”-shaped plot of S_w versus pore size is seen at S_{or} (Fig. 6 plots (1) S_{or} or (3) S_{or}) in accordance with the classic expectation of no significant water penetration into small pores at residual oil conditions in a strongly oil-wet medium. In water-wet Berea however, we detect significant oil penetration into small pores⁴ at S_{wr} (Fig. 5, plot (1) S_{wr}), Norman Morrow (U. Wyoming) has offered a credible explanation for this behavior. Berea pores are typically coated with kaolinite, significantly increasing surface roughness. In contrast, the pore walls in polyethylene are quite smooth. At S_{or} in polyethylene, an extremely thin (nanometer scale) or (possibly) no oil film may coat pore walls, whereas, in water-wet Berea, at S_{wr} the rough clay coating may make the effective water film of greater thickness. With a thicker effective wetting film, water may drain fairly efficiently from the smallest detected Berea pores when oil is injected, allowing the smallest detected pores ($\sim 5 \cdot 10^{-6} \mu\text{m}^3$) to reach water saturations comparable to those in larger pores. In contrast, when water is injected into porous polyethylene, oil can become hydraulically isolated in the smallest detected pores as remaining wetting films are too thin to effectively drain oil.

The injection of aqueous-based polymer gel mobilizes residual oil in both Berea (water wet) and polyethylene (oil wet) cores. A comparison of the sequential plots S_{or} and gel in either Fig. 7 or 8 shows further mobilization of the residual oil upon gel injection. We have eliminated [16, 21] the possibilities that: high pressure gradients; the high viscosity (20 cp) of the injected gel; and alteration of the the wettability by polymer or Cr(III) adsorption are responsible for this mobilization. Wang [26] has suggested that viscoelastic forces associated with the flow of (non-Newtonian) polymer solutions may re-distribute forces on a microscopic scale and produce the observed oil mobilization.

⁴Our voxel resolution of between 4-5 μm (depending on the experiment) provides a cutoff length scale for the smallest detectable pores. This may also be a significant factor for Berea cores where clays lining the pore surfaces may result in significantly smaller pore pathways than can be imaged.

Figure 5: Distribution of water saturations as a function of pore volume at the sequence (1) $\rightarrow$ (5) of residual fluid conditions investigated in a water-wet Berea core. For each volume range, we present a box plot summarizing the distribution of saturations measured in all pores having volume in the specified range.

Figure 6: Distribution of water saturations as a function of pore volume at the sequence (1) → (6) of residual fluid conditions investigated in an oil-wet polyethylene core. For each volume range, we present a box plot summarizing the distribution of saturations measured in all pores having volume in the specified range.

Figure 7: Distribution of fluid "blob" sizes at the sequence (top to bottom) of residual fluid conditions investigated in the water-wet Berea core of Fig. 5.

Figure 8: Distribution of fluid "blob" sizes at the sequence (top to bottom) of residual fluid conditions investigated in an oil-wet polyethylene core of Fig. 6.

Immediately after gel placement in either Berea or polyethylene, an extremely high resistance ($F_{rrw} > 10^4$) to water flow occurs. This agrees with previous laboratory experiments on larger rock cores, supporting the conclusion that “impermeable” gel is occupying all of the aqueous pore space.

In both core types, during oil flow after gel placement, gel becomes dehydrated, opening flow paths to oil resulting in F_{rro} values of the order of 10-20. Oil injection after gelation reduces gel volume. In Berea, gel saturation is reduced from 65% (Fig. 7 gel) to 32% (Fig. 7 gels_{wr}); in polyethylene, the reduction is from 99.8% (Fig. 8 gel) to 85% (Fig. 8 gels_{wr}). The possible causes for the gel volume reduction, include. i) mechanical breakage (“ripping”) of the linked polymer network, ii) concentration (dehydration) by compressing the polymer network, iii) gel mobilization, and iv) chemical destruction of the gel. As hexadecane is not reactive with the gel, brine or solid matrix, chemical destruction is unlikely. Close monitoring of pressure gradients during flooding indicates gradients were below thresholds needed to mobilize gel. In addition, in similar bulk core floods gel production has never been observed. Ripping should occur with predominance in large pores; our results show insensitivity of gel volume changes with pore size. In fact, with a fixed driving pressure gradient, one would expect gel compression (dehydration) to occur uniformly with pore size - in agreement with observation.

In Berea, oil trapping is the dominant mechanism for disproportionately high F_{rrw} values. In Berea, during the final brine flood, oil becomes trapped (Compare Fig. 7 gels_{or} with S_{or}). The invading water either encounters these significant trapped oil regions or gelled aqueous regions, resulting in values for F_{rrw} of $\sim 10^3$ that are disproportionately high (compared to oil). We have not yet ascertained the mechanism for the oil trapping. We have however eliminated gel concentration (dehydration) in throat regions as a mechanism for such trapping [16]. We note that fluid-fluid specific surface area (surface area per unit pore volume) increases by a factor of 2-3 for fluid partitioning in floods after gel placement. This implies a more convoluted shape to fluid blobs and may provide some clue to the trapping mechanism.

In polyethylene, we postulate rehydration of the gel as the mechanism for the disproportionately high F_{rrw} . We have seen no evidence of oil trapping in polyethylene cores, (compare Fig. 8 gels_{or} with S_{or}) suggesting the injected water serves to rehydrate gel, effectively blocking aqueous flow paths that may try to re-form. Rehydration may also occur in Berea, but appears less dominant a blocking mechanism compared to the oil trapping.

In Berea, residual phase pore occupancy follows a power-law distribution. In a study on the structure of residual oil saturation, Chatzis et al. [2] reference earlier work [17] on flow in unconsolidated bead packings that found 65% of the oil blobs at residual oil saturation were singlets (i.e. fully contained in single pores), 20% of the blobs were doublets (i.e. spanned two pores), and the rest displayed greater pore occupancy. In observing blobs of volume larger than $1.2 \cdot 10^{-5} \text{ mm}^3$, we observe a singlet frequency of 60% and a double frequency of 25%. The number frequency distribution however is quite susceptible to changing the imposed cut-off defining small blob size. To remove this dependence, we consider not the fraction of blobs, but the fractional volume of blobs, a measure which is less sensitive to fluid segmentation errors (which may produce isolated phase blobs of small size). Let V_{1-9} denote the total volume occupied by all blobs of the residual phase, and $V_{1-9}(i)$ denote the total volume occupied by residual phase blobs of occupancy i . Our results indicate

$$f_V(i) = f_V(1) i^{-\alpha}, \quad i = 1, \dots, 9$$

for occupancy values in the range 1-9, with $0.7 \lesssim_{14} \alpha < 1.0$ and $f_V(1) \sim 0.3$.

The “continuous part” of the distribution of blob sizes for either fluid phase is bounded by the largest pore size. From Figs. 7 and 8 we see, at any residual condition, that the blob size distribution for the dominant fluid phase is dominated by a single connected blob occupying the majority of the volume for that phase plus a continuous size spectrum of smaller blobs. For the residual phase a large blob is usually not present (unless gel injection causes trapping) and the residual phase blob size distribution exists a continuous spectrum of small blobs. For either phase, the continuous part of the spectrum of blob sizes is bounded by the largest pore size. This is shown explicitly in Fig. 7 for Berea, where the pore size distribution is plotted along with the blob size distributions on the gel graph.

5 Technology Transfer

I am receiving an ever increasing number of e-mail requests for use of the 3DMA-Rock software package. The source code is downloadable by ftp from the Stony Brook Department of Applied Mathematics and Statistics ftp server. I have established a web site [5] containing compilation and execution instructions, runtime examples, explanation of the major algorithms for the software, and a bibliography of reference papers. Appendix A gives a partial list of scientists (excluding my direct collaborators) who have made inquiries/downloaded the software.

The three dimensional image analysis aspect of this work is, not surprisingly, of interest in other applications. The support provided by DOE Geosciences in developing algorithms for the analysis of XCMT images of geologic porous media has also been the seed for technology transfer to the followings areas of industry and science.

Neuron Anatomy. Neuron morphology, particularly dendritic structure and the placement and plasticity of synaptic junctions have been shown to be associated with experience-dependent plasticity, learning and memory, as well as to forms of neural dysfunction. 3D images provided by laser scanning microscopy are an essential tool for studying nerve cell structure. However state-of-the-art analysis of such images requires the human eye to perform feature recognition, which translates in practice to structure tracing via “mouse-click”. We have developed automated algorithms for dendrite tracing [13, 27] and for automated recognition of dendritic spines (post-synaptic terminals) [4]. This development has led to NSF funding in support of development of the next generation of analysis software for neural images providing automated feature recognition.

Our algorithms have been incorporated into a software package, 3DMA-Neuron [11], available for distribution to federally funded researchers. A list of recent scientists making inquiries/downloads of 3DMA-Neuron is also presented in Appendix A.

Paper Products. In collaboration with, and funded by, Kimberly Clark Corp. we have developed a software package, 3DMA-Fiber, to perform automated geometric characterization of fiber mat products. Our early work was focused on mats of natural and artificial fibers. Current research focuses on characterization of tissue products. The goal is the rapid characterization of the physical properties of tissue products, with an ultimate goal of developing “designer” tissue products having specific properties.

Bone. In collaboration with Prof. Y.-X. Qin, Department of Biomedical Engineering, Stony Brook University, and Dr. J. Pinezich, Advanced Acoustic Concepts (AAC), Hauppauge NY, with funding provided by AAC and New York State, we are applying our image analysis expertise to the study of trabecular bone. The emphasis is on the development of early detection of osteoporosis by acoustic means. As acoustic (ultrasound) resolution is still too coarse, osteoporosis detection

will require inference from ultrasound signals. Our current study involves simulated erosion of trabecular bone and quantification of the early stages of significant damage due to erosion. We are concentrating on detection and quantification of topological changes occurring in trabecular bone during the erosion process. This is achieved using an extension of the erosion/topological change detection algorithms utilized in skeletonization schemes. To handle fine scale erosion effects, the goal is to design algorithms for parallel processing architecture. The development will occur on the department's Linux cluster supercomputer, the Stony Brook Galaxy, consisting of 275 Pentium-based processors.

References

- [1] J. Bloomenthal. Polygonization of implicit surfaces. *IEEE Comput. Graph. App.*, 5:341, 1988.
- [2] I. Chatzis, N.R. Morrow, and H.T. Lim. Magnitude and detailed structure of residual oil saturation. *Soc. Petrol. Eng. J.*, 23:311–326, 1983.
- [3] H.W. Deckman, J.H. Dunsmuir, K.L. D’Amico, S.R. Ferguson, and B.P. Flannery. Development of quantitative X-ray microtomography. *Mater. Res. Soc. Symp. Proc.*, 217:97, 1991.
- [4] I.Y.Y. Koh, W.B. Lindquist, K. Zito, E.A. Nimchinsky, and K. Svoboda. An image analysis algorithm for the fine structure of neuronal dendrites. *Neural Comput.*, 14:1283–1310, 2002. ftp://ams.sunysb.edu/pub/papers/2001/susb01_01.pdf.
- [5] W.B. Lindquist. 3DMA-Rock. http://www.ams.sunysb.edu/~lindquis/3dma/3dma_rock/3dma_rock.html.
- [6] W.B. Lindquist. Network flow model studies and 3D pore structure. *Contemp. Math.*, 295:355–366, 2002. ftp://ams.sunysb.edu/pub/papers/2001/susb01_14.pdf.
- [7] W.B. Lindquist. Quantitative analysis of three dimensional X-ray tomographic images. In U. Bonse, editor, *Developments in X-ray Tomography III*, volume 4503 of *Proc. SPIE*, pages 103–115, Bellingham, WA, 2002. SPIE. ftp://ams.sunysb.edu/pub/papers/2001/susb01_06.pdf.
- [8] W.B. Lindquist, S.-M. Lee, D.A. Coker, K.W. Jones, and P. Spanne. Medial axis analysis of three dimensional tomographic images of drill core samples. *J. Geophys. Res.*, 101:8297–8310, 1996. ftp://ams.sunysb.edu/pub/papers/1995/susb95_01.ps.gz.
- [9] W.B. Lindquist and A. Venkatarangan. Investigating 3D geometry of porous media from high resolution images. *Phys. Chem. Earth*, A25:593–599, 1999. ftp://ams.sunysb.edu/pub/papers/1998/susb98_01.ps.gz.
- [10] W.B. Lindquist, A. Venkatarangan, J. Dunsmuir, and T.-f. Wong. Pore and throat size distributions measured from synchrotron X-ray tomographic images of Fontainebleau sandstones. *J. Geophys. Res.*, 105:21508–21528, 2000. ftp://ams.sunysb.edu/pub/papers/1999/susb99_13.pdf.
- [11] W.B. Lindquist and C.M. Weaver. 3DMA-Neuron. http://www.ams.sunysb.edu/~lindquis/3dma/3dma_neuron/3dma_neuron.html.
- [12] W.E. Lorensen and H.E. Cline. Marching cubes: a high resolution 3-D surface construction. *ACM Comput. Graph.*, 21:163, 1987.
- [13] M. Maravall, Y.Y. Koh, W.B. Lindquist, and K. Svoboda. Experience-dependent changes in basal dendritic branching of layer 2/3 pyramidal neurons during a critical period for developmental plasticity in rat barrel cortex. *Cerebral Cortex*. in press.
- [14] W. Oh. *Random Field Simulation and an Application of Kriging to Image Thresholding*. PhD thesis, Stony Brook University, 1998. <ftp://www.ams.sunysb.edu/pub/papers/theses/woh.ps.gz>.

- [15] W. Oh and W.B. Lindquist. Image thresholding by indicator kriging. *IEEE Trans. Pattern Anal. Mach. Intell.*, 21:590–602, 1999. ftp://ams.sunysb.edu/pub/papers/1998/susb98_02.ps.gz.
- [16] M. Prodanovic, W.B. Lindquist, and R.S. Seright. 3D microtomographic study of fluid displacement in rock cores. To be presented at the Computational Methods in Water Resources XV Conference, Chapel Hill, NC, June 13–17, 2004. ftp://ams.sunysb.edu/pub/papers/2004/susb04_01.ftp.
- [17] R.L. Robinson and R.E. Haring. Experimental study of residual oil configuration in unconsolidated sand. Technical report, Jersey Prod. Res. Co. Report, Prod. Div., Jan. 1962.
- [18] R.S. Seright, J. Liang, W.B. Lindquist, and J.H. Dunsmuir. Use of X-ray computed microtomography to understand why gels reduce permeability to water more than to oil. *J. Petroleum Sci. Eng.*, 39:217–230, 2003. ftp://ams.sunysb.edu/pub/papers/2002/susb02_03.pdf.
- [19] R.S. Seright, J.-T. Liang, W.B. Lindquist, and J.H. Dunsmuir. Characterizing disproportionate permeability reduction using synchrotron X-ray computed microtomography. *SPE Reserv. Eval. Eng.*, 5:355–364, 2002. ftp://ams.sunysb.edu/pub/papers/2002/susb02_02.pdf.
- [20] R.S. Seright, J.-T. Liang, and H. Sun. Gel treatments in production wells with water coning problems. *In Situ*, 17:243–272, 1993.
- [21] R.S. Seright, M. Prodanovic, and W.B. Lindquist. X-ray computed microtomography studies of disproportionate permeability reduction. SPE paper #89393. To be presented at the 14th SPE/DOE Symposium on Improved Oil Recovery, Tulsa, OK, Apr. 17–21, 2004. ftp://ams.sunysb.edu/pub/papers/2003/susb03_19.doc.
- [22] H. Shin. *A Throat Finding Algorithm for Medial Axis Analysis of 3D Images of Vesiculated Basalts*. PhD thesis, Stony Brook University, 2002. <ftp://www.ams.sunysb.edu/pub/papers/theses/shinhyun.ps.gz>.
- [23] H. Shin, W.B. Lindquist, D.L. Sahagian, and S.-R. Song. Analysis of the vesicular structure of basalts. *Comput. Geosci.*, submitted. ftp://ams.sunysb.edu/pub/papers/2003/susb03_18.pdf.
- [24] S.-R. Song, K.W. Jones, W.B. Lindquist, B.A. Dowd, and D.L. Sahagian. Synchrotron X-ray computed microtomography studies on vesiculated basaltic rocks. *Bull. Volcan.*, 63:252–263, 2001. ftp://ams.sunysb.edu/pub/papers/2003/susb03_01.doc.
- [25] A.B. Venkatarangan. *Geometric and Statistical Analysis of Porous Media*. PhD thesis, Stony Brook University, 2000. <ftp://www.ams.sunysb.edu/pub/papers/theses/syanora.ps.gz>.
- [26] D. Wang, X. Huifen, L. Zhongchun, and Y. Qingyan. Study of the mechanism of polymer solution with visco-elastic behavior increasing microscopic oil displacement efficiency and the forming of steady oil thread flow channels. SPE paper #68723 presented at the 2001 SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, Apr. 17–19, 2001.
- [27] C.M. Weaver, P.R. Hof, S.L. Wearne, and W.B. Lindquist. Automated algorithms for multi-scale morphometry of neuronal dendrites. *Neural Computation*. ftp://ams.sunysb.edu/pub/papers/2003/susb03_17.pdf.

7 Publications Sponsored by this Grant

1. M. Prodanovic, W.B. Lindquist, and R.S. Seright. 3D Image-based characterization of fluid displacement in a Berea core. Submitted to Advances in Water Resources.
2. H. Shin, W.B. Lindquist, D.L. Sahagian and S.-R. Song. Analysis of the vesicular structure of basalts. Comput. & Geosci., to appear. ftp://ams.sunysb.edu/pub/papers/2003/susb03_01.ftp
3. M. Prodanovic, W.B. Lindquist, and R.S. Seright. 3D microtomographic study of fluid displacement in rock cores. Proceedings, Computational Methods in Water Resources XV Conference, Chapel Hill, NC, June 13–17. ftp://ams.sunysb.edu/pub/papers/2004/susb04_01.ftp
4. R.S. Seright, M. Prodanovic, and W.B. Lindquist. X-ray computed microtomography studies of disproportionate permeability reduction. SPE paper #89393, presented at the 14th SPE/DOE Symposium on Improved Oil Recovery, Tulsa, OK, Apr. 17–21, 2004. ftp://ams.sunysb.edu/pub/papers/2003/susb03_19.doc
5. I. Kim, W.B. Lindquist and W.B. Durham. Fracture flow simulation using a finite difference lattice Boltzmann method. *Phys. Rev. E*, **67**, 046708 (2003) ftp://ams.sunysb.edu/pub/papers/2002/susb02_21.pdf
6. K.W. Jones, H. Feng, W.B. Lindquist, P.M. Adler, J.-F. Thovert, B. Vekemans, L. Vincze, I. Szaloki, R. Van Grieken, F. Adams, C. Riekell. Study of the microgeometry of porous materials using synchrotron computed microtomography. In *Applications of X-ray Computed Tomography in the Geosciences*, F. Mees, R. Swennen, M. Ven Geet, P. Jacobs, eds. Geological Society, London, Special Publications, **215** (2003) 39–49.
7. R.S. Seright, J. Liang, W.B. Lindquist and J.H. Dunsmuir. Use of X-ray computed microtomography to understand why gels reduce permeability to water more than to oil. *J. Petroleum Sci. Eng.*, **39** (2003) 217–230. ftp://ams.sunysb.edu/pub/papers/2002/susb02_03.pdf
8. W.B. Lindquist. Network flow model studies and 3D pore structure. *Contemp. Math.*, **295** (2002) 355–366. ftp://ams.sunysb.edu/pub/papers/2001/susb01_14.pdf
9. W.B. Lindquist. Quantitative analysis of three dimensional X-ray tomographic images, in Developments in X-ray Tomography III, U. Bonse (ed.), Proceedings of SPIE **4503**, 103–115. SPIE, Bellingham, WA, 2002. ftp://ams.sunysb.edu/pub/papers/2001/susb01_06.pdf
10. R.S. Seright, J.-T. Liang, W.B. Lindquist, and J.H. Dunsmuir. Characterizing disproportionate permeability reduction using synchrotron X-ray computed microtomography. *SPE Reserv. Eval. Eng.*, **5** (2002) 355–364. ftp://ams.sunysb.edu/pub/papers/2002/susb02_02.pdf
11. C.H. Arns, M.A. Knackstedt, W.V. Pinczewski and W.B. Lindquist. Accurate estimation of transport properties from microtomographic images. *Geophys. Res. Lett.*, **28** (2001) 3361–3364.
12. S.-R. Song, K.W. Jones, W.B. Lindquist, B.A. Dowd, and D.L. Sahagian. Synchrotron X-ray computed microtomography (CMT) studies on vesiculated basaltic rocks. *Bull. Volcanology*, **63** (2001) 252–263. ftp://ams.sunysb.edu/pub/papers/2003/susb03_01.doc
13. R.M. Sok, M.A. Knackstedt, A.P. Sheppard, W.V. Pinczewski, W.B. Lindquist, A. Venkatarangan, L. Paterson. Direct and stochastic generation of network models from tomographic

images: Effect of topology on residual saturations. *Transp. Porous Media*, **46** (2002) 345–371.

14. W.B. Lindquist, A. Venkatarangan, J. Dunsmuir and T.-f. Wong. Pore and throat size distributions measured from synchrotron X-ray tomographic images of Fontainebleau sandstones. *J. Geophys. Research*, **105B**, (2000) 21508–21528. ftp://ams.sunysb.edu/pub/papers/1999/susb99_13.pdf
15. W.B. Lindquist. 3DMA General Users Manual, SUNY-Stony Brook technical report SUNYSB-AMS-99-20, 1999.
16. J.T. Fredrich, D.R. Noble, R.M. O'Connor, and W.B. Lindquist. Development, implementation, and experimental validation of the lattice Boltzmann method for modeling three-dimensional complex flows. Sandia National Laboratory report SAND99-0369. February, 1999.
17. W. Oh and W.B. Lindquist. Image thresholding by indicator kriging, *IEEE Trans. Pattern Anal. Mach. Intell.*, **21**, (1999) 590–602. ftp://ams.sunysb.edu/pub/papers/1998/susb98_02.ps.gz
18. W.B. Lindquist and A. Venkatarangan. Investigating 3D geometry of porous media from high resolution images, *Phys. Chem. Earth (A)*, **25**, (1999) 593–599. ftp://ams.sunysb.edu/pub/papers/1998/susb98_01.ps.gz
19. J.T. Fredrich and W.B. Lindquist. Statistical characterization of the three-dimensional microgeometry of porous media and correlation with macroscopic transport properties, *Int. J. Rock Mech. & Min. Sci.*, **34:3–4**, Paper No. 85. (1997).
20. W.B. Lindquist, S.M. Lee, D. Coker, K. Jones and P. Spanne. Medial axis analysis of void structure in three-dimensional tomographic images of porous media. *J. Geophys. Res.*, **101B**, (1996) 8297–8310. ftp://ams.sunysb.edu/pub/papers/1995/susb95_01.ps.gz
21. P. Spanne, J.F. Thovert, C.J. Jacquin, W.B. Lindquist, K.W. Jones and P.M. Adler, Synchrotron computed microtomography of porous media: topology and transports. *Phys. Rev. Lett.*, **73**, (1994) 2001–2004.

The following publications arose as a result of technology transfer from this grant:

1. C.M. Weaver, P.R. Hof, S.L. Wearne and W.B. Lindquist. Automated algorithms for multi-scale morphometry of neuronal dendrites. *Neural Computation*, **16** (2004) 1353–1383.. ftp://ams.sunysb.edu/pub/papers/2003/susb03_17.pdf
2. M. Maravall, Y.Y. Koh, W.B. Lindquist, and K. Svoboda. Experience-dependent changes in basal dendritic branching of layer 2/3 pyramidal neurons during a critical period for developmental plasticity in rat barrel cortex. *Cerebral Cortex*, **15** (2004) 655–664.
3. A. Kulkarni, J. Gutleber, S. Sampath, W.B. Lindquist, A. Goland, H. Herman, B. Dowd and A.J. Allen. Studies of the microstructure and properties of dense ceramic coatings produced by high-velocity oxygen-fuel combustion spraying. *J. Mater. Sci. Engin. A*, **369** (2004) 124–137. ftp://ams.sunysb.edu/pub/papers/2004/susb04_04.pdf
4. C. M. Weaver, J.D. Pinezich, W.B. Lindquist and M. Vazquez. An algorithm for reconstruction of neurite outgrowth images. *J. Neurosci. Meth.* **124** (2003) 197–205. ftp://ams.sunysb.edu/pub/papers/2001/susb01_10.pdf

5. I.Y.Y. Koh, W.B. Lindquist, K. Zito, E.A. Nimchinsky and K. Svoboda. An Image Analysis Algorithm for the Fine Structure of Neuronal Dendrites. *Neural Comput.*, **14** (2002) 1283–1310. ftp://ams.sunysb.edu/pub/papers/2001/susb01_01.pdf
6. I.Y.Y. Koh and W.B. Lindquist. Automated 3D dendritic spine detection and analysis from two-photon microscopy, in Three-Dimensional and Multidimensional Microscopy: Image Acquisition and Processing VIII, J.-A. Conchello, C.J. Cogswell and T. Wilson (eds.), Proceedings of SPIE, **4261**. SPIE, Bellingham, WA, 2001.
7. H. Yang and W.B. Lindquist. Three-dimensional image analysis of fibrous materials. Applications of Digital Image Processing XXIII, A.G. Tescher (ed.), Proceedings of SPIE **4115**, 275–282. SPIE, Bellingham, WA, 2000.
8. I.Y.Y. Koh and W.B. Lindquist. 3DMA Dendrite/Spine Detection Users Manual. SUNY-Stony Brook technical report, SUNYSB-AMS-00-03, 2000.

8 Theses Sponsored by this Grant

1. S.-M. Lee, Geometric and Stochastic Analysis of Poursous Media Structure, Stony Brook University, 1995.
2. W. Oh, Random Field Simulation and an Application of Kriging to Image Thresholding, Stony Brook University, 1998.
<ftp://www.ams.sunysb.edu/pub/papers/theses/woh.ps.gz>
3. A.B. Venkatarangan, Geometric and Statistical Analysis of Porous Media, Stony Brook University, 2000.
<ftp://www.ams.sunysb.edu/pub/papers/theses/syanora.ps.gz>
4. H. Shin, A Throat Finding Algorithm for Medial Axis Analysis of 3D Images of Vesiculated Basalts, Stony Brook University, 2002.
<ftp://www.ams.sunysb.edu/pub/papers/theses/shinhyun.ps.gz>
5. I. Kim, Fluid Flow in a Rock Fractures using Finite Difference Lattice Boltzmann Method, Stony Brook University, 2002.
<ftp://www.ams.sunysb.edu/pub/papers/theses/kbkim.ps.gz>
6. M. Prodanovic, Fluid Displacement in Rock Cores: A Study Based on Three Dimensional X-ray Microtomography Images, Stony Brook University, 2005 (expected).

The following theses developed from technology transfer derived from this grant.

1. H.M. Yang, A Geometric and Statistical Analysis of Fibrous Materials from Three-Dimensional High Resolution Images, Stony Brook University, 2001.
<ftp://www.ams.sunysb.edu/pub/papers/theses/hmyang.ps.gz>
2. I.Y.Y. Koh, Automated Recognition Algorithms for Neural Studies, Stony Brook University, 2001.
<ftp://www.ams.sunysb.edu/pub/papers/theses/ingrid.ps.gz>
3. C.M. Weaver, Automated Morphometry for Neural Cells, Stony Brook University, 2003.
<ftp://www.ams.sunysb.edu/pub/papers/theses/weaver.ps.gz>

9 Appendix A

Recent inquiries/downloads of 3DMA-Rock have been received from the following. Indicated applications have ranged from rock and soil core samples, to concrete and bone.

- Dr. O. Bachmana, Mineralogy, Univ. of Geneva;
- Dr. D.R. Baker, Geochemistry, McGill, Canada;
- Dr. F. De Carlo, Advanced Photon Source, Argonne Nat'l Lab.;
- Dr. D. Coombe, Computer Modeling Group, LTD, Canada;
- Dr. E. Dalla, Earth and Atmosph. Sci, Universita' di Milano-Bicocca P.za della Scienza 1,. Italy;
- Dr. S.M. Ezzedine, Lawrence Livermore National Lab.;
- Dr. S. Favretto, Civil Engin., Trieste;
- Dr. C.J. Gantzer, Environmental Soil Sci., Univ. Missouri;
- Dr. N. Gaspar, Engineering, Exeter, UK;
- Dr. R. Glantz, Environmental Engin., Johns Hopkins Univ.;
- Dr. P. Gouze, Lab. Tectonophysics, Univ. Montpellier 2, France;
- Dr. A.S. Grader, Petroleum and Natural Gas Engineering Program, Penn. State. Univ.;
- Dr. L. Hernandez, Instituto Mexicano del Petroleo;
- Dr. S. Hilgenfeldt, Fluid Dynamics and Heat Transfer, Univ. of Twente, Holland;
- Dr. L. Jassogne, Earth and Environ. Sci., Univ. Adelaide, Australia;
- V. Khvatkov, CEO, Smart Imaging Technologies Co.
- Dr. M. Koster, Instit. Building Materials Res., Aachen Univ., Germany;
- J. Leward, Millipore Inc;
- Dr. W. Losert, Physics, IPST and IREAP, Univ. Maryland;
- Dr. J. Ma, Institute Petroleum Engin, Heriot-Watt Univ.;
- Dr. D. Peak, Environ. Soil Chem, Univ. Saskatchewan, Canada;
- Dr. M. Politits, Aerosol & Particle Technology, Chemical Process Engineering Research Instit., Thessaloniki, Greece;
- Dr. A.S. Simionovici, Earth Sci., Ecole Normale Supérieure de Lyon, France;
- Dr. J.M. Smucker, Crop and Soil Sciences, Michigan State Univ.;

- Dr. G. Stockman, Comp. Sci and Engin., Michigan State Univ.;
- K. Taki, Director, Nihon Visual Science, Inc., Tokyo, Japan;
- Dr. W. Timm, Medical Physics, Univ. Hosp. Schleswig-Holstein, Kiel, Germany;
- Dr. I.N. Veretennikov, Dept. Physics, Univ. Notre Dame;
- Dr. C. Willson, Civil and Environ Engin., Louisiana State Univ.; Dr. H.S. WWong, Civil and Environ. Engin., Imperial College, London;
- X. Yang, Civil and Environ. Engin., Georgia Instit. Tech.

Recent inquiries/downloads of 3DMA-Neuron have been received from:

- Dr. T. Bonhoeffer, Max-Planck Instit. Neurobiology, Munich;
- Dr. A. Jeromin, Neuroscience, Baylor College of Medicine;
- Dr. V.T. Marta, Anatomy and Embriology, Univ. Valencia, Spain;
- Dr. E.L. Ritman, Physiology & Biophysics, Mayo Clinic;
- Dr. E.S. Ruthazer, Cold Spring Harbor Lab.;
- Dr. B. Sabatini, Bioinformatics, Harvard Medical School;
- Dr. N. Shahani, Neurobiology, Univ. Osnabrueck, Germany;
- Dr. H. Shu, Biomed. Engin., Southeast Univ., Nanjing, China;
- Dr. E. Shuman, Biology, Clatech;
- Dr. I. Vida, Instit. Anatomy, Univ. Freiburg;
- Dr. X. Xu, Harvard Center for Neurodegeneration and Repair;
- Dr. F.C. Zhou, Neurobiology, Indiana Univ. School of Medicine

Recent inquiries/downloads of 3DMA-Fiber have been received from:

- Dr. C.A. Bronkhorst, Fiber Sciences, Weyerhaeuser Co., WA;
- Dr. J. Seidler, Physics, Univ. Washington