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Development and implementation of a dual-porosity pore network structure using X-ray computed tomography for pore network modeling purposes

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DEVELOPMENT AND IMPLEMENTATION OF A DUAL-POROSITY PORE NETWORK STRUCTURE USING X-RAY COMPUTED TOMOGRAPHY FOR PORE NETWORK MODELING PURPOSES

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in

The Department of Civil and Environmental Engineering

By
Samuel Best
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Abstract

3-D pore network modeling based on high-resolution X-ray computed tomography (XCT) is a useful tool for simulating pore-scale processes and phenomena within porous media in fields such as chemical and petroleum engineering and groundwater hydrology. XCT images provide the opportunity to capture the true topology of the porous system, retaining important characteristics such as pore geometry, location, and connectivity. However, a major limitation of XCT is its inability to resolve features smaller than the image resolution such as intraparticle porosity and void-space within secondary phases such as clay and micrite, here called microporosity. Identifying this microporosity is important for modeling fluid flow through rocks lacking macropore connectivity or to better understand transport processes in systems where there is an apparent interaction between the bulk fluid and stagnant void space within the microporous phase.

This work attempts to address the impact of incorporating microporosity into a physically representative macropore network on pore network models of single-phase permeability and quasi-static drainage. XCT images were collected for three geologic systems (a Castlegate Sandstone, an Indiana Limestone, and a Winterset Limestone) with very different pore structures, and then augmented with conventional core analyses to generate geologically based dual-porosity pore networks. A layered-sand system was imaged and analyzed as a semi-control for validation of our approach. The dual-porosity networks were developed using statistically generated pore networks for the microporous phases, which were integrated with the macropore networks generated on the resolvable void space.
The results suggest that incorporating microporosity into a pore network model is essential for simulating permeability and drainage in systems of low macropore connectivity and high microporosity content such as the Indiana and Winterset limestones, but only aids in drainage simulation for systems of high macropore connectivity and low microporosity content such as the Castlegate Sandstone. The layered sand analysis suggests that a statistically based dual-porosity pore network could help predict both permeability and drainage. This research was only a first step towards developing an approach for the implementation of a dual-porosity pore network, and it highlights issues obstructing this process and the areas to which future research should be focused.
1 Introduction

Generation of 3-D pore network models based on high-resolution XCT is becoming increasingly popular for simulating pore-scale processes and phenomena within porous media. A pore network structure is a simplistic approach for describing the pore structure of a porous media by characterizing the pore space as a ball and stick lattice based on a physically representative 3-D image. The lattice is built directly off of the 3-D image; thereby, retaining important characteristics such as pore location, pore geometry, and pore connectivity. Approximate solutions to the governing equations can then be obtained by imposing conservation equations across the domain of the pore network structure. This allows for orders-of-magnitude larger characteristic scales to be modeled as compared to finite-element and lattice-Boltzmann techniques for solving equations of energy (e.g. Navier-Stokes). (Thompson, Willson, et al. 2008)

Pore network modeling using XCT is a very useful tool in fields such as chemical and petroleum engineering and groundwater hydrology for modeling and understanding a variety of pore-scale processes and phenomena such as single phase permeability and capillary pressure (Bhattad, Willson and Thompson 2010), multiphase fluid flow and distribution (Lerdahl, Oren and Bakke 2000, Al-Raouch and Willson 2005), solute transport (Raoof, Hassanizadeh and Leijnse 2010), and chemical reactions (Li, Peters and Celia 2005). One of the most vital components of pore-network modeling is generating a realistic representation of the pore structure within the media of interest. The accuracy of the image-based pore network structure can be highly influenced by the characteristic length scale of the pore structure and the image resolution due to the significance of pore connectivity and spatial correlations.
Indirect methods for determining pore structure such as using capillary pressure-saturation curves to estimate pore sizes, fitting measured pressure-saturation curves to curves generated by network models, and 3-D characterization using 2-D images have been used for generating the pore network structure of porous systems. The first two methods, however, lack a uniqueness of the solution due to the dependency of their retention curves on both pore size distribution and topology of the pore space. Both methods also lack the ability to directly measure the connectivity of the pore space (i.e. provide information about each individual pore-throat) (Al-Raouch and Willson 2005). Assuming that the image resolution is sufficient to capture the length scales and connectivity, 3-D images can provide the basis for generating physically representative or “realistic” models of pore network structures that are unique to the media of interest.

Several approaches to obtaining 3-D representations of pore network structures such as simulation of random close packing (Thompson and Fogler 1997, Bryand, King and Mellor 1993) and 3-D reconstruction based on measured porosity and correlation of serial cross-sections (Vogel and Roth, 1997, 2001; Liang et al., 1999) exist. However, a random close packing lacks the ability to accurately represent the 3-D pore network structure due to its idealistic nature, and preparation of 2-D cross-sections is a laborious and destructive technique. XCT imaging, on the other hand, allows for direct imaging of real materials by nondestructive and noninvasive means, compensating for the limitations of the former methods. Al-Raoush and Willson (2005) and Prodanovic et al. (2004) showed that XCT is an effective tool for accurately characterizing the pore network structure of unconsolidated and consolidated porous media, respectively.
Although XCT images have been used to generate physically representative pore network structures for a variety of porous media, this technique also has limitations. Many advanced XCT systems today have resolutions up to approximately 1 μm, which is sufficient for capturing macroporosity (intercrystalline pore space larger than ~2 μm and/or pore space resolvable in the XCT image, which is pore space greater than ~2x the XCT voxel resolution) such as that between the crystalline grains of sandstones, but is not adequate for capturing microporosity (pore space smaller than ~2 μm and/or pore space not resolvable in the XCT image, which is pore space less than ~2x the XCT voxel resolution) such as that within authigenic clay (e.g. kaolinite) in sandstones and micritized fossil fragments in carbonates. When modeling processes such as Darcy and non-Darcy single-phase flow through fairly homogenous porous systems with high levels of macropore connectivity, such as most sandstones, microporosity does not contribute significantly to primary fluid flow (Thompson, Willson, et al. 2008); therefore, this scale of characterization is not necessary. However, for heterogeneous porous systems such as carbonate rocks that lack a well-connected macropore network, flow from one macropore to another can occur through micropores between them and characterization or knowledge of the microporosity and fine-scale connectivity is necessary to accurately model the pore-scale flow. An understanding of the microporous structure is also important for modeling processes such as multiphase flow where one or more of the fluids may enter or exit the pore space due to capillary forces and solute transport where chemicals may be diffusing to and from micropores, sorbing to the organic clay within a sandstone, and/or being captured in small pore-throats such as that within micrite (small calcite crystals
approximately 2 μm in diameter which form from the recrystallization of lime mud (Flugel 2004)).

One method for obtaining the pore structure of the microporous phase is Focused Ion Beam coupled with Scanning Electron Microscope (FIB/SEM) imaging. FIB/SEM allows one to obtain 2-D images at sub-micron resolutions that can be stacked to generate a 3-D (volume) image. FIB/SEM works by ion milling the surface of the rock, taking an SEM image of the milled surface, milling down some designated increment, and then taking another SEM image. This can be repeated to obtain multiple 2-D images that can be stacked to generate a 3-D image. Tomutsa and Radmilovic (2003) successfully used serial sectioning and FIB/SEM imaging to generate 3-D images of a Belridge diatomite and an epoxy impregnated North Sea Chalk. For network modeling purposes, however, this sub-micron pore network structure derived from FIB/SEM imaging would have to then be correlated/integrated with an existing “macro” pore network structure.

Although in some cases XCT imaging is resolution-limited for resolving the microporosity with a geologic system, it can, however, provide information on the spatial distribution of the different lithological phases. This is achieved through either a difference in elemental composition or density between mineralogical/lithological phases resulting in different X-ray absorption values between them. If enough contrast exists between these phases, multi-phase segmentation is possible, which will provide a 3-D mapping of the void space and the microporous phase. To assist with the 3-phase segmentation, XCT scan data can be augmented with conventional core analyses such as thin sections images, SEM photographs, and mercury
injection data. XCT will provide the foundation for (1) void/solid segmentation (i.e. generating a two-phase image where all voxels are populated into two “phases” with intensity values being assigned either a 0 or a 1 from a gray-scale image where voxel values range from 0 to 255 for an 8-bit binary image) and (2) determining the spatial location of mineralogical/lithological phases that exhibit different X-ray absorption values. Conventional core analysis techniques can then provide (1) mineralogical/lithological details of the system that can help make decisions concerning the accuracy and applicability of using XCT images to extract the pore network structure, can (2) aid in distinguishing between multiple phases seen in the XCT image, and can (3) determine how representative the XCT image is of the geologic system due to heterogeneity. Distinguishing between solid material and void space may be easy, but distinguishing between two solid phases of similar absorption values may be difficult without an understanding of the mineralogy/lithology of the system.

Once the location of the “microporous” phase is mapped, it is then possible to insert a pore network structure into it that can be connected to the macropore network generated on the void space to obtain a dual-porosity pore network structure. The sub-micron pore structure can be obtained from 3-D FIB/SEM images or generated from pore statistics obtained from conventional core analyses. Note that the FIB/SEM data will not give you a physically-representative pore network structure of the entire volume of the microporous phase; therefore, FIB/SEM data will still need to be either: (1) copied to the rest of the microporosity within the sample; or (2) used to generate the statistics that are used to generate the micropore network structure.
There is no question that development of a dual-porosity pore network structure will have significant effects on the ability of pore network models to characterize fluid flow processes in systems of low macropore connectivity. However, whether the micropore network is generated from a physically representative 3-D image or from pore statistics may have significant effects on the feasibility of the dual-porosity pore network structure. This Thesis will look at the feasibility of inserting a statistically based pore network structure into the microporous phase of three geologic systems for better predicting single-phase permeability and quasi-static drainage.
2 Scope and Objectives

The objective of this thesis is to (1) augment the XCT scan data with conventional core analyses and to (2) assess the impact of incorporating microporosity into a physically representative macropore network structure on pore network models of single-phase permeability and quasi-static drainage. This research will be conducted on four porous systems: 1) an unconsolidated layered sand, 2) a Castlegate Sandstone, 3) an Indiana Limestone, and 4) a Winterset Limestone. The layered sand system will be used for validation of the approach due to the simplistic shape of the pore structure and ease of quantitative characterization compared to the other samples. The Castlegate Sandstone is a homogenous system through which primary fluid flow is most likely conducted through the macropores only. The Indiana Limestone is a heterogeneous system with a large percentage of microporosity, which may or may not play a roll in fluid flow and transport processes. The Winterset is an example of a porous system with very low macropore connectivity, meaning the micropores will most probably play a major role in fluid flow and transport processes.

Augmentation of the XCT scan data with conventional petrophysical and petrographic data will consist of XCT image processing, thin section and SEM image analysis, correlating the thin-section and SEM images with the XCT images, and 3-phase XCT image segmentation, which will spatially and geometrically map the void space and the microporous phases within the XCT images. Assessing the impact of including the microporosity in the macropore network structure on permeability and drainage simulations will consist of extracting the macropore network structures from the 3-phase XCT images of the four systems, performing single phase Darcy permeability and drainage simulations on the macropore networks,
developing/generating a dual-porosity pore network structure for each system, and re-running the permeability and drainage simulations.

The following chapters of this thesis will consist of: Ch. 3) a literature review which will include background on XCT Imaging, conventional petrophysical and petrographic analyses, pore network modeling, and physically representative pore network generation; Ch. 4) methods for conducting this research which includes sample preparation, conventional core analyses, XCT imaging, XCT image processing including augmentation with conventional core analyses, macropore network extraction, development of the dual-porosity pore network, and permeability and drainage simulations; Ch. 5) results; Ch. 6) discussion; and Ch. 7) conclusions and recommendations for future work.
3 Literature Review

3.1 X-ray Computed Tomography

XCT is a non-destructive and non-invasive imaging technique for investigating the internal structure of an object. X-rays are emitted through the object and collected by detectors on the downstream side measuring the X-ray attenuation through the object. The attenuation of the material depends on its chemical composition and the energy of the incident X-rays. Projections are obtained by measuring the 2-D X-ray attenuation coefficient projection map at a series of angles as the object is rotated. These projection maps are then used to reconstruct a 3-D volume file. (Al-Raouch and Willson 2005)

There are two types of XCT systems available with advantages and disadvantages depending on the scope of the research. Until recent years, industrial systems had resolutions only up to ~10 μm and because of there high energies, they were ideal for viewing and characterizing large and dense samples and capturing macroscopic features. However, new industrial systems have the ability to reach resolutions at the sub-micron scale. Synchrotron-based XCT, which due to very high photon fluxes, can reach resolutions on the range of 1-20 μm. Unlike industrial systems, because of this high photon flux, synchrotron XCT systems have the ability to monochromatize the incident photon energy providing a much greater contrast between phases within the system and allowing for element-specific imaging. Element-specific imaging means to image a sample above and below the X-ray absorption (k) edge of a particular element of interest producing two images, one which the element of interest is much more visible than in the other. These two images can then be subtracted enhancing the visibility of
the element of interest (i.e. absorption edge imaging). This feature can be extremely helpful for differentiating fluid phases or for qualitative identification of mineralogy. (Al-Raouch and Willson 2005)

Due to the lower energies produced by a synchrotron X-ray source (typically below 50 keV), a major limitation of synchrotron XCT is the sample size that can be imaged. Typically, the sample size is limited to a few centimeters to assure complete beam penetration through the sample. (Wildenschild, et al. 2002) Regardless of the XCT device, one major issue with the use of XCT is that the higher the resolution desired, the smaller the pixel size becomes, resulting in a reduction in the maximum window of projection. Thus, higher resolution images require smaller sample sizes, which create concern about the ability to image a representative elementary volume (REV) of the media at very high resolutions. Proper statistical analysis should be conducted to insure that a REV is achieved for the study at hand.

Due to the advantages of synchrotron systems for image resolution, image clarity, and the ability to use monochromatic energies, they were chosen for image collection. The samples were imaged at three different synchrotron sources: the Advanced Photon Source (APS) at Argonne National Laboratory (ANL), Argonne, IL, the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, Brookhaven, NY, and the Center for Advance Microstructures and Devices (CAMD), Louisiana State University, Baton Rouge, LA. The image collection process at each beamline differs to some extent, but all fundamentally work in the same manner. X-rays are emitted through a monochromator and then through the sample and are collected on the downstream side by a high-resolution scintillator, converting the
attenuation map to a visible image. A 45° mirror is used to reflect the image towards a microscope magnifying the image. This image is then collected by a cooled charged-coupled device (CCD) camera and saved to a file. The sample is then rotated a specified angular increment and another image is taken. Images are taken over an 180° range capturing the entire volume of the sample. **Figure 3-1-1** is a schematic of an XCT unit. (Al-Raouch and Willson 2005)

![XCT Imaging Schematic](image)

**Figure 3.1-1. XCT Imaging Schematic**

Once the imaging process is complete, the images are reconstructed to generate the image volume. The first step in the reconstruction process is to correct for dark and white fields by subtracting dark and white field images taken without the sample in the projection window. Next, the images are rearranged as sinograms, which are 2-D images with axes representing the field of view and the total number of images. This allows for adjusting each sonogram for proper alignment with respect to the center of gravity of the system and fits it to a sine wave. A filtered back-projection reconstruction process (Rivers, Sutton and Eng 1999) is then used to obtained 2-D sections from sinograms. In most cases, filters are applied to
remove impurities in the image such as ring artifacts. The final step is to use imaging software to stack the 2-D images into a 3-D volume. (Al-Raouch and Willson 2005)

3.2 Conventional Petrographic and Petrophysical Analysis

Porosity determination from cores and conventional porosity logs (neutron, density, sonic) typically measures the total porosity in reservoir rocks, including microporosity that is often too small to contribute to fluid flow or store hydrocarbons. Another common technique utilized to characterize the pore system is capillary pressure measurements using mercury injection, which provides a distribution of pore-throat sizes.

These petrophysical measurements are commonly used in conjunction with petrographic (thin section) and Scanning Electron Microscope (SEM) analyses to create a three dimensional understanding of the pore networks. A diagram of the range in scales of characterization for each technique is presented in Figure 3.2-1. Pore sizes as small as 0.05 μm can be imaged with the SEM, and mercury injection can measure pore-throats less than 0.005 μm, allowing an understanding of the total pore space in the rock. The combination of thin section and SEM data allows the total pore space to be divided into macroporosity (interparticle pores greater than ~2 microns) and microporosity (any pore space less than ~2 microns). This also allows the distribution of microporosity to be tied to geologic processes, such as the formation of authigenic clay in sandstones and the micritization of fossil fragments in carbonates. This data can also be used to estimate the distribution of pore-throat sizes, which can be verified by comparison with mercury injection data. This combination of
petrophysical, thin section, and SEM data has been used to predict permeability, water saturation and other parameters in oil and gas reservoirs. (Lucia 1995, Sears 1984)

![Diagram showing porosity scales captured by various petrophysical and petrographic techniques.](image)

**Figure 3.2-1.** Porosity scales captured by various petrophysical and petrographic techniques.

### 3.3 Network Modeling

Pore-scale modeling by directly solving equations of motion (Navier-Stokes, Stokes, and other transport equations along with conservation equations) using numerical techniques such as finite-element, finite-difference, finite-volume, boundary element, and lattice-Boltzmann methods is a very rigorous process, and because of that, it must be performed on relatively small characteristic scales to maintain sufficient numerical resolution. Network modeling, on the other hand, gives approximate solutions to the governing equations by imposing conservation equations at the pore scale. This allows for orders-of-magnitude larger characteristic scales to be modeled (Thompson, Willson, et al. 2008). The earliest network models consisted of highly simplified 2-D square or hexagonal lattices made of tubes of which experimentally obtained pore-size distributions were imposed by randomly assigning tube sizes. Pores were located at the intersection of tubes but had no volume. Bryant et al. (1993; 2003) developed a second generation of network models that directly map the network from the void
structure in a 3-D packing. Bryant et al. (1993) referred to this model as a physically representative model. This new approach incorporates pore-scale spatial correlations into the network model due to one-to-one mapping of the pore structure, which was missed with the statistically based approach. Also, the networks are described using rigorous geometric parameters ensuring that the pore morphology is not compromised. Because of the physically representative nature of this model, adjustable parameters are no longer required.

Recently, a third-generation of network models, which directly map the network from 3-D images such as XCT images of porous media, has been developed. This approach allows for essentially any type of pore structure to be mapped instead of only simple geometric packings. (Thompson, Willson, et al. 2008, Bhattad, Willson and Thompson 2010, Bryant, Mellor and Cade 1993)

3.4 Realistic Pore Network Generation

XCT images allow for extracting a realistic representation of the pore network that can then be used for network modeling. Various algorithms have been developed for extracting the pore structure from 3-D images that generally fall into two categories: skeletonization algorithms which typically employ either the medial axis technique or a geometrical thinning technique, or a hybrid of the two, for describing the pore space, and geometric algorithms which build the network structure based on pore locations defined by geometric analysis. (Bhattad, Willson and Thompson 2010, Thompson, Willson, et al. 2008)

One such geometric algorithm is the grain-based algorithm. The grain-based algorithm first characterizes the grain structure of the medium which is then used as the template for
creating the pore and pore-throat network. This approach is beneficial because it is less sensitive to image resolution than directly mapping the pore skeleton, the pores are defined by their surrounding grains, and the number of grains is orders-of-magnitude smaller than the number of voxels, which makes it much faster than equivalent voxel-based algorithms. However, grain based algorithms are best suited for unconsolidated granular packings and are not well suited for consolidated systems such as carbonates and highly consolidated sandstones. For this research, a non-grain-based geometric algorithm called vox2net was used because the samples are consolidated carbonates and/or sandstones with non-granular geometries. (Thompson, Willson, et al. 2008, Bhattad, Willson and Thompson 2010)

Vox2net works by characterizing each pore and pore-throat with a maximum inscribed sphere that is constrained from movement and growth by the surrounding solid phase. A voxel burn or erosion procedure is first employed to locate the pore center or seed of the hypothetical maximum inscribed sphere. Three different schemes for doing this are described in detail in Bhattad et al. (2010). For this research, scheme 1, which uses a voxel burn to define voxels that are local maxima, is used. Once the seeds are located, a non-linear optimization procedure is employed, which uses a variant of the watershed algorithm to collect voxels belonging to that particular pore from the center moving outward. Overlapping pores are merged together if the center of one pore is contained within another pore. Once all pores are located and fitted with maximum inscribed spheres, the pore-network structure is created and parameters such as the porosity, pore radii, pore volume, pore surface area, and pore coordination number, throat radii, throat volume, throat surface area, throat hydraulic
conductance, and throat coordination number are calculated (Thompson, Willson, et al. 2008, Bhattach, Willson and Thompson 2010).
4 Methods

4.1 Sample Preparation

The layered sand was prepared by filling a 6 mm ID, 1.5 cm tall plastic column with three layers of sand. The side of the column was continuously tapped while it was being filled to ensure proper settling of the sand grains. The top and bottom layers, \( \sim 3.22 \) mm and \( \sim 6.36 \) mm, respectively, consist of 30/40 Accupack sand manufactured by Unimin Corporation and the middle layer, \( \sim 3.62 \) mm, of 50/100 F75 sand. The average grain size of the 30/40 Accupack is 0.5 mm in diameter (Schroth, et al. 1996). This size sand was chosen because it is small enough to achieve roughly 12 grains across the diameter of the column, but large enough so that once packed, the pores and pore-throats would be large enough to easily resolve at 8.05 \( \mu \text{m} \) and 16.1 \( \mu \text{m} \) pixel resolutions. In Hofstee et al. (1997), it is indicated that the smallest pore-throats within a packed F75 Ottawa sand column are \( \sim 24 \) \( \mu \text{m} \) in radius. It is believed that the XCT images are sufficient at accurately resolving pore space up to twice the image resolution; therefore, the 8.05 \( \mu \text{m} \) resolution is believed to be sufficient for capturing the smallest pore-throats within the F75 sand layer, but the 16.1 \( \mu \text{m} \) resolution is not. The F75 sand was sieved with a 50 (0.297 mm openings) and a 100 (0.149 mm openings) size sieves to extract out any very large or very small sand grains. Unfortunately, because the F75 sand was sieved, a direct comparison between the modeling results and the data in Hofstee et al. (1997) will not be able to be made.

The idea behind the layered sand system is that the true pore network structure is believed to be extractable from the 8.05 \( \mu \text{m} \) resolution image for both sand systems but not
from the 16.1 μm resolution image. If we can replace the F75 sand system in the 16.1 μm resolution image with a statistical based micropore structure obtained from the F75 sand layer of the 8.05 μm image, we could compare the results of the permeability and drainage simulations with those from simulations of the 8.05 μm resolution system. This will provide insight into the practicality of this approach.

The Indiana Limestone, Castlegate Sandstone, and Winterset Limestone samples were extracted from 1-inch drill cores provided by ExxonMobil with an in-house drill press. 3, 4, and 6 mm electroplated diamond tip drill bits manufactured by UKAM Industrial Super Hard Tools were used for coring the samples from the end (horizontal face) of the 1-inch drill cores. Multiple size samples of each system were cored and imaged, but only certain image volumes were chosen for this analysis and will be discussed in detail later.

4.2 Conventional Core Analyses

1-inch subsets of the original drill cores were sent to Weatherford Laboratories, Houston, Texas for petrophysical analyses. Weatherford performed mercury injection and capillary pressure analyses, permeability analyses, and porosity measurements, obtained SEM photographs, and cut and prepared thin-sections of each core. The thin sections were returned for in-house analysis. Point counting to determine the relative abundances of the different constituents was performed on each thin section. A high-density point count of 300 points was performed by Dr. Stephen Sears, Chair of the Craft and Hawkins Department of Petroleum Engineering, on ~1-in² sections of each sample, which results in a probable error of +/- 3-6% at a 95% confidence level (E. R. Carver 1971). This point count was conducted on the actual thin
section using a Leitz 2500 Polarizing Microscope; therefore, magnification adjustments could be made to resolve submicron features. Additional point counting of 100 points was performed on 10 different 1.9x1.4 mm sections each of the Indiana Limestone and the Castlegate Sandstone to better understand the heterogeneity of the two systems. This point count was conducted on images taken with the polarizing microscope at a 50X magnification; therefore, magnification adjustment was not possible as in the high-density point count. There is an error of +/- 4-8% associated with the low-density point count. (E. R. Carver 1971) The SEM photographs taken by Weatherford were also analyzed in-house to further obtain lithological/mineralogical information about the geologic systems, specifically with regard to the microporous phases within them. Petrographic descriptions of each rock were written by Dr. Sears and were used in this analysis. Summaries of his results are presented in Chapter 5.

4.3 XCT Imaging

Images of the four systems were collected at three different synchrotron beamlines and one industrial XCT unit. The Indiana and Castlegate image volumes were collected at the X2B Beamline at the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory (BNL), Brookhaven, NY and the GSECARS Beamline at the Advanced Photon Source (APS), Argonne National Laboratories (ANL), Argonne, IL, the Winterset image volumes were collected at the X2B Beamline at NSLS and at Naval Research Laboratory’s Stennis Space Center (NRL-SSC), MS and the layered sand image volume was collected at LSU’s Center for Advanced Microstructures and Devices (CAMD). Imaging details pertaining to each core analyzed in this research are presented in Table 4.3-1 below. The layered sand XCT volume was re-binned by a
factor of 2 (i.e. 4 voxels now equal 1 voxel) to produce an image with a voxel resolution half that of the original resolution. The reasoning behind this will be explained later.

**Table 4.3-1. Core and XCT imaging details**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Core Size</th>
<th>Beamline</th>
<th>Voxel Resolution</th>
<th>X-ray Energy</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castlegate NSLS</td>
<td>6 mm</td>
<td>NSLS</td>
<td>7.57 μm</td>
<td>30 keV</td>
<td>CASTLEGATE_A</td>
</tr>
<tr>
<td>Castlegate APS</td>
<td>6 mm</td>
<td>APS</td>
<td>5 μm</td>
<td>33 keV</td>
<td>CASTLEGATE_B</td>
</tr>
<tr>
<td>Indiana NSLS</td>
<td>3 mm</td>
<td>NSLS</td>
<td>3.9 μm</td>
<td>28 keV</td>
<td>INDIANA_A</td>
</tr>
<tr>
<td>Indiana APS</td>
<td>6 mm</td>
<td>APS</td>
<td>5 μm</td>
<td>28 keV</td>
<td>INDIANA_B</td>
</tr>
<tr>
<td>Winterset NSLS</td>
<td>3 mm</td>
<td>NSLS</td>
<td>4 μm</td>
<td>26 keV</td>
<td>WINTERSET_A</td>
</tr>
<tr>
<td>Winterset NRL</td>
<td>10 mm</td>
<td>NRL</td>
<td>19.9 μm</td>
<td>70 keV</td>
<td>WINTERSET_B</td>
</tr>
<tr>
<td>SANDMIX</td>
<td>6 mm I.D.</td>
<td>CAMD</td>
<td>8.05 μm</td>
<td>30 keV</td>
<td>SANDMIX_A</td>
</tr>
</tbody>
</table>

The beamlines at NSL, APS, and CAMD all use the same fundamental approach as described in Chapter 3.1. Differences in hardware such as the camera, scintillator, and monochromator and the image reconstruction software will not be discussed here because the resulting XCT images are the same.

### 4.4 Image Processing

Image processing involves three main steps: 1) image cropping and conversion from 16-bit to 8-bit data, 2) noise removal with a non-linear anisotropic diffusion program (ad_202) and 3) image segmentation using an image thresholding algorithm (ik3p). Noise in XCT images can be very problematic to the segmentation of the gray-scale image. The idea of segmentation is to convert a gray-scale image to a 2- or 3-phase binary image by assigning voxels of similar intensity to a single intensity. This process allows one to populate features such as solid sand grains and void space into two populations of voxel intensities, 1 and 0, respectively, making it

20
possible to then quantitatively characterize the pore structure later on with the extraction of the physically representative pore network structure. A significant amount of noise in the gray-scale image can cause inaccuracies in the thresholding process by adding voxels to or subtracting voxels from a particular phase within the image.

4.4.1 Image Cropping and Conversion from 16-bit to 8-bit

Imaging processing requires the XCT images to be in 8-bit binary format and to be cubical in shape (cubical because the voxels are cubical). The original gray-scale XCT images, however, are 16-bit binary and the core is cylindrical in shape; therefore, cubical sub-volumes must be cropped from inside the cores and converted to 8-bit binary images before further image processing. This is done very easily and quickly using the imaging program ImageJ. Usually the largest possible sub-volume is extracted from inside the cylindrical column in hopes to ensure a representative elementary volume (REV) of the system, assuming the original volume is an REV. Conversion from 16-bit to 8-bit can be difficult due to noise in the image that makes the voxel intensity range much larger than the actual range of interest within the sample. The image brightness/contrast must first be adjusted to remove outlying noise and to reduce the intensity range before converting to 8-bit. This is important because a much smaller range of intensities is now being compressed an intensity range 255 values as in an 8-bit image, which helps preserve subtle features such as edges within the image. All voxels of intensities that were removed by brightness/contrast adjustment are assigned either a 0 or 255 depending on which end of the histogram it resided. After the image is converted to an 8-bit binary image, it is ready for ad_202. Sub-volume sizes extracted for each image are presented in Table 4.4-1.
Table 4.4-1. XCT Sub-volume dimensions.

<table>
<thead>
<tr>
<th>File Name</th>
<th>X-Y (Voxels)</th>
<th>Z (Voxels)</th>
<th>X-Y (mm)</th>
<th>Z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASTLEGATE_A</td>
<td>300</td>
<td>425</td>
<td>2.271</td>
<td>3.217</td>
</tr>
<tr>
<td>CASTLEGATE_B</td>
<td>550</td>
<td>1040</td>
<td>2.750</td>
<td>5.200</td>
</tr>
<tr>
<td>INDIANA_A</td>
<td>425</td>
<td>640</td>
<td>1.658</td>
<td>2.496</td>
</tr>
<tr>
<td>INDIANA_B</td>
<td>600</td>
<td>840</td>
<td>3.000</td>
<td>4.200</td>
</tr>
<tr>
<td>WINTERSET_A</td>
<td>500</td>
<td>600</td>
<td>2.000</td>
<td>2.400</td>
</tr>
<tr>
<td>WINTERSET_B</td>
<td>350</td>
<td>535</td>
<td>6.965</td>
<td>10.647</td>
</tr>
<tr>
<td>SANDMIX_A</td>
<td>550</td>
<td>1625</td>
<td>4.428</td>
<td>13.081</td>
</tr>
<tr>
<td>SANDMIX_B</td>
<td>275</td>
<td>812</td>
<td>4.428</td>
<td>13.073</td>
</tr>
</tbody>
</table>

4.4.2 ad_202

ad_202 is a non-linear anisotropic diffusion algorithm for removing noise from a gray-scale image. It works by equilibrating voxel-level noise to values similar to that in the surrounding voxels. ad_202 uses the tensor form of the nonlinear isotropic diffusion coefficient (NIDC) proposed by Perona and Malik (1990). The NIDC is an inverse function of the local image gradient, meaning that diffusion normal to object boundaries is minimized, preserving the edges of features such quartz grains. The tensor form of the NIDC additionally causes the tangential component of the NIDC to remove noise near object edges, now making it an anisotropic diffusion process. This equilibration of voxel-level noise to its surrounding area provides greater distinction between peaks within the histogram of the gray-scale XCT image and makes the peaks more pronounced (Figure 4.4-1). More detail into ad_202 can be found in Bhattad et al. (2010). ad_202 was run on all XCT images prior to image segmentation, except for both XCT images obtained from NRL.
Figure 4.4-1. Pre-anisotropic diffusion (left) vs. post-anisotropic diffusion (right)

4.4.3 ik3p

Image segmentation, as mentioned before, is the process of populating an 8-bit binary gray-scale image with voxel intensities ranging from 0 to 255 into two distinct populations of similar voxel intensities so that the end result is an 8-bit binary image with only two voxel intensities (e.g. 0 and 1). One method of doing this is to apply a single threshold value based on the histogram of the image (Figure 4.4-2a) so that all voxels of intensities below that value will be designated 0 and all above that value designated 1. This procedure is referred to as simple thresholding. This approach, however, can lead to phase misidentification due to uncertainty of voxels that lie between peaks in the histogram such as those at phase interfaces. To more accurately assign these voxels to a particular phase, an indicator kriging approach is employed. (Al-Raouch and Willson 2005, Bhattad, Willson and Thompson 2010)
Figure 4.4-2. a) Simple Threshold; b) Indicator Kriging using two thresholds (vertical lines correspond to T1 and T2, respectively)

Kriging is a statistical method that uses probability to assign a location of uncertainty to a known value by using linear-weighted combinations of neighboring measured values. *ik3p* employs two threshold values, T1 and T2, based on the histogram of the image (Figure 4.4-2b). All voxels of intensities below T1 are designated 0 and all voxels above T2 are designated 1. All voxels between T1 and T2 will be designated to 0 or 1 based on the probability that they are 0 or 1. This is determined by their spatial proximity to either voxel population (i.e. 0 or 1) by using the two-point correlation function. T1 and T2 are manually chosen by analyzing the histogram of the gray-scale XCT image using ImageJ. (Bhattad, Willson and Thompson 2010, Oh and Lindquist 1999, Ketcham 2006)

3-phase segmentation can be employed on an XCT image to analyze multi-phase fluid distribution within a porous column (Bhattad, Willson and Thompson 2010) or to characterize a porous system with multiple mineral/lithological phases (Ketcham 2006). To achieve a 3-phase segmentation, the gray-scale XCT image must be segmented twice. The first segmentation will populate the void space into one phase (0) and all of the solid phase into a second phase (1).
The second segmentation will populate the void space plus the lighter of the solid, but microporous, phase into one phase (0) and the solid material into a second phase (1). The two segmented images can then be added together to generated a 3-phase segmented image where values that were designated 0 in both original segmented images will remain 0, voxels that were designated 0 in the first segmented image but 1 in the second segmented image will now be 1, and voxels that were designated 1 in both original segmented images will now be 2. Hence, void space will remain 0, the microporous phase will now be 1, and the solid phase will now be 2.

4.4.4 Augmentation of XCT Scan Data with Conventional Core Analyses

Most reservoir rocks are comprised of a variety of mineralogical/lithological phases such as quartz grains and clay within a sandstone rock (mineralogical differences) and fossil fragments, calcite cement, and micrite within a carbonate rock (lithological differences). Because of elemental and/or density differences between mineral/lithological phases within a rock, the X-ray attenuation should vary between them. Element specific imaging, as mentioned in Section 3.1, has been successfully applied to multi-phase fluid distribution within porous media (Al-Raouch and Willson 2005); therefore, if enough contrast exists between phases within an XCT image of a geologic core, multi-phase segmentation should be possible. However, to qualitatively characterize the different phases that may be apparent in an XCT image, an understanding of the geologic system must be known.

Thin section and SEM photographs can provide a thorough understanding of the mineralogical/lithological structure of the rock (what mineralogical/lithological species exist in
the rock, their volume fractions, their spatial locations, and their geometric characteristics), which can be incorporated during the XCT segmentation process. This is useful because of the high amount of porosity residing as microporosity within “semi-solid” or porous phases such as clay and micrite within a geologic system. Depending on the geologic system of interest, conducting strictly solid/void segmentation may produce porosity values that are much less than the petrophysical porosity. However, if the microporosity within a porous phase within the system can be accounted for, XCT produced porosity values should more closely match petrophysical values.

3-phase segmentation was conducted on the XCT images of the three geologic cores used in this research. Thin section and SEM photographs were used to augment the XCT images to more accurately segment them into 3-phases. In doing this, multiple segmentations of each image were generated in an effort to produce the “best” segmentation possible. The criteria used in this research to obtain the “best” segmentation were both the petrophysical total porosity and the point count estimated porosity along with the visually best segmentation. A good deal of discrepancy exists in determining the visually best segmentation and it is up the person performing this segmentation to make a well-informed judgment based on a thorough investigation of the segmented images. Usually, the final “best” segmented image is a trade-off between a segmentation that visually looks best based on direct comparison with the original gray-scale XCT image and one that gives a porosity that most closely matches the point count estimated porosity. It should be noted, however, that there is a 3-6% error in the point count estimated porosity (E. R. Carver 1971); therefore, this value should only be used as a reference
and not an exact target value. Table 4.4-2 gives the threshold values used for segmentation of each XCT image.

Table 4.4-2. Image processing details including whether or not \textit{ad\_202} was run and the threshold values for both the void/solid segmentation and the microporous phase/solid phase segment of each XCT image

<table>
<thead>
<tr>
<th>File Name</th>
<th>\textit{Ad_202} Run?</th>
<th>Threshold Void/Solid (T1, T2)</th>
<th>Threshold Microporous Phase/Solid (T1, T2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASTLEGATE_A</td>
<td>Yes</td>
<td>90, 100</td>
<td>120, 130</td>
</tr>
<tr>
<td>CASTLEGATE_B</td>
<td>Yes</td>
<td>65, 75</td>
<td>84, 94</td>
</tr>
<tr>
<td>INDIANA_A</td>
<td>Yes</td>
<td>56, 62</td>
<td>100, 110</td>
</tr>
<tr>
<td>INDIANA_B</td>
<td>Yes</td>
<td>75, 85</td>
<td>140, 154</td>
</tr>
<tr>
<td>WINTERSET_A</td>
<td>Yes</td>
<td>80, 90</td>
<td>150, 170</td>
</tr>
<tr>
<td>WINTERSET_B</td>
<td>No</td>
<td>60, 68</td>
<td>136, 146</td>
</tr>
<tr>
<td>SANDMIX_A</td>
<td>Yes</td>
<td>90, 100</td>
<td>NA</td>
</tr>
<tr>
<td>SANDMIX_B</td>
<td>Yes</td>
<td>87, 95</td>
<td>NA</td>
</tr>
</tbody>
</table>

XCT porosity is calculated by performing a voxel count on each phase within the XCT volume. Macroporosity, or void space, simply equals the number of voxels that make up the void space divided by the total number of voxels in the XCT image. The microporosity is equal to the number of voxels making up the microporous phase divided by the total number of voxels in the XCT image, multiplied by the estimated porosity of that microporous material. So, for the micrite phase within the Indiana Limestone, the volume of the micrite phase determined from the 3-phase segmented XCT image of the Indiana was multiplied by a porosity of 25%, which was estimated from the SEM photographs of the micrite. The kaolinite phase in the Castlegate was multiplied by 40%, which was estimated from SEM images of the kaolinite within the Castlegate and from Hurst and Nadeau (1995). The layered sand XCT volumes were only segmented into two phases, solid sand and void space.
4.5 Macropore Structure Extraction (Vox2net)

Macropore network structures for each system were generated from the 3-phase images presented in Table 4.4-2 using vox2net. The networks were built on the voxels tagged as void space (i.e. voxels labeled 0) only. The layered sand systems were divided into three sections corresponding to grain size: H1 is the top coarse 30/40 Accupack; H2 is the middle fine 50/100 F75 sand; and H3 is the bottom coarse 30/40 Accupack. As mentioned previously, scheme 1 for defining the stop criteria was used. Quantitative data pertaining to the pore structure was extracted with the program nettable. Nettable generates a text file called nettableP that can be imported into an excel worksheet. NettableP includes data for each pore such as the x, y, and z coordinates, pore volume, pore radius, pore coordination number, the neighboring pore, connecting throats, throat cross-sectional area, throat surface area, throat inscribed radius, throat aspect ratio to each connecting pore, throat length, and hydraulic conductance through each pore-throat. Pore and throat radii data were used to generate pore and throat size frequency distributions for each system. Pore and throat size frequency plots for each system are provided in Chapter 5.

4.6 Development of the Dual Porosity Pore Network Structures

The idea behind developing the dual-porosity pore network structure for each of the porous systems is that once the XCT images are segmented into three phases (void space/microporous phase/solid phase), a pore network representing the microporosity can be inserted into the microporous regions, which are spatially and geometrically mapped by the 3-phase segmented images, and integrated with the macropore network structures generated on the visible void space. As previously mentioned, one method for obtaining the pore structure
of the microporous phase is FIB/SEM. However, correlating/integrating this micropore structure back into the macropore network is not trivial, and since the scale of the FIB/SEM is at the sub-micron range, it would have to be assumed that the network generated through FIB/SEM analysis is representative of all the microporosity within the larger XCT volume. Also, FIB/SEM is a destructive method and generating a 3-D image from it is difficult.

Another approach is to populate the voxels corresponding to the microporous phase within the 3-phase XCT image with pore statistics obtained from petrophysical mercury injection and SEM and thin section image analyses. A pore of a radius corresponding to the to the porosity of the respective material can be inserted into each voxel and pore connectivity can be obtained from mercury injection data for the respective material. This approach works directly on the 3-phase segmented XCT image, making integration with the micropore network structure trivial. This approach is simple and straightforward to implement, making it an appealing first approach for developing and implementing a dual-porosity network structure.

One may argue that this statistical approach is taking a step back in the advancement of realistic pore network modeling where pore networks are directly extracted from 3-D images and that the FIB/SEM approach can provide a much more realistic pore structure. This is true; however, due to time constraints and limited resources, the FIB/SEM approach was not feasible. Also, FIB/SEM would only provide a network for a few specific locations of the microporous phase, so incorporating that pore structure into the entire microporous phase will not substantially reduce the uncertainty in the network. The statistical approach, although introducing old issues such as lacking the ability to directly measure the connectivity of the pore
space, is still moving forward toward the development of a physically representative dual-
porosity pore network model.

During the application of this approach to the imaged systems, it was realized that this
approach might not be feasible for most dual-porosity systems. Taking the Indiana Limestone
as an example, the number of voxels pertaining to the micrite phase in INDIANA_A is around
25,163,600. Thankfully, at 3.9 μm resolution and an average pore size of ~1 μm, only one pore
per voxel is required to meet a porosity of ~25%. Still, this will add over 25 million pores to the
total pore network, which is an extremely large number resulting in long computation times,
defeating the main purpose of pore network modeling. One option is to cut out a small sub-
volume from the system to decrease the number of pores, but for a heterogeneous system like
the Indiana, a system small enough to reasonably reduce the number of pores so that
computation time is significantly reduced would not be representative of the real system.
However, for a homogeneous system like the Castlegate Sandstone, this approach may be
feasible. Plus, the percentage of voxels pertaining to the clay phase within the Castlegate is
much smaller than that of the Indiana Limestone.

Dual-porosity networks were only generated for the Castlegate Sandstone and the 16.1
μm layered sand system. A 200³ sub-volume was cut from the center of the original 3-phase
segmented Castlegate volume. The first step in generating the dual-porosity pore network
structure is to create the macropore network structure of the system with vox2net. Once the
macropore structure is generated, the 3-phase binary image file is used to populate the voxels
corresponding to the microporous phase (i.e. clay) with pore statistics. The algorithm
createdpn, written by Dr. Karsten Thompson, reads in both the macropore network file (.psn file) created with vox2net and the 3-phase binary image file (.bin file) along with a text file containing a pore-throat size distribution. createdpn creates a regular network on the voxel population representing the microporosity using the pore-throat distribution provided in the text file and a pore size calculated based on the porosity of that phase, which is an input parameter for the algorithm. The pore-throat size distribution for the clay was obtained from the mercury injection data. To obtain a distribution around the pore-throats corresponding the clay phase only, that section of the drainage data was extracted and new adjusted saturations were calculated. Pore radii were calculated using

\[ r = -\frac{2T_s \cos \alpha}{u_p}, \]  

Eq. 4.37c, Lu and Likos (2004), where \( r \) is the pore-throat radius, \( T_s \) is the surface tension of the wetting fluid, \( \alpha \) is the contact angle, and \( u_p \) is the capillary pressure. Once the regular network is generated, createdpn integrates it with the .psn file for the macropore network to generate the dual-porosity network. The output file for the Castlegate dual-porosity network is CASTLEGATE_B200DP.

The layered sand system is a proof-of-concept mechanism for this approach. The idea is that the true pore structure for both the coarse-grained 30/40 Accupack and the fine-grained 50/100 F75 sand systems can be extracted from the 8.05 \( \mu \text{m} \) SANDMIX_A XCT volume with vox2net, but that only the pore structure of the 30/40 Accupack can be accurately obtained from the 16.1 \( \mu \text{m} \) SANDMIX_B XCT volume. The fine sand layer from the 16.1 \( \mu \text{m} \) SANDMIX_B
system can then be replaced with an artificial pore network generated from the pore statistics obtained from the fine sand layer of the 8.05 μm SANDMIX_A system. Permeability and drainage simulations can then be run on both the real and artificial systems and compared. This will give insight as to whether using a statistical approach for mapping the micropore structure of a porous system is useful.

To insert pores into each voxel of the fine sand layer so that the pore volume equals the porosity of that phase, but at the same time the pore radius matches the average pore radius of that phase, a voxel size adjustment was required. The average pore radius in the 8.05 μm resolution F75 sand system is ~32 μm. The porosity of this system is 39.8%. So 32/0.398 is 80.4 μm. A sphere of a volume equal to 39.8% of 80.5³ corresponds to a pore radius of 36.7 μm; therefore, a voxel resolution of 80.5 μm is appropriate. The voxel size had to be increased by a factor of 5 for the 16.1 SANDMIX_B system making the new resolutions 80.5 μm. Voxel adjust also makes the layered sand system more representative of a geologic system since in a geologic system, the pore sizes of the microporous phase will be smaller than the voxel resolution. Note that any voxel size theoretically could be used.

The following is an overview of how the dual-porosity pore network structure for the layered sand system was generated:

1. The original SANDMIX_B file contained 812 vertical slices; therefore, to make the height a factor of 5, two slices were cropped from its bottom. The three zones are now assumed to be: 1-210: coarse (210 slices); 211-410: fine (200
slices); 411-810: coarse (400 slices). This new file was saved as layeredsand_2x2_v2.bin

2. A MatLab code, 'creategrayzone', was run to convert the middle 200 slices to a gray phase. The new file was titled 'layeredsand_v2_grayHR.bin' and now has voxel labels: 0=void; 1=gray; 2=solid.

3. vox2net201 was run to create the network structure of the coarse sand regions of the system. The network was created from the 0 phase, which means there are no network pores in the middle section of the domain. A conversion factor of 0.05 was used so that the pore locations will correctly correspond to the five-times-smaller 55x55x162 voxel file that will be used for creating the sub-porosity.

4. The code vox2net201 was also set to create the file imatp.bin, which is a 550x550x1620 voxel file in which each voxel is tagged with the pore number to which it belongs. A new program (binporenumbers) was created that bins these pore numbers in 5x5x5 blocks. The file is called imatp_binned.bin and has dimensions 55x55x162. This file is needed because, as mentioned above, we are going to create sub-porosity in the network by using a 55x55x162 segmented image (0,1,2), and a corresponding imatp data file is needed to figure out which pores to tie the sub-porosity network into.

5. An artificial voxel file was created with dimensions 55x55x162. It has voxels tagged with 1 (gray) in the range z=[43,82]. This is the region where the sub-
network will be created. The tagging in the rest of the image does not matter (as long as it is not "gray") because this step in the algorithm tags only the gray voxels.

6. The program "createdpn" (create dual-porosity network) was then run. This program adds an additional pore at the center of each gray voxel. In this case, it is being added based on the coarsened/binned network. Hence, it adds 55x55x40 = 121,000 new pores. The pores were sized so that each pore made up 39.8% of each voxel. The pore-throat sizes were selected from the distribution generated from the true pore structure of the 8.05 μm fine sand layer. For simplicity, the pore-throat sizes were sorted in a random order and the pore-throats in the artificial network were assigned by pulling in order from top to bottom from the pore-throat distribution text file. The number of pore-throats in the 8.05 μm fine sand network is 211,785, which is less than the number of throats to be added; therefore, once the end of the file is reached, it will move back to the top. The final output file, which is the dual-porosity network for the layered sand system, is SANDMIX_B_DP.

A second artificial (i.e. dual-porosity network) SANDMIX_B system, SANDMIX_B_DP2, was generated by re-sorting the pore-throats in the pore-throat distribution text file to see if re-randomizing the pore-throats has any effects on permeability and drainage. Note that this layered sand system is a special case because for most geologic systems of interest, the true pore-throat distribution will not be known. A distribution can, however, be taken from mercury
injection capillary pressure data as was done for CASTLEGATE_B200DP, but some assumptions and generalizations are required.

4.7 Permeability and Drainage Simulation

Permeability and drainage simulations were performed on the single-porosity pore networks for all four systems and on the dual-porosity pore networks SANDMIX_B_DP(2) and CASTLEGATE_B_200DP. The .psn files generated with vox2net are the input files for the permeability program spflow and the drainage program qsdrain. Permeability and drainage simulations were performed on the entire layered sand systems and on layers H2 and H3 separately. Results for the rock systems were compared to the petrophysical results (permeability and MIP) provided by Weatherford Laboratories. Results for the 30/40 sand were compared to data taken from Schroth, et al. (1996). Results for the F75 sand was not compared to literature data since the F75 sand used in this analysis was sieved.

4.7.1 Single Phase Permeability (Spflow)

Spflow imposes constant-pressure boundary conditions at each end of the network and no-flow boundary conditions on the sides of the network so that flow is only conducted in and out of the faces at each end. Conservation of mass is then applied at each pore (i.e. node) within the network. The flow rate between two adjacent pores is described by

\[ q_{i,j} = \frac{K_{i,j}}{\mu} (P_j - P_i), \]

where \( q_{ij} \) is the flow rate between pores \( i \) and \( j \), \( K_{ij} \) is the hydraulic conductance of the throat \( ij \), \( P_j \) is the pressure at pore \( j \), and \( P_i \) is the pressure at pore \( i \). The sum of flow rates into each pore
is equal to zero. This allows for a system of equations that can be solved to obtain the total flow rate through the network at a given pressure. Permeability is then calculated by solving the one-dimensional Darcy equation,

\[ k = \frac{Q}{A \left( \frac{\Delta P}{L} \right)} , \]

where \( k \) is the permeability through the entire network, \( Q \) is the total flow rate through the entire network, \( A \) is the average surface area at each adjacent face of the network, \( \Delta P \) is the pressure gradient across the network, and \( L \) is the length of the network. (Bhattad, Willson and Thompson 2010)

*Spflow* was run on each image in all three flow directions. However, petrophysical permeability was measured only along the vertical direction of the core, which corresponds to the \( z \) direction of the images; therefore, only permeability in the \( z \)-direction will be used for comparison with the petrophysical permeability. The H2 and H3 layers of the layered sand systems were analyzed separate to obtain values for each sand system. H1 was not analyzed since it is the same as H3 and H3 is the larger of the two layers. Effective vertical permeability was also calculated for SANDMIX_A, SANDMIX_B, and SANDMIX_B_DP for comparison with the \( z \)-direction permeability through the entire layered sand column. Effective vertical permeability was calculated by dividing the total length of the column by the sum of the lengths of each layer divided by their individual permeability. Since H1 was not analyzed, the permeability value for H3 was used for H1.
4.7.2 Quasi-static Drainage (Qsdrain)

Qsdrain is a quasi-static drainage simulator that models immiscible displacement starting at a wetting phase saturation of 1. A positive capillary pressure is applied at one face of the network and a search is performed that locates all pores at the inlet face that are accessible at the current capillary pressure. Invasion will then occur and will proceed inward through connecting pores until all accessible pore-throats/pores are invaded. Once equilibrium is reached, the capillary pressure is increased at the inlet and the invasion search process is repeated. (Bhattad, Willson and Thompson 2010)

Input parameters pertaining to the wetting and non-wetting phase fluids are required in the input file for qsdrain. For this research, the wetting phase was water and the non-wetting phase was air. The interfacial tension for air/water is 72 dynes/cm and the contact angle is 0 degrees. The output from qsdrain is a text file that includes two columns containing the capillary pressure and wetting phase saturation. Pore-throat radii were calculated from the capillary pressures using Equation 1 (Lu 2004). Plots of saturation versus pore-throat radius were plotted against the laboratory mercury injection data for comparison.
5 Results

5.1 Thin Section and SEM

Thin section and SEM images of the Castlegate Sandstone, Indiana Limestone, and Winterset Limestone were thoroughly analyzed to gain a geologic understanding of the three systems. Results from the high-density point count on the thin sections are presented in Tables 5.1-1, 5.1-2, and 5.1-3. Statistical results from the low-density (100 points) point count of the ten Castlegate and Indiana thin section locations are presented in Table 5.1-4. Summaries of the petrographic descriptions written by Dr. Sears are provided below along with the thin section and SEM photographs and mercury injection plots for each system, which are presented in Figures 5.1-1 through 5.1-12.

Table 5.1-1. High-density point count results for the Castlegate Sandstone

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz Grains</th>
<th>Rock Fragments</th>
<th>Clay</th>
<th>Macroporosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castlegate Sandstone</td>
<td>56%</td>
<td>18%</td>
<td>5%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Table 5.1-2. High-density point count results for the Indiana Limestone

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fossil Fragments</th>
<th>Calcite Cement</th>
<th>Micrite</th>
<th>Macroporosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indiana Limestone</td>
<td>31%</td>
<td>30%</td>
<td>29%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 5.1-3. High-density point count results for the Winterset Limestone. At a porosity of 25%, the micrite contributes 3% microporosity to the total porosity of this rock. The 3% porosity from the micrite plus the 1% from the intercrystalline pore space equals a total microporosity of 4%.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Calcite Cement</th>
<th>Micrite</th>
<th>Moldic Pores</th>
<th>Intercrystalline Pores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winterset Limestone</td>
<td>57%</td>
<td>12%</td>
<td>28%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Table 5.1-4. Low-density (100 points) point-count statistics for the Castlegate Sandstone and the Indiana Limestone.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average Porosity</th>
<th>Porosity Stdev</th>
<th>Porosity Range</th>
<th>Avg. Clay/Micrite</th>
<th>Stdev for % Clay/Micrite</th>
<th>Clay/Micrite Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castlegate SS</td>
<td>16%</td>
<td>3.9%</td>
<td>11-25%</td>
<td>3.5%</td>
<td>1.35%</td>
<td>1-5%</td>
</tr>
<tr>
<td>Indiana LS</td>
<td>5%</td>
<td>2.3%</td>
<td>1-7%</td>
<td>35%</td>
<td>8.12%</td>
<td>25-49%</td>
</tr>
</tbody>
</table>

The Castlegate is a very well sorted sandstone primarily made up of quartz and aphanitic igneous rock fragments. Most grains range from ~150-180 μm, and some rock fragments seem to be altering to authigenic clay or have been subdued to partial dissolution; therefore, contain intraparticle porosity (Figure 5.1-1). Two types of clays are also seen. The first and most abundant form is as discrete particle clays scattered through the pore space (i.e. Kaolinite). The second and less abundant form is pore-lining clays (illite, chlorite, and montmorillonite) that appear as coatings on some of the quartz grains (Figure 5.1-2). The mercury injection data, presented in Figures 5.1-3 and 5.1-4, shows that ~70% of the pore space is accessible through pore-throats between ~10 and ~11 μm and that ~80% is filled through pore-throats between ~5 and ~11 μm.

The Indiana Limestone (Figures 5.1-5 and 5.1-6) is a highly heterogeneous crinoid-bryozoan packstone comprised of 100 μm fossil fragments, calcite cement, and ~2 μm crystals of calcite (micrite; Figure 5.1-6). Interparticle pores around 50 μm are seen in Figure 5.1-5. The fossil fragments and calcite cement do not appear to exhibit any intraparticle porosity. However, the micrite appears to have ~1 μm pores between its grains, contributing about 25% microporosity to the total porosity of the rock. The high-density point count results are presented in Table 5.1-2. The mercury injection data, presented in Figures 5.1-7 and 5.1-8,
shows a wide distribution of pore-throats sizes between 0.02 and 7 μm, with two sub-
distributions centered around ~0.1 and ~1.5 μm. 90% of the pore space is accessible through 
throats smaller than ~3 μm.

The Winterset is a moldic oolitic limestone made of calcite cement (grains ~40 μm in 
diameter) and large moldic pores ~300 μm in diameter due to the leaching of ooids (Figures 
5.1-9 and 5.1-10). Some of the moldic pores contain finer grained calcite crystals 
approximately 5 microns in diameter (similar to the micrite in the Indiana). There is also about 
1% intercrystalline pore space between the calcite cement crystals. This is the only pore space 
available for fluid flow through the rock, resulting in a rock with very low permeability and high 
porosity. The high-density point count results are presented in Table 5.1-3. The mercury 
injection data, Figures 5.1-11 and 5.1-12, shows that ~80% of the pore space is accessible 
through pore-throats between 1 and 3 μm.

Figure 5.1-1. Castlegate Sandstone 50X (Left) and 200X (Right) plane light thin section 
images. (Left) The white grains are primarily quartz and igneous rock fragments. The dark 
grains are primarily shale or rock fragments that have partially altered to clay. (Right) A 
deformed rock fragment between quartz grains is reducing the interparticle porosity.
Figure 5.1-2. Castlegate Sandstone 50X (Left) and 500X (Right) SEM photographs. (Left) Minor coating of clay is seen on the well-sorted quartz grains. (Right) Kaolinite clay is seen between quartz grains. ~40% microporosity can be seen between the clay booklets.

Figure 5.1-3. Castlegate Sandstone pore-throat radius (μm) versus cumulative mercury saturation generated from the petrophysical mercury injection capillary pressure data. ~70% of the pore space is accessible through throats between ~10 and ~11 μm in radius.
Figure 5.1-4. Castlegate Sandstone pore-throat radius (µm) versus incremental mercury saturation generated from the petrophysical mercury injection capillary pressure data. A second population of pore-throats of radius between ~0.1 to ~0.2 µm can be seen, which provide access to ~5% of the total pore space.

Figure 5.1-5. Indiana Limestone 50X (Left) and 200X (Right) plane light thin section images.
Figure 5.1-6. Indiana Limestone 200X (Left) and 1000X (Right) SEM photographs. Micrite is seen coating the majority of the fossil fragments. (Right) ~1 μm pores between calcite crystals of the micrite. The micrite is estimated to have a porosity of ~25%.

Figure 5.1-7. Indiana Limestone pore-throat radius (μm) versus cumulative mercury saturation (%) generated from the petrophysical mercury injection capillary pressure data.
Figure 5.1-8. Indiana Limestone pore-throat radius (μm) versus incremental mercury saturation generated from the petrophysical mercury injection capillary pressure data. Two slightly more distinct distributions are seen centered around ~0.1 and ~1.5 μm.

Figure 5.1-9. Winterset Limestone 50X (Left) and 400X (Right) plane light thin section images. (Right) Intercrystalline porosity is seen between the calcite cement grains.
Figure 5.1-10. Winterset Limestone 50X (Left) and 200X (Right) SEM photographs. \( \sim 5 \, \mu\text{m} \) calcite crystals is seen within the moldic pores.

Figure 5.1-11. Winterset Limestone pore-throat radius (\( \mu\text{m} \)) versus cumulative mercury saturation (%) generated from the petrophysical mercury injection capillary pressure data. 80% of the pore-throats exist between 1 and 3 \( \mu\text{m} \).
Figure 5.1-12. Winterset Limestone pore-throat radius (µm) versus incremental mercury saturation generated from the petrophysical mercury injection capillary pressure data. Majority of the pore space is accessed through 1 µm throats.

5.2  XCT Analysis

2-D slices of the 3-D XCT images are presented for each system (Figures 5.2-1 through 5.2-10). Gray-scale XCTs after noise reduction with ad_202 are compared to the corresponding 3-phase segmented XCTs for discussion. Figure 5.2-3 and 5.2-6 are presented to show the heterogeneity of the Indiana Limestone and the particular locations of which the 2-D horizontal slices in Figures 5.2-4, 5.2-5, and 5.2-7 are located.
Figure 5.2-1. CASTLEGATE_A gray-scale XCT after noise reduction (Left) and the corresponding 3-phase segmented XCT (Right). Black, green, and grey correspond to void space, clay, and solid sand grains, respectively. The macroporosity and microporosity here are 18.5% and 6.6%, respectively. The image resolution is 7.57 μm.

Figure 5.2-2. CASTLEGATE_B gray-scale XCT after noise reduction (Left) and the corresponding 3-phase segmented XCT (Right). Black, green, and grey correspond to void space, clay, and solid sand grains, respectively. The macroporosity and microporosity here are 22.9% and 1.3%, respectively. The image resolution is 5 μm.
Figure 5.2-3. Three vertical slices of the INDIANA_A gray-scale XCT image after noise reduction. A large degree of heterogeneity is seen within this sample.

Figure 5.2-4. Horizontal slice of the INDIANA_A gray-scale XCT image after noise reduction at location A in Figure 5.2-3 (Left) and the corresponding 3-phase segmented XCT image (Right). (Right) Black, gray, and white correspond to void space, micrite, and solid calcite and cemented fossil fragments, respectively. The macroporosity and microporosity of the 3-phase segmented XCT are 8.5% and 5.4%, respectively. The image resolution is 3.9 μm.
Figure 5.2-5. Horizontal slice of INDIANA_A gray-scale XCT image after noise reduction at location B in Figure 5.2-3 (Left) and the corresponding 3-phase segmented XCT image (Right).

Figure 5.2-6. Three vertical slices of the INDIANA_B gray-scale XCT image after noise reduction. This sample does not show the large degree of heterogeneity as seen in the I3 XCT volume.
Figure 5.2-7. Horizontal slice of INDIANA_B gray-scale XCT image after noise reduction at location A in Figure 5.2-6 (Left) and the corresponding 3-phase segmented XCT image (Right). (Right) Black, gray, and white correspond to void space, micrite, and solid calcite and cemented fossil fragments, respectively. The macroporosity and microporosity of the 3-phase segmented XCT are 4.9% and 2.9%, respectively. The image resolution is 5 μm.

Figure 5.2-8. Winterset_A gray-scale XCT image after ad_202 (Left) and the 3-phase segmented XCT image (Right). (Right) Black, gray, and white correspond to void space, micrite, and solid calcite grains, respectively. The macroporosity and microporosity here are 15.7% and 3.5%, respectively. The image resolution is 4 μm.
Figure 5.2-9. WINTERSET_B gray-scale XCT image (Left) and the 3-phase segmented XCT image (Right). (Right) Black, gray, and white correspond to void space, micrite, and solid calcite grains, respectively. The macroporosity and microporosity here are 6% and 4.7%, respectively. The image resolution is 19.9 μm.
Figure 5.2-10. SANDMIX_A (8.05 μm resolution) XCT after noise reduction (Left) and the corresponding 2-phase segmented XCT (Right). (Right) Black is void space and white is quartz grains. The three layers, H1-H3, are indicated in the figure. Again, H1 and H3 are the 30/40 Accupack sand layers and H2 is the 50/100 F75 sand.
Petrophysical and petrographic porosities for each system including that determined from the 3-phase XCT volumes are presented in Table 5.2-1. Rows in black/purple text represent the volumes that were further analyzed with the dual-porosity pore network.

Table 5.2-1. Petrophysical and petrographic porosity. The point count porosity is from the high-density (300 points) point count.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Petrophysical Porosity</th>
<th>Point Count Macroporosity</th>
<th>Point Count Microporosity</th>
<th>XCT Macroporosity</th>
<th>XCT Microporosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASTLEGATE_A</td>
<td>25.1</td>
<td>21</td>
<td>2</td>
<td>18.5</td>
<td>6.6</td>
</tr>
<tr>
<td>CASTLEGATE_B</td>
<td>25.1</td>
<td>21</td>
<td>2</td>
<td>22.9</td>
<td>1.3</td>
</tr>
<tr>
<td>CASTLEGATE_B200</td>
<td>25.1</td>
<td>21</td>
<td>2</td>
<td>24.4</td>
<td>1.1</td>
</tr>
<tr>
<td>INDIANA_A</td>
<td>15.1</td>
<td>10</td>
<td>7</td>
<td>8.5</td>
<td>5.4</td>
</tr>
<tr>
<td>INDIANA_B</td>
<td>15.1</td>
<td>10</td>
<td>7</td>
<td>4.9</td>
<td>2.9</td>
</tr>
<tr>
<td>WINTerset_A</td>
<td>32.2</td>
<td>28</td>
<td>4</td>
<td>15.7</td>
<td>3.5</td>
</tr>
<tr>
<td>WINTerset_B</td>
<td>32.2</td>
<td>28</td>
<td>4</td>
<td>6</td>
<td>4.7</td>
</tr>
<tr>
<td>SANDMIX_A</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>36.5</td>
<td>NA</td>
</tr>
<tr>
<td>SANDMIX_B</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>35.9</td>
<td>NA</td>
</tr>
<tr>
<td>SANDMIX_A_H2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>39.8</td>
<td>NA</td>
</tr>
<tr>
<td>SANDMIX_B_H2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>38.2</td>
<td>NA</td>
</tr>
<tr>
<td>SANDMIX_A_H3</td>
<td>33-35</td>
<td>NA</td>
<td>NA</td>
<td>35.01</td>
<td>NA</td>
</tr>
<tr>
<td>SANDMIX_B_H3</td>
<td>33-35</td>
<td>NA</td>
<td>NA</td>
<td>35.04</td>
<td>NA</td>
</tr>
</tbody>
</table>

5.3 Nettable Pore and Pore-throat Size Distributions

Figures 5.3-1 through 5.3-4 present pore and pore-throat size frequency distributions generated from the nettable results for the Castlegate Sandstone, the Indiana Limestone, and the layered sand pore networks. Pore size distributions were not generated for the Winterset Limestone because they were not required for further analysis.
Figure 5.3-1. Nettable pore and pore-throat cumulative frequency plots for the NSLS and APS Castlegate networks. (PSD = pore size distribution; TSD = throat size distribution)

Figure 5.3-2. Nettable pore and pore-throat cumulative frequency plots for the APS Castlegate networks.
Figure 5.3-3. Nettable pore and pore-throat cumulative frequency plots for the NSLS and APS Indiana Limestone networks.

Figure 5.3-4. Nettable pore and pore-throat cumulative frequency plots for the SANDMIX_A_H3 and SANDMIX_B_H3 systems.
5.4 Permeability

Permeability for the single-porosity and dual-porosity pore networks for each porous system is presented in Table 5.4-1. Petrophysical permeability for the entire layered sand system and for the 50/100 F75 sand layer is not provided.

Table 5.4-1. Single-porosity (SP) and dual-porosity (DP) simulated and petrophysical permeability. SANDMIX_A Eff, SANDMIX_B Eff, and SANDMIX_B_DPEff correspond to the effective permeability for each of those systems.

<table>
<thead>
<tr>
<th>File Name</th>
<th>Spflow X Perm. (mD)</th>
<th>Spflow Y Perm. (mD)</th>
<th>Spflow Z Perm. (mD)</th>
<th>Spflow Avg. Perm. (mD)</th>
<th>Petrophysical Perm. (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INDIANA_B</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2.69</td>
</tr>
<tr>
<td>INDIANA_A</td>
<td>272</td>
<td>355</td>
<td>59</td>
<td>229</td>
<td>2.69</td>
</tr>
<tr>
<td>CASTLEGATE_A</td>
<td>1,505</td>
<td>1,337</td>
<td>1,310</td>
<td>1,384</td>
<td>1040</td>
</tr>
<tr>
<td>CASTLEGATE_B</td>
<td>1,671</td>
<td>2,116</td>
<td>1,570</td>
<td>1,785</td>
<td>1040</td>
</tr>
<tr>
<td>CASTLEGATE_B200</td>
<td>1,761</td>
<td>2,748</td>
<td>1,914</td>
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5.5 Capillary Pressure/Drainage

Figures 5.5-1 – 5.5-6 present plots of both the single and dual-porosity simulated drainage (i.e. qsdrain) and laboratory mercury injection data. Due to very low pore connectivity in the INDIANA_B network and both Winterset networks, qsdrain results were not obtained.
Figure 5.5-1. Castlegate simulated pore-throat radius (μm) versus saturation (%) plotted against the petrophysical mercury injection saturation versus pore-throat radius.

Figure 5.5-2. Pore-throat radius (μm) versus saturation (%) for the single and dual-porosity CASTLEGATE_B networks and the petrophysical mercury injection capillary pressure data.
Figure 5.5-3. Indiana Limestone (INDIANA_A) simulated saturation (%) versus pore-throat radius (µm) plotted against the petrophysical mercury injection saturation (%) versus pore-throat radius (µm).

Figure 5.5-4. Indiana Limestone (INDIANA_A) simulated saturation (%) versus pore-throat radius (µm) plotted against the petrophysical mercury injection saturation (%) versus pore-throat radius (µm). The X-axis is adjusted here to better resolve the data.
Figure 5.5-5. 30/40 Accupack sand capillary pressure (cm of water) versus volumetric water content (m⁴/m³).

Figure 5.5-6. Pore-throat radius (µm) versus saturation (%) for the SANDMIX_A_H3 and SANDMIX_B_H3 networks plotted against the 30/40 Sand data from Schroth et al. (1996)
Figure 5.5-7. Simulated capillary pressure (cm of water) vs. saturation (%) for the single and dual-porosity layered sand networks.

Figure 5.5-8. Simulated saturation (%) versus pore-throat radius (μm) for the single and dual-porosity layered sand networks.
6 Discussion

6.1 Factors Affecting XCT Image Segmentation

The accuracy of a physically representative pore network model begins with the quality of the XCT image. Factors such as image resolution and the characteristic length scale of the pore structure, image noise, and image contrast due the mineralogy/lithology of the media and the X-ray energy used greatly affect the segmentation process, which is the crucial step in generating an accurate physically representative pore network model. Segmentation determines the distribution of phases (void, solid, microporous phase) within the XCT image; therefore, it controls parameters such as porosity, pore size, and pore connectivity, which all play a major role in fluid flow and transport processes.

Image resolution and the characteristic length scale of the pore structure dictate the ability of the XCT image to capture the true porosity and pore connectivity of the system. As shown in Figures 5.1-1, 5.1-2, (Castlegate thin section and SEM photographs) and 5.1-3 (Castlegate pore-throat radius versus mercury saturation plot), the Castlegate Sandstone is a fairly homogenous system where 80% of the pore space is accessible though throats greater than ~5 µm in radius and 70% is accessible through throats ~10 µm radius. It is these pore-throats that connect the large interparticle pores seen in Figure 5.1-1. A second population of pore-throats with a radius of ~0.1 to 0.2 µm, which correspond to pore-throats between clay particles and within rock fragments, allow access to approximately 5% of the pore space. The remaining pore-throat sizes reflect smaller interparticle pore-throat radii (1-10 µm) and smaller micropores within the clay and rock fragments (0.01-0.1 µm radii). Due to the homogeneous
nature of this rock and its high degree of macropore connectivity, this is a system where the primary fluid flow is expected to be governed only by interparticle porosity. Both, the macroporosity (pore space resolvable in the XCT image, which is larger than ~2 times the XCT voxel resolution) and microporosity (pore space not resolvable in the XCT image, which is smaller than ~2 times the XCT voxel resolution) determined following segmentation of the two Castlegate XCT images fall within the ranges obtained from the point count method, suggesting that the Castlegate XCT images are sufficient in capturing the true pore space of this geologic system. Further discussion to support this claim will be made in the following sections.

The Winterset Limestone, on the other hand, is a very heterogeneous system with large voids that have a very low degree of connectivity between them. The large size of these voids is why the petrophysical analysis gives a porosity of 32.2%, but a permeability of only 2.69 mD. Fluid flow through the Winterset is governed by a small percentage of interparticle pores (~1%) between calcite cement grains on the order of 1-5 μm (Dr. Sear’s petrographic description).

Figure 5.1-11 (Winterset petrophysical drainage curve) indicates that 80% of the pore space is accessed by pore-throats between 1 and 3 μm. Therefore, it is expected that the 4 μm resolution of WINTERSET_A and the 19.9 μm resolution of WINTERSET_B is not sufficient to capture the pore space that governs fluid flow through this system. The XCT macroporosity for WINTERSET_A and WINTERSET_B is 15.7% and 6%, respectively, which are about half and one fifth the petrophysically-estimated (i.e., high-density point count) macroporosity of 28%. These porosity results support the former notion that the resolution here is not sufficient to capture the characteristic length scale governing fluid flow and transport processes in this geologic system.
Image contrast can play a major role in the ability to accurately segment an XCT image and is affected by noise within the image, differences in X-ray attenuation values between different mineralogical/lithological phases within the image, and the X-ray energy used for image collection. As mentioned before, noise can distort the contrast between features within an image by either blurring edges or by covering up features such as pore-throats all together. Noise that is not removed can also add to or take away from a particular phase within the image. The noise removal algorithm, \textit{ad\_202}, is, therefore, applied to each XCT image in an effort to remove the noise. However, although \textit{ad\_202} is designed to preserve edges, it has been seen to smooth the edge of features such as quartz grains within a sandstone system, reducing the contrast between it and adjacent phases. Note that the benefit of \textit{ad\_202} significantly out-weighs the detriment.

The two Castlegate gray-scale XCT images, \textit{CASTLEGATE\_A (Figure 5.2-1)} and \textit{CASTLEGATE\_B (Figure 5.2-2)}, are good examples of the effect of noise on the segmentation process. It can be seen that the gray-scale XCT in \textbf{Figure 5.2-1} is less clear than the gray-scale XCT in \textbf{Figure 5.2-2}. Noise removal through \textit{ad\_202} has been performed on both of these images. The histograms of the two gray-scale XCTs shown in \textbf{Figure 6.1-1} show that the contrast between the void and solid phase is much greater in \textit{CASTLEGATE\_B} than in \textit{CASTLEGATE\_A}. As a result, the two-phase segmentation of \textit{CASTLEGATE\_B} was much easier than on \textit{CASTLEGATE\_A} and the resulting pore network structure is believed to be more accurate. The XCT macroporosity determined from \textit{CASTLEGATE\_B} has a better correlation with the high-density point estimated macroporosity, although a large range in porosity is shown to exist throughout the thin section as determined from the low-density point counting
(Table 5.1-4). Note that due to the inability to adjust the magnification during the low-density point counting, subtle features such as small pore-throats or kaolinite sandwiched between quartz grains could not be accurately accounted for, which can explain the lower porosity determined by the low-density point count.

![Histograms](image)

**Figure 6.1-1. CASTLEGATE_A histogram (Left) and CASTLEGATE_B histogram (Right).**

Although noise affects the 2-phase segmentation process, it has been seen to have a much greater affect on the 3-phase segmentation process. Noise seen in both of the Castlegate XCT images has intensities near that of what is believed to be the clay and rock fragments in the gray-scale image. Therefore, if not properly removed, it is very difficult to exclude this noise from the intermediate microporous phase when segmenting. Also, the blurred edges that result from noise removal tend to be of the same intensity as the microporous phase; therefore, as seen in the 3-phase segmented XCT in **Figure 5.2-1**, a population of voxels around the edges of almost all the quartz grains is included in the microporous phase. This was also seen in the CASTLEGATE_B 3-phase segmented image, but a “remove islands and holes” algorithm *(removeih)* was applied, which successfully removed the majority of voxels around
the quartz grains that were assigned to the microporous phase (Figure 5.2-2). was also applied to CASTLEGATE_A, but due to the thickness of the intermediate layer around the quartz grains, it had little affect.

Mineralogical/Lithological differences between phases are probably the most significant factor affecting phase identification within an XCT image, particular when attempting a 3-phase segmentation. The elemental composition and density of a particular phase are the primary factors that determine the X-ray attenuation of a material in synchrotron source XCT images. So, phases that are similar in either elemental composition or density will tend to have similar X-ray attenuation values, reducing the contrast between them. The X-ray attenuation values of the solid calcite grains and calcite cement in both the Indiana Limestone and the Winterset Limestone have drastically different X-ray attenuation values from the micrite seen in both systems (Figures 5.2-3, -5, -8, and -9). Micrite is made of small calcite crystals; hence, there is no elemental difference between the calcite grains/cement and the micrite. However, micrite has a porosity of ~25%, making its bulk density less than that of the calcite grains/cement. It is this density difference that is contributing to the difference in X-ray attenuation between these phases within the Indiana and Winterset systems. Distinct differences in the X-ray attenuation values of the clay/rock fragments and the quartz grains within the Castlegate XCT, on the other hand, are not seen. Obviously, there is an elemental difference between kaolinite clay (alumina silicate clay; \( \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \)) and quartz; therefore, their densities must be the controlling factor affecting the contrast between them. The density of quartz is around 2.65 g/cc and the density of kaolinite is 2.62 g/cc; therefore, it is this characteristic that is is believed to be causing the low X-ray attenuation differences between them.
The ability to distinguish between mineralogical/lithological phases in the XCT of a geologic system is crucial to accurately characterize the system. Knackstedt, et al. (2006) demonstrated a method to more accurately identify the microporous phase in carbonate rock XCT images (specifically a Gambier limestone and a West Texas field carbonate) by first imaging the dry cores, then injecting an X-ray opaque fluid into the cores, draining them until only the micropores were filled, and then re-imaging the cores. The idea here is that the fluid will help identify the locations of the microporous phase within the system. Their results showed good distinction between the different lithological phases within the rocks. Note that this approach is not intended to better resolve the features of the microporous phase, but to help locate it. Also note that Knackstedt, et al. (2006) used a commercial XCT system, which does not provide the contrast as synchrotron systems do (synchrotron XCT systems utilize monochromatic X-rays, providing much better contrast than commercial/medical XCT units), and, therefore, this method may only be required when the mineralogical/lithological phases within a system exhibit little X-ray attenuation difference.

X-ray energy also plays a major role in the contrast between features within an XCT image. Typically, the slope of the X-ray energy versus attenuation curve is greater at lower X-ray energies than at higher energies; therefore, contrast between phases will be greater at lower energies. Hence, one solution to help increase the contrast between the quartz grains and the clay/rock fragments within the Castlegate is to decrease the X-ray energy. However, X-ray penetration through the sample may become an issue at lower energies (due to increased X-ray attenuation); therefore, a compromise between contrast and X-ray attenuation will have to be made.
6.2 XCT Augmentation with Conventional Core Analyses

The mineralogical/lithological insights gained from the thin section and SEM photographs of the three geologic cores provided a geologic basis for the 3-phase segmentations, making the resulting segmented images defendable. Attributes obtained from the conventional core analyses such as spatial location, size, and volume percentage of the microporous phases within each rock were linked back to the XCT images, aiding in the segmentation process. However, due to the factors such as limited contrast due to noise and mineralogical/lithological differences discussed in 6.1, the accuracy and, therefore, feasibility, of the 3-phase segmentation varies from one system to another.

The thin section and SEM images of the Indiana Limestone presented in Figures 5.1-5 and 5.1-6 clearly show two primary lithological phases (solid calcite as fossil fragments and calcite cement and micrite) and void space within the rock. These same three phases can be correlated back to the XCT gray-scale images. Three phases (black, light gray, and dark gray) are clearly seen in the INDIANA_A XCT gray-scale image in Figures 5.2-3, 5.2-4, and 5.2-5. After a thorough analysis of the XCT image by comparing it to the thin section and SEM images, it was determined that most of the dark gray phase is micrite and the light gray phase is the calcite grains/fossil fragment/cement. The black is pore space. The gray-scale XCT was segmented into a 3-phase system where black, gray, and white correspond to void space, micrite, and calcite grains/fossil fragments/cement, respectively. The percent of the micrite phase in this image is 21.8%, which is slightly less than the high-density point count value of 28% and is just outside the range of micrite (25-49%) estimated from the low-density point count. The total porosity of the 3-phase INDIANA_A XCT is 13.9%, which is just under the petrophysical porosity.
of 15.1%. These results indicate that without accounting for the microporosity through the 3-phase segmentation, a porosity of only 8.5% would be produced from the INDIANA_A XCT image, which is significantly less than the total porosity. This is significant because the mercury injection data shows that 90% of the pore space is accessed through pore-throats smaller than ~3 µm in radius and 65% is accessed through pore-throats smaller than ~1um, which corresponds to the micrite. This indicates that the micrite possible plays a role on the fluid flow through the Indiana Limestone; therefore, accounting for the micrite with the pore network structure is significant.

Three phases are also seen in the INDIANA_B gray-scale XCT (Figure 5.2-6 and 5.2-7), but they are not as distinct as in the INDIANA_A gray-scale XCT and the amount of micrite is significantly less. CASTLEGATE_A and CASTLEGATE_B were imaged at the same X-ray energy; therefore, heterogeneity must be the reason for the drastic differences between these two XCT images. The low-density point count results of the Indiana thin section (Table 5.1-4) and the INDIANA_A gray-scale XCT (Figure 5.2-3) clearly indicate that the Indiana Limestone is a very heterogeneous system. The spatial locations and the geometry of the dark gray features seen in Figure 5.2-7, however, do clearly resemble the micrite seen in the thin section images. Unfortunately, accurate segmentation between the solid calcite and the micrite phase was difficult due to the limited contrast between them. The final 3-phase segmented image for the INDIANA_B XCT image produced a macroporosity and a microporosity of 4.9% and 2.9%, respectively. These values are significantly less than the high-density and low-density point count porosity estimations and fall outside the error in those analyses. With 90% of the pore space being accessed through pore-throats smaller than ~3 µm, the 5 µm resolution of the
EM_3B_APS XCT image is ineffective in accurately capturing the significant features of this system. More so, the inability to differentiate between the solid calcite and micrite phases within this XCT image significantly inhibits the ability to accurately model fluid flow through this system.

This same process of augmenting the XCT image with thin section and SEM photographs was applied to the Castlegate and the Winterset XCT images. Multiple phases (void space, quartz grains, rock fragments, and clay) are clearly seen in the Castlegate thin section and SEM images (Figure 5.1-1 and 5.1-2); however, multiple phases are not clearly seen in the Castlegate gray-scale XCT images (Figures 5.2-1 and 5.2-2). Although the elemental make up of kaolinite clay is different from that of quartz, their densities are almost identical, causing their X-ray attenuation to be very similar. After a thorough analysis of the Castlegate XCT images and thin section images, a third phase can be seen in the XCT images sandwiched between quartz grains and as coating on some of the quartz grains. Note that some of the apparent clay coating on the quartz grains is noise due to edge smoothing during noise removal.

The 3-phase segmentation of the Castlegate gray-scale XCTs produced macroporosities of 22.9% and 18.5% and microporosities of 6.6% and 1.3% for the CASTLEGATE_B and CASTLEGATE_A images, respectively. All macroporosity and microporosity values fall within the range of point count porosities, and the total porosities are almost equal to the petrophysical porosity. The petrophysical mercury injection capillary pressure data shows that ~15% of the pore space is accessed by pore-throats less than ~1 μm in radius. 15% of the total petrophysical porosity (25.1%) equals 3.77%. This suggests that ~3.77% of the pore space is
made up of microporosity in the form of clay, rock fragments, intraparticle porosity, and secondary porosity, which is consistent with the point count estimates and the XCT microporosity. It should be kept in mind, however, that although pore space is filled through pores that correspond to microporosity, that pore space is not necessarily microporosity itself. For example, an interparticle pore between quartz grains can be cut-off from the rest of the pore system by clay; therefore, in order to fill this particular macropore, capillary entry pressures of the pore-throats within the clay have to first be overcome. Due to the large amount of noise in the CASTLEGATE_A XCT, we have little confidence in the accuracy of the percentage of microporosity within that system; therefore, only the CASTLEGATE_B XCT was used to develop a dual-porosity network.

The Winterset Limestone is primarily made up of calcite cement and large moldic pores with 5 µm calcite crystals (micrite) occupying some percentage of the moldic pore space. This is clearly seen in the thin section and SEM images (Figures 5.1-9 and 5.1-10) as well as the gray-scale XCT images (Figures 5.2-8 and 5.2-9). Sufficient contrast between these two phases (calcite cement and the micrite) in the WINTERSET_A XCT image makes for an easy 3-phase segmentation. Unlike the Indiana Limestone, however, the micrite in the Winterset does not play a significant roll in fluid flow through this system. As shown in the Winterset’s petrophysical drainage curve (Figure 5.1-11), almost all pore-throats are less than 4 µm in radius, which from thin section and SEM analysis, correspond to intercrystalline pores within the calcite cement that make up only ~1% of the total pore space. The 4 µm resolution of the WINTERSET_A XCT image is not sufficient to capture the intercrystalline pores that provide the connectivity. Also, although an accurate 3-phase segmentation can be made to divide the
image into void space, solid calcite cement, and micrite, the nature of this rock prevents 3-phase segmentation from capturing the important pore space controlling fluid flow. However, the micrite may play a role in solute transport and multi-phase fluid flow; therefore, being able to account for it within their XCT image is significant.

The lower resolution imaging of a Winterset core (WINTERSET_B) was not intended to help characterize the Winterset system at the micron scale, but to gain a better understanding to the heterogeneity of this system. The WINTERSET_B XCT images (Figure 5.2-9) show that at the millimeter scale, the Winterset Limestone is a heterogeneous rock, which may explain the differences in porosity values between the XCT image and the petrophysical analysis.

6.3 Single Porosity (Macro) Pore Network Modeling Results

6.3.1 Single-phase Permeability

The single-porosity, or macropore, network permeability results highlight important characteristics regarding each porous system. The permeability results for the CASTLEGATE_A and CASTLEGATE_B networks are 26% and 51% higher, respectively, than the petrophysical value of 1,040 mD. The current version of the network modeling algorithm was validated using unconsolidated materials, and it appears to overestimate the permeability of consolidated materials by ~10–30% in many cases (personal communication with Dr. K. Thompson). Permeability for the CASTLEGATE_A network is consistent with this trend; however, permeability for the CASTLEGATE_B network is much higher. 80% of the pore space, as indicated from the mercury injection data, is accessed through pore-throats ~5 μm in radius and larger, which corresponds to a porosity of 20.1%, slightly less than the porosity of the
CASTLEGATE_B network (22.9%). This porosity difference is most likely the cause for the significantly higher permeability seen for the CASTLEGATE_B network.

The porosity and permeability for the CASTLEGATE_B200 network are 6.6% and 20% higher, respectively, than that of CASTLEGATE_B. Although these values are higher, they still indicate that the 200^3 voxel volume of CASTLEGATE_B200 is representative of the sample and supports the notion that the Castlegate Sandstone is a very homogeneous system. In any case, the permeability results for the Castlegate XCT networks indicate that the single-porosity pore network structure is more than adequate for capturing the pore space that contributes to the primary fluid flow, and, therefore, suggest that including the microporosity into the pore network structure to characterize single-phase fluid flow is not necessary.

Permeability results could not be obtained for the Winterset Limestone due to the limited macropore connectivity. This suggests, as suspected, that the single-porosity pore network structure is not sufficient for characterizing fluid flow in the Winterset. Mixed permeability results are seen for the Indiana Limestone. Permeability for the INDIANA_B XCT image could not be simulated for flow in the y and z directions, but a value of 2 mD was produced for flow in the x direction. An average permeability of 229 mD and a z direction permeability of 59 mD were produced for the INDIANA_A XCT network. The petrophysical permeability for the Indiana Limestone is only 2.69 mD. These drastic differences can be attributed to both the heterogeneity and anisotropy of this system. The petrophysical permeability analysis was conducted for flow in the z direction (the vertical direction of the core) only; therefore, there is no petrophysical data to support the implied anisotropy by the
INDIANA_A XCT. The order of magnitude larger permeability for INDIANA_A network in the $x$ and $y$ directions than in the $z$ direction, however, does suggest anisotropy at the pore scale within the Indiana Limestone. More insight into this phenomenon will come from the drainage results.

The permeability results for SANDMIX_A_H3 and SANDMIX_B_H3 have very good agreement with the permeability value of 155 D calculated from the hydraulic conductivity given in Schroth et al. (1996) for the 30/40 Accusand. The average value of 139.0 D for SANDMIX_A_H3 is within 10.3% of 155 D and the average value of 154.6 D for SANDMIX_B_H3 is within 0.3% of 155 D, which is excellent agreement.

6.3.2 Quasi-static Drainage

The simulated Castlegate drainage curves in Figure 5.5-1 show good agreement with the mercury injection curve above a pore-throat radius of $\sim 10 \, \mu m$. Below $\sim 10 \, \mu m$, the mercury injection curve shifts away from the two simulated curves due to the microporosity within the clay. This result suggests that the Castlegate XCT images are sufficient at resolving pore space $\sim 2$ times the XCT voxel resolution (i.e. the image resolutions are 5 $\mu m$ and 7.57 $\mu m$ for CASTLEGATE_B and CASTLEGATE_A, respectively). Including the microporosity into the pore network structure will increase to total porosity of the system causing the CASTLEGATE_A and CASTLEGATE_B curves to shift towards the mercury injection curve at pore radii less than $\sim 10 \, \mu m$. Castlegate drainage curves in Figure 5.5-2 show that CASTLEGATE_B200 agrees very well with CASTLEGATE_B, which is consistent with the permeability results for this system, and,
therefore, supports the before mentioned notion that the 200^3 voxel volume of the CASTLEGATE_B200 is representative of CASTLEGATE_B.

The Indiana Limestone simulated drainage curves in **Figure 5.5-3 and 5.5-4** show poor agreement with the petrophysical drainage curve. The petrophysical drainage curve (**Figure 5.1-7**) indicates that 90% of the pore space is accessed through pore-throats smaller than ~3 μm in radius, which is smaller than the resolution of the INDIANA_A XCT image. The simulated drainage curve for INDIANA_A, however, indicates that ~60% of the pore space is accessed through throats ~10 μm in radius, which is supported by the pore and throat distribution plots (**Figure 5.3-3**) generated from the pore statistics for this network. The absence of the microporosity in the INDIANA_A network allows fluid flow through this network to be governed by the macropore-space instead of by the micropore-space as indicated by the petrophysical drainage curve. The macropore connectivity seen here explains the large simulated permeability obtained from this network.

The 30/40 Accusand drainage curves (**Figures 5.5-5 and 5.5-6**) indicate that the 30/40 Accusand layer analyzed here is either a tighter packing than that analyzed by Schroth et al. (1996) or that the image was under segmented with respect to void space (i.e. T1 was too low). The required capillary pressure in **Figure 5.5-5** to drain SANDMIX_A_H3 and SANDMIX_B_H3 is between 20 and 40 cm of water, whereas, it is between 10 and 20 cm of water for the 30/40 Accusand system analyzed by Schroth et al. (1996). **Figure 5.5-6** indicates the majority of pore space in SANDMIX_A_H3 and SANDMIX_B_H3 is accessible through throats between 30 and 70 μm, whereas, a majority of the drainage occurs through throats between 80 and 140 μm for the
30/40 Accusand analyzed by Schroth et al. (1996). The pore size data for the layered sand systems presented in Figure 5.3-4 shows that the majority of pore-throats in the H3 layer are between 15 and 65 μm, which supports the drainage results for this system.

The porosity of the SANDMIX_A_H3 and SANDMIX_B_H3 systems is 35.01% and 35.04%, respectively, which is at the upper bounds of the porosity range for the various Accusands analyzed by Schroth et al. (1996), suggesting the image was actually possibly over segmented with respect to void space (i.e. T1 is too high). Although the throat sizes of SANDMIX_A_H3 and SANDMIX_B_H3 indicate that these systems are more tightly packed than the 30/40 Accusand analyzed by Schroth et al. (1996) or under segmented, the porosity is approximately the same or even slightly larger. This suggests that the image was properly segmented and that this system is just a tighter packing than the 30/40 sand system analyzed by Schroth et al (1996). Another explanation maybe that a slight increase in T1 and/or T2 may have a greater effect on the pore size, and, therefore, porosity, than on the pore-throat size. In other words, the voxels corresponding to throats maybe of larger intensities than the grain edges, so as T1 and/or T2 are increased, the pores become larger before some of the throats open up. This would increase the pore size, therefore, increasing the porosity, without increasing the size of the pore-throats, which is what is seen in the results here.

The layered sand simulated drainage curves (Figure 5.5-8) show that the majority of the pore space, ~60%, is drained by throats between 26 μm and 30 μm for SANDMIX_A and between 32 μm and 37 μm for SANDMIX_B. This corresponds to breakthrough of the fine sand layer. Once breakthrough of the fine sand layer is achieved, the bottom coarse sand layer will
immediately drain, which is seen in Figures 5.5-7 and 5.5-8. Assuming that SANDMIX_A accurately captures the true pore structure of the fine sand layer, the SANDMIX_B drainage plot also supports the notion that an XCT image can accurately resolve pore space ~2 times the XCT voxel resolution (i.e. the voxel resolution of SANDMIX_B is 16.1 μm).

6.4 Dual Porosity Pore Network Modeling Results

6.4.1 Single-phase Permeability

The average permeability (Table 5.4-1) for the CASTLEGATE_B200DP network is 2.2% higher than that of CASTLEGATE_B200. This result indicts that the addition of the microporosity did not have a significant effect on the permeability for this system. The z direction permeability for SANDMIX_B_DP is ~57% and ~106% larger than the z direction permeability for SANDMIX_B and SANDMIX_A, respectively. The average permeability for SANDMIX_B_DP is ~25% and ~46% larger than the average permeability for SANDMIX_B and SANDMIX_A, respectively. Theses results indicate that the z direction permeability for the dual-porosity (artificial) system is much larger than that of the real systems, but that the horizontal permeability is nearly the same. Obviously the z-direction permeability of SANDMIX_B_DP will be larger than that of SANDMIX_A because of the larger permeability seen in the H3 layer of SANDMIX_B than in that of SANDMIX_A. It would be expected, though, that the z direction permeability for SANDMIX_B_DP would fall somewhere between that of SANDMIX_A and SANDMIX_B as shown from the effective permeability for the dual-porosity system due to the replace of the fine sand layer in SANDMIX_B with pore statistics from the fine sand layer in SANDMIX_A, which has a smaller permeability.
The number of pores added to the artificial fine sand layer can explain the high permeability of the dual-porosity layered sand systems. 121,000 pores with a coordination number of 6 results in approximately 363,000 pore-throats that are being added to the artificial layer of SANDMIX_B_DP. This is ~1.7 times larger than the number of pore-throats (216,802) that actually exist in the fine sand network of SANDMIX_A. This large increase in the number of pore-throats significantly increases the connectivity of the system, which in return, results in a larger permeability (i.e. less resistance). Another factor that may be at play here is the throat lengths in the artificial layer. The shorter the throat length, the larger the permeability will be. Quantification of this has not yet been done.

6.4.2 Quasi-static Drainage

The drainage results for CASTLEGATE_B200DP in Figure 5.5-2 show that the addition of the microporosity in the Castlegate pore network structure does slightly shift the simulated drainage curve toward the mercury injection curve at pore radii less ~10 µm. However, this shift is very small. This small shift can be explained, however, by the amount of microporosity added to the CASTLEGATE_B200DP pore network structure. Only 1.1% additional porosity was added, whereas the mercury injection curve and thin section analysis suggest that approximately 3-4% microporosity actually exists in the Castlegate system. If an additional 2-3% microporosity were added to CASTLEGATE_B200DP network, a much better agreement between it and the mercury injection curve would be seen.

The layered sand simulated drainage plots (Figures 5.5-7 and 5.5-8) show that the SANDMIX_B_DP drainage curve shifts from the SANDMIX_B drainage curve to the SANDMIX_A
drainage curve around a capillary pressure of ~41 cm of water and a pore-throat radius of ~37 µm. Between a capillary pressure of ~41 and ~60 cm of water, the SANDMIX_B_DP drainage curve agrees very well with the SANDMIX_A drainage curve. At a capillary pressure of ~60 cm of water, the SANDMIX_B_DP drainage curve returns to following the SANDMIX_B drainage curve. Drainage simulation for SANDMIX_B_DP2 produces almost exactly the same results as the drainage simulation for SANDMIX_B_DP, indicating that the randomization of the pore-throat sizes has no affect on drainage prediction for this system. Nonetheless, SANDMIX_B_DP shows good agreement with the coarse sand regions of SANDMIX_B and the fine sand region of SANDMIX_A, suggesting that the artificial network generated from pore statistics is successful in accurately predicting drainage for this layered sand system.
7 Conclusion and Future Work

Although XCT is resolution limited to resolve sub-micron features, coupled with conventional core analyses, it can provide a physically representative mapping of multiple mineralogical/lithological phases. In systems such as the Indiana Limestone where the microporous phase, micrite, plays a major role in the primary fluid flow, this multi-phase mapping can be used to develop a dual-porosity pore network structure. However, the task of developing a dual-porosity pore network structure for complex porous systems such as the Indiana Limestone is not trivial.

Many factors such as the quality of the XCT image and the characteristic length scale of the media of interest controlling fluid flow and transport processes affect one’s ability to characterize and develop a physically representative network model. Limited contrast due to small X-ray adsorption differences between phases or due to noise, as seen in the Castlegate XCT images, presents challenges to the 3-phase segmentation process, which directly affects ones ability to develop an accurate dual-porosity network. If the microporous phase cannot be accurately mapped, one cannot confidently insert a pore structure into that phase. Augmentation of the XCT images with conventional core analysis has proven to aid in the 3-phase segmentation process by providing a geologic basis for the resulting 3-phase segmentations.

This research had two primary objectives: 1) to determine the feasibility of developing a dual-porosity pore network structure using pore statistics through the analysis of a layered sand system and 2) to determine the applicability of this approach to three specific geologic
systems. The layered sand results suggest that if quality information regarding the pore structure of the microporous phase can be obtained, an accurate dual-porosity network can be developed. The drainage results for the layered sand systems show good agreement between the dual-porosity (artificial) network and the “real” networks. The permeability results, however, do not show good agreement between the dual-porosity and the real systems. This disagreement can, however, be explained by the additional pore connectivity within the artificial layer of the dual-porosity layered sand system, which can easily be modified by adjusting the pore coordination number. Investigation into how to properly assign a pore coordination number for a specific geologic system will first be required. An understanding of the pore connectivity can certainly be obtained from SEM analysis and/or FIB/SEM analysis. Either way, model calibration will have to be performed.

The conventional core analyses and the network modeling results indicate that the Castlegate Sandstone is a system where macropore-throats dictate single-phase permeability and the majority (~70%) of the pore space is accessible through interparticle pore-throats approximately 10 µm in radius. The simulation results for the Castlegate system indicate that 5 um resolution is adequate for modeling single-phase permeability, but that including the microporosity is necessary for full drainage characterization. The simulated drainage results for the Castlegate dual-porosity network indicate that adding the microporosity to the macropore network does a better job at predicting drainage through this system, but that an accurate mapping of the clay phase through the 3-phase segmentation process is vital.
The conventional core analyses and the network modeling results indicate that the Indiana and Winterset limestones are systems where microporosity dictates single-phase permeability and 80-90% of the pore space is accessed through micropore-throats less than ~3 μm in radius. Although an accurate mapping of the micrite could be made for INDIANA_A (Indiana Limestone), a dual-porosity pore network structure is not practical with the current approach due to the high percentage of micrite seen in this XCT volume. The Winterset is a system where the microporosity that controls fluid flow cannot be mapped via 3-phase segmentation; therefore, a completely difference approach for generating a dual-porosity pore network structure will have to be taken.

Microporosity plays a vital role in fluid flow and transport process for many geologic systems, especially in carbonate rocks. In order to quantify the effects of microporosity on fluid flow and transport processes through network modeling, it must first be accounted for in a three-dimensional image and then incorporated into the network structure. This research was a first step towards the development and implementation of a dual-porosity pore network structure. Future work should focus on three main areas: 1) alternative approaches for implementing a statistically and non-statistically based dual-porosity pore network structure; 2) FIB/SEM generated 3-D images should be investigated for providing physically representative network structures of the microporous phase and how then to integrate this with the macropore network generated via XCT; and 3) techniques such as injection of X-ray opaque fluids for providing better contrast between mineralogical/lithological phases need to be investigated.
References


Vita

Samuel Taylor Best was born on December 3, 1985, to James and Toni Best. He grew up in a small rural town approximately thirty-five minutes northwest of Baton Rouge, Louisiana, called New Roads. Growing up, Samuel lived a very active life, playing recreational sports such as football and baseball and enjoying hunting and fishing. At an early age he discovered his true passions in life, music, particular blues, folk, and southern rock, and exploring the great outdoors, particularly the Rocky Mountains, which he visited on family vacation numerous times throughout his childhood.

In high school, Samuel excelled at mathematics and science and graduated high school at the top of his class in May 2004 from Catholic High School of Pointe Coupee, located in New Roads. Not know exacting what career path he would like to pursue, he began his freshman year at Louisiana State University in August 2004 as undecided. Shortly after attending Louisiana State University he enrolled in the College of Civil and Environmental Engineering. After his first year, he declared his major as environmental engineering because it complemented his love for both the outdoors and science and mathematics.

Samuel graduated from Louisiana State University in December 2008 with a Bachelor of Science in Civil and Environmental Engineering. Upon graduation, he accepted a full-time position with ICON Environmental Services, a small environmental consulting firm based out of Port Allen, Louisiana. At Icon he performed activities such as groundwater and soil analytical data analysis, groundwater and soil sampling, soil conductivity surveying, and remedial investigation and design of contaminated oil fields. It was at ICON that he was first exposed to
groundwater hydrology, which inspired him to return to school to pursue a Master of Science in Civil Engineering in the water resources engineering program.

Samuel received a research assistantship with Associate Professor and Graduate Program Coordinator, Clinton Willson, Ph.D., P.E., and began his graduate studies in August 2008. Under the advisory of Dr. Willson, Samuel conducted research in X-ray computed tomography of geologic systems, which was funded through a contract with ExxonMobil Upstream Research Company. His thesis, Development and Implementation of a Dual-porosity Pore Network Structure Using X-ray Computed Tomography for Pore Network Modeling Purposes was derived from his research for ExxonMobil.

Samuel completed his thesis in late May 2011 and will receive a Master of Science in Civil Engineering at the Summer Commencement in August 2011. Samuel has accepted an environmental engineering position with the environmental consulting firm, Anchor QEA in Austin, Texas, and will begin in early June 2011.