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Comparing thresholding techniques for quantifying the dual porosity of Indiana Limestone and Pink Dolomite

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Carbonate reservoirs, and in particular, saline aquifers are globally abundant and promising for carbon dioxide (CO_2) storage. Pore network modeling of CO_2 storage in porous networks extracted from imaged carbonates provides a tool for evaluating potential storage sites. Capturing the multi-scale porosities (porosity at multiple length scales from nanometers to millimeters) inherent in carbonates is key to producing reliable pore network simulation results. Thresholding techniques that can extract the multi-scale pore space from micro computed tomography (microCT) or scanning electron microscopy (SEM) are needed. In this work, the application and evaluation of thresholding techniques originally developed for sandstones were applied and evaluated for Indiana Limestone and Pink Dolomite, carbonates that exhibit dual porosities (porosities that represent two distinct pore size distributions). The objective was to determine whether there is a single method or imaging technique that can reliably evaluate the porosity of carbonate rocks. The evaluation of the thresholding techniques applied to carbonate rocks showed that one single imaging technique or thresholding method cannot be solely used for all carbonate rocks. Instead, the evaluated porosity is a function of the microporosity, rock type and image resolution. The sensitivities of existing methods to thresholding techniques, imaging method and material structure were shown. This work provides a preliminary assessment of thresholding dual porosity carbonates.

1. Introduction

Carbon dioxide (CO_2) sequestration in underground geologic reservoirs is recognized as a viable method for reducing atmospheric greenhouse gas emissions [1]. In geologic carbon sequestration, CO_2 from large emitters, such as fossil fuel-based electricity generation or energy-intensive processing, is injected into a high-permeability geologic formation, where it fills the void space of the reservoir.

An evaluation of reservoir suitability is based on an estimation of the CO_2 storage capacity [2], which is found from reservoir-scale transport properties such as the permeability and pore connectivity [3]. These values are determined from an accurate assessment of the rock structure, including its porosity. While these transport properties are known for conventional oil-bearing formations such as sandstone [4–8], they have not been characterized for carbonates. Carbonate formations have recently been considered as suitable reservoirs for sequestration, due to their abundance at suitable depths for sequestrations [9,10]. However, determining CO_2 bulk storage capacity and permeability has remained a challenge due to the spatial heterogeneity of the rocks and the associated difficulty in obtaining accurate bulk porosity measurements [11].

Imaging methods used to measure the local pore structure of geological materials include thin-sectioning [12], backscattered electron scanning electron microscopy (SEM) [13,14], and micro-computed tomography (microCT) [15–17]. Thin-sectioning analysis involves optical microscopy of thin cross-sections of rock samples, and the subsequent combination of the individual images into a volumetric representation [12]. This technique is destructive and further limited by the resolution capabilities of light microscopy and by the thickness of rock core sections. SEM involves the imaging of a polished rock surface at resolutions up to 1 nm/pixel [18]. SEM can measure the local porosity, but is limited to a two-dimensional (2D) plane, so the volumetric pore connectivity cannot be determined.

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MicroCT is a non-destructive technique for volumetric characterization of porous materials at spatial resolutions as low as 1 μm/voxel[1] [15–17]. MicroCT has enabled the evaluation of sandstone transport properties from three-dimensional (3D) images of the internal pore space [19–21]. Deriving relationships between porosity and flow-based properties for carbonate reservoirs remains an area of active research, due mainly to the complexity of carbonate structures because of their dual porosity [22–32]. Dual porosity refers to a void volume with porous features across two length scales, and is characterized by a bimodal grayscale image histogram. Characterizing the dual porosity has been challenging since the pore sizes range from nanometers [19] to centimeters [33]. A single imaging technique cannot be used solely to visualize pore sizes across disparate length scales, so the use of multiple imaging modalities is required [34,35]. As a result, a robust method is still required to estimate the transport properties such as permeability and tortuosity for rocks with multi-scale porosities, such as carbonates [36].

For microCT and SEM, the output is a digital image where each pixel[2] is assigned a grayscale value representing the relative density of that point in the material. When the area or volume being imaged exhibits features below the spatial resolution, the grayscale value represents an average of the relative amounts of void and material across each digitized area.

Despite the limited spatial resolution that microCT provides in comparison to SEM, microCT has been a popular method for characterizing pore space, since it provides 3D volumetric imaging data [15]. Porosity is estimated from 2D or 3D imaging data by converting grayscale images into binary images representing solid material (white) and void space (black). Above a threshold grayscale value all pixels are considered solid space, and below this threshold all pixels are considered void (pore) space. Thresholding techniques are categorized in the literature as *local* [37] if they depend on the spatial variation of the grayscale values; or *global* [38] when they rely on the grayscale histogram of the entire image. Global thresholding techniques, suited for 3D volumes [38], include Otsu's method [31,39–44]. This method is commonly employed for rock formations and uses a grayscale threshold value that minimizes the variance between black (void) and white (solid) pixels. Readers are directed to an excellent review of thresholding techniques prepared by Sezgin et al. [45].

However, carbonate porosity measurements derived solely from microCT data have limited applicability because pores below the spatial resolution cannot be detected. The resulting underestimation of porosity can lead to errors in permeability calculations, which could compromise eventual CO_2 capacity estimations. To compensate for this, advanced image processing techniques must be applied for rocks that exhibit this dual porosity.

For dual porosity rocks such as carbonates, many researchers [22,30,39] have introduced new imaging and modeling techniques to capture the full range of the pore structure features. Galaup et al. [22] performed experimental measurements using SEM to quantify the microporosity of carbonates and dolomites. Bauer et al. [30] developed a pore network model to account for the dual porosity of carbonates by segmenting the grayscale histogram from microCT data into three regions: solid, microporous and macroporous. Ji et al. [39] used Otsu's method directly on the grayscale histogram to determine two thresholds and divided the grayscale histogram into three regions.

The literature lacks a systematic comparison of available thresholding techniques and corresponding porosity calculations for carbonate rocks. The objective of this work is to determine whether there is a single method or imaging technique that can reliably evaluate the porosity of carbonate rocks. This will be achieved by comparing the results of thresholding techniques for high-resolution 2- and 3D images of porous carbonate materials.

2. Methods

In this study, three techniques for measuring the porosity of carbonates from SEM and microCT data of Indiana Limestone and Pink Dolomite were compared: “single Otsu's” method [44]; dual Otsu method of Ji et al. [39] “Dual Otsu”; and “averaged SEM threshold” method involving the application of an SEM-informed threshold value.

2.1. Sample selection and preparation

For this study, physical samples from a carbonate saline aquifer were not obtained due to licensing rights. Instead, model carbonate samples of Indiana Limestone and Pink Dolomite were chosen to represent sequestration sites in carbonate formations [46]. All rock cores were obtained from Kocurek Industries (Caldwell, TX, USA). The sample cores were sectioned into four cylindrical pieces approximately 1 cm × 0.6 (∅) cm prior to scanning. The sample sizes used were at least 66.5 mm^3 for the Indiana Limestone, and 53.5 mm^3 for the Pink Dolomite to enable detection of the macropores within each sample and allow for future investigations of permeability for the samples [47].

2.2. Scanning electron microscopy

The rock samples were analyzed using a JEOL JSM6610-Lv Scanning Electron Microscope (JEOL Ltd., Tokyo, Japan). Prior to imaging, the samples were first epoxy-impregnated, then polished with a fine grain diamond polisher. The polished sample was sputter-coated with a 200 nm layer of gold to provide a conductive layer for the electron beam [48]. A sample of each carbonate was chosen for SEM imaging (see Table 1).

2.3. X-ray micro-computed tomography

MicroCT imaging was performed using a General Electric Phoenix v|tome|x s (General Electric, CT, USA) with a 180 kV/15 W nano-focus X-ray tube. The sample was fixed to the rotating table using hot-melt glue. To minimize beam hardening and ring artefacts, a 5 mm thick copper filter was used between the X-ray beam source and the sample. Table 2 provides a summary of the settings, resolutions, and dimensions of each scan.

The datos|x acquisition software (Phoenix|x-ray, release 2.0) provided by the equipment manufacturer was used to calibrate the images prior to data acquisition and to reconstruct the microCT scanned images once the image data was collected. Calibration entailed a pixel correction mask to minimize hotspots on the detector.

Table 1
Summary of the core properties obtained from Kocurek Industries indicating the porosity of Indiana Limestone and Pink Dolomite.

Geologic material	Formation and location	Porosity (%)
Indiana Limestone	Bedford, Indiana, USA	19
Pink Dolomite	Edwards Plateau, Texas, USA	29

[1] A voxel is a 3D pixel, while the pixel is the smallest unit of a 2D image.
[2] Or voxel, in the case of microCT.