Carbonate Petrophysical Parameters Derived from 3d Images*

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Summary

Carbonate rocks are extremely diverse and their pore spaces complex and heterogeneous. Large uncertainties in the petrophysical properties of carbonates are due to wide variations in pore type, pore shape and interconnectivity. Petrophysical properties such as acoustic velocity, permeability, and resistivity are directly correlated to the amount and type of porosity, the dominant feature size, and the interconnectivity of different porosity types. Accurately measuring these attributes requires the quantitative 3D analysis of the pore structure of carbonates. In this article we describe the imaging and analysis of two types of carbonate core: a set of vuggy, recrystallized dolostones and a set of oomoldic limestones. The structure and topology of the pore space is accurately determined via micro-CT analysis and the porosity consistent with experimental data. Acoustic velocity-porosity, pore connectivity, and porosity permeability relationships are derived directly on the image data via numerical simulation and compared with measured data on the same rock. Acoustic velocity:porosity trends are good. Pore structural properties (pore size, aspect ratios, pore and throat shape and connectivity) are determined. The correlations between pore geometry and topology and elastic and flow properties can be directly probed in a systematic manner. Three dimensional imaging and analysis of carbonate core material can provide a basis for more accurate petrophysical modeling and improve carbonate reservoir characterization.

Introduction

Many studies have demonstrated the importance of the pore structure in carbonates on petrophysical properties (e.g., Anselmetti and Eberli, 1993, Wang, 1997; Saleh and Castagna, 2004; Kumar and Han, 2005; Rossebø et al., 2005). Traditional pore type classifications describe the pore structures but fail to quantify the pore system for correlations to the rock's physical properties. In order to quantitatively describe 2-D pore size, pore surface roughness, aspect ratio, and pore network complexity in carbonates, a digital image analysis (DIA) methodology was developed that produces repeatable quantitative pore shape parameters (Weger, 2006). Each of these quantitative parameters describes a certain aspect of the pore shape. When these parameters are compared to acoustic data, the two DIA parameters that capture the pore complexity and the pore size plus the amount of microporosity prove to be the most influential for the acoustic behavior of the samples. Each of these parameters explains about 60% of the variations in velocity at similar porosity (Baechle et al., 2004; Weger et al., 2005, Weger 2006). These 2D studies have added much to the understanding of the influence of the pore structure on acoustic properties, yet their 2D nature is a limiting factor for a comprehensive mathematical treatment of pore shapes in simulations of acoustic properties.

There is now an opportunity to image and characterise the pore structure of cores in 3D. This is based on coupling high resolution x-ray micro-tomography and high end computational software methods, including visualizing core material at the pore scale in 3D, measuring structural properties, and directly predicting physical properties directly from digitised 3D images (Arns, 2004; Arns, 2005) . This allows one to extend previous 2D studies to the 3D pore scale structure. In this paper we describe the 3D study of a set of carbonate samples including pore partitioning and simulation of the elastic properties directly on image data. Predictions from digital images are directly compared to measured data.

Results

The investigated samples are three recrystallized dolostones and three oolitic grainstones with moldic pores and variable amounts of microporosity. These samples were considered as they are end members in regards to pore structure. In all samples the 2-D pore structure was analyzed using the DIA methodology. In addition, porosity, permeability and the elastic properties were measured on the samples. 3D micro-CT scans (2.8 micron per voxel) were obtained on sub-samples of 5.5 mm in diameter drilled out of the original plug. Slices from images are shown in Figure 1. Microporosity is estimated by analyzing the attenuation of the x-ray signal, and its structure is correlated to analysis of SEM images at higher (down to 100 nm) resolution.

In the recrystallized dolostone samples, the separation between pores and grains (crystals) is easily achieved. In the moldic limestones two pore size populations are detected; large, partly leached, round pores and small pores (1-2 micron). In these samples mercury injection indicates presence of micro- or disconnected porosity (Figure 1). The volume of the microporosity in these three samples is 0.3% of 14.1%, 8.3% of 24.8%, and 10.4% of 19.5% total porosity. The porosity is calculated directly from the image data. In all samples the image porosity is comparable to the measured porosity.

From the 3D images the elastic properties of the samples are calculated using an elastic simulation (FEM) that takes into account both the solid matrix and the microporosity (Arns, 2002). Voxels in the solid matrix are assigned values of the elastic moduli for calcite (K,G = 63.7, 31.2 GPa) and the elastic properties in the microporous regions are based on the effective medium theory for sintered granular like structure in which the bulk (K) and shear modulus (G) are a function of porosity. Comparison of the simulated and measured sonic velocities are given in Figure 2. For both the re-crystallized dolostones and moldic limestones, the calculated sonic velocity:porosity (Vp:porosity) does compare very well with the measured velocity.

Macro/Microporosity and Macropore Phase Connectivity

The three dolostone samples exhibit 100% connected porosity; in Figure 3 we show an example of the pore partitioning within a slice of one dolostone sample and a 3D network structure for the same sample. The 3D volume allows displaying the pore connectivity. In the sample a number of pore structural parameters can be measured; for example, the average pore connectivity is measured as 15.7, meaning that a pore is connected to 15 other pores. The maximum pore connectivity is 83. Connectivity, pore size information and pore shape can be directly used to calculate permeability and multiphase flow properties (Arns, 2005).

The oolitic limestone samples exhibit both resolvable macroscopic porosity and significant microporosity. Tests for connectivity of the resolved macroporous phase in the oolitic systems show that only one system is macroscopically connected at image resolution (see Figure 4). The other two samples exhibit disconnected macropores at the resolution of the image.

Conclusion

The results of the 3D imaging and analysis study show that the structure and petrophysical properties of carbonate core can be quantified in 3D. Specific conclusions include:

1. High-resolution CT scans with a resolution of 2.5 microns provide a 3D quantitative structure of carbonate samples. Image porosity correlates well with measured plug porosity.
2. Calculated sonic velocities from FEM simulation based on information from high-resolution CT scans compare well to measured sonic velocities.
3. Recrystallized dolostones exhibit well connected porosity which can be directly quantified in 3D. The pore space topology and pore size information is directly measurable. Moldic rocks exhibit significant proportions of microporosity (porosity below image resolution of ~5 microns). Only one of three moldic samples exhibits connected porosity in 3D.
4. Permeability:porosity crossplots for the same rock type will be undertaken. Correlation of permeability to key geometrical attributes (e.g., pore connectivity and pore to throat aspect ratios) and to acoustic data will be undertaken.

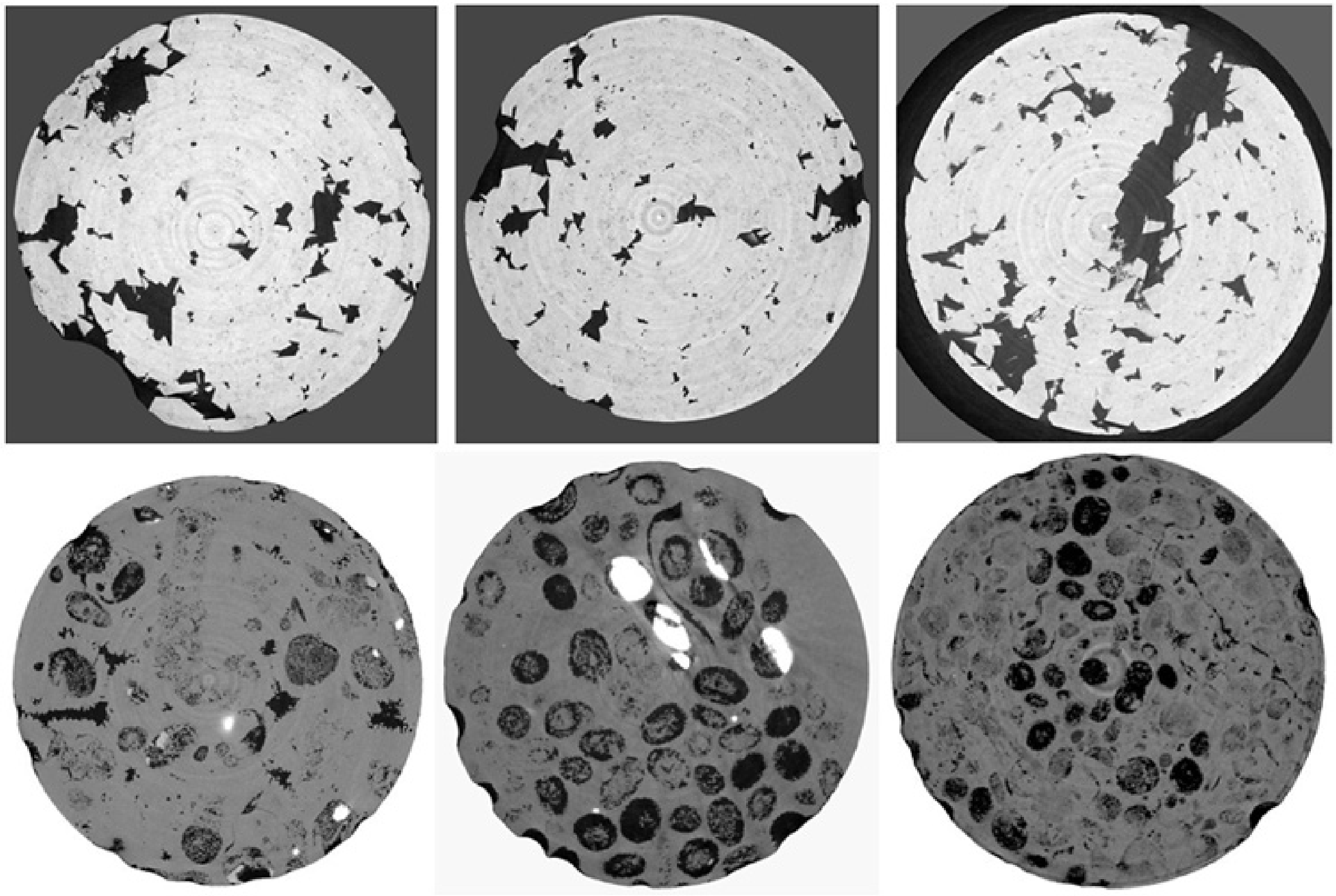

Figure 1. 2D slices within 3D tomographic images of (upper row) three recrystallized dolostones and (lower row) three oolitic grainstones.

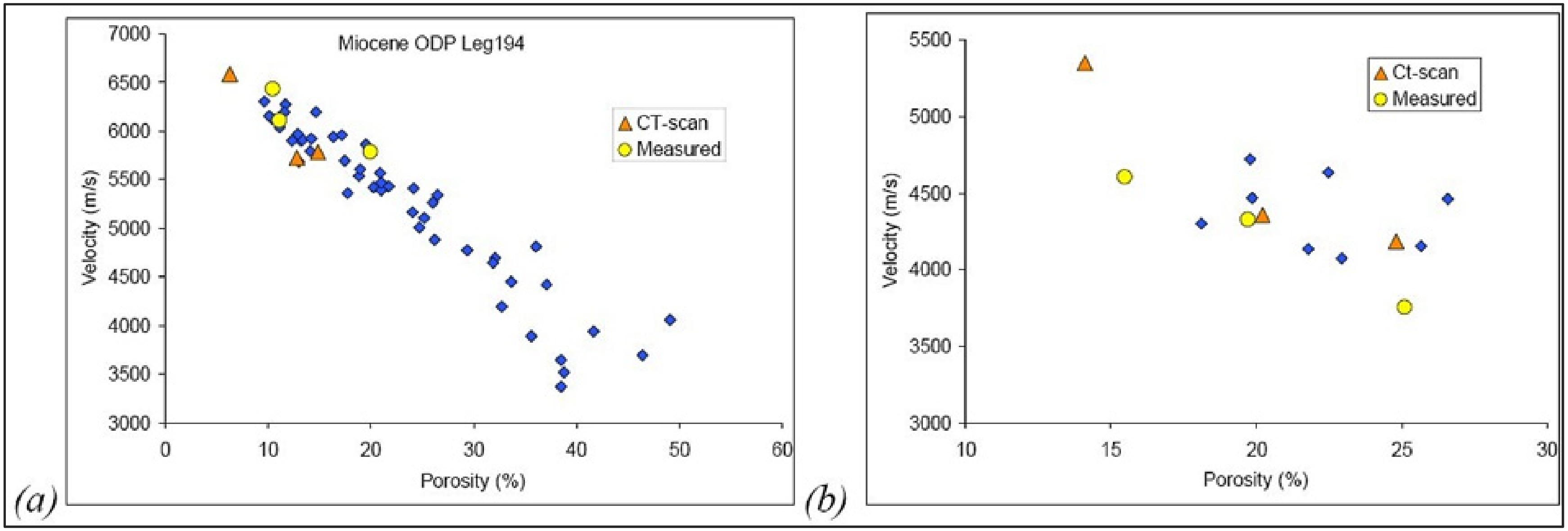

Figure 2. Comparison of moduli measured for (a) recrystallized dolostones and (b) oolitic grainstones. The results on the full core are shown in yellow and the comparable data for the micro-CT image is shown in orange. Data on the full set of rock types are shown in blue.

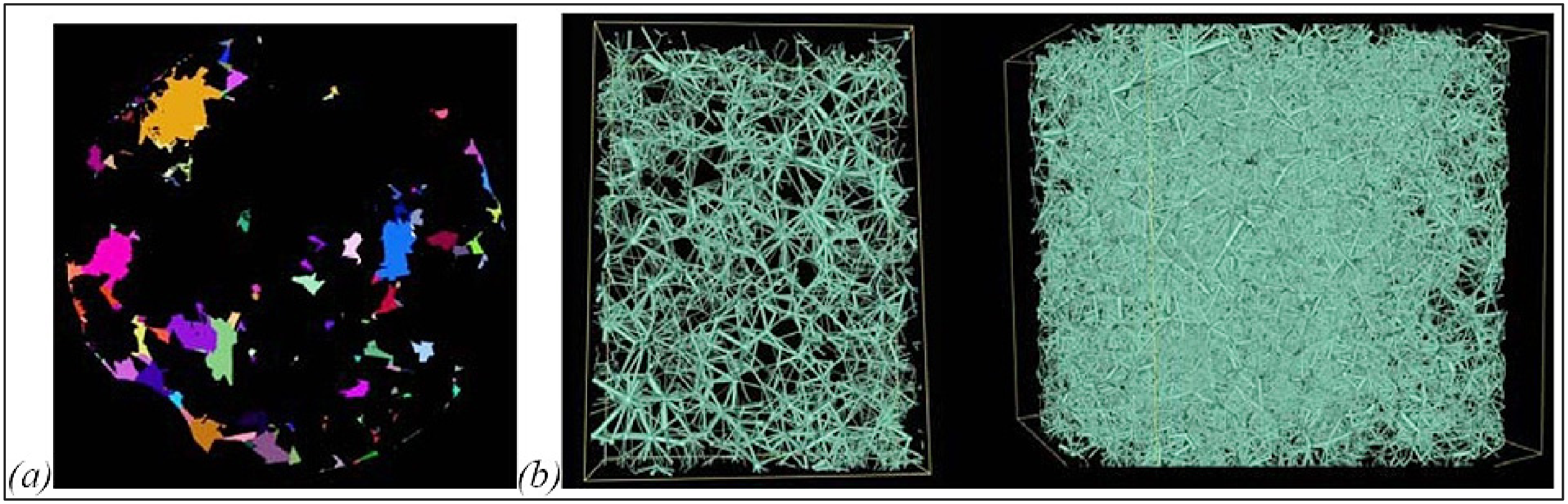

Figure 3. (a) Pore partitioning of sample in upper left of Figure1 shown by different colors. (b) Left; focus on a subset of the pore network in a sub-sample of the entire volume. Right: Pore network of most of the volume of sample; over 250,000 pores and throats are visible. The thickness of the pore connection is a direct measurement of the pore throat.

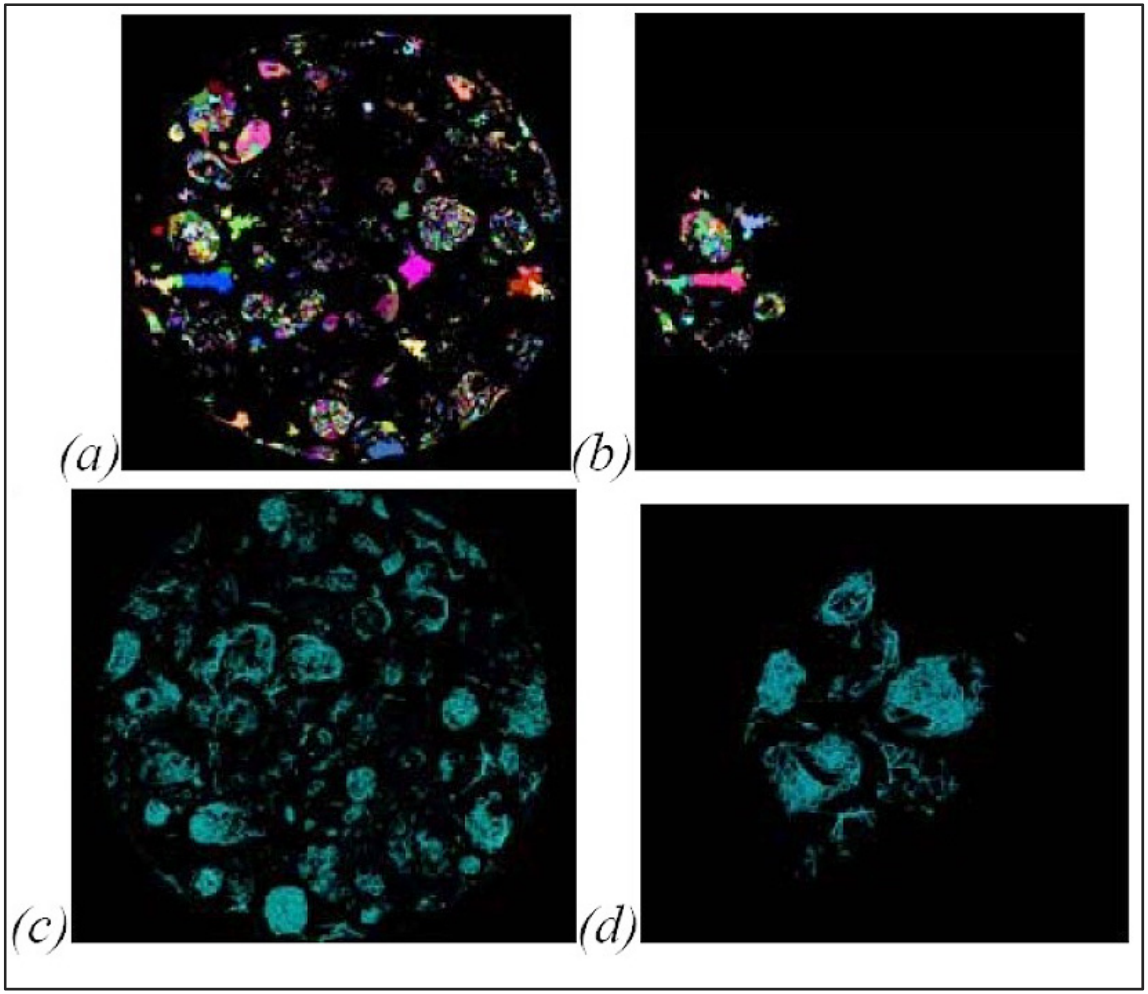

Figure 4. Pore partitioning of sample in lower left of Figure1 shown by different colors; (a) shows the partitioning of all pores, while (b) shows the macroscopically connected pores only; a small subset of the pore space is connected; (c) shows the network based analysis of all pores while (d) shows the connected porosity.

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