Integrating Petrographic, Petrophysical, and 3D Pore-Scale Measurements of Core Material from the Shuaiba Reservoir in Al Shaheen, Qatar*

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ABSTRACT

The understanding of petrophysical and multiphase flow properties is essential for the assessment and exploitation of hydrocarbon reserves; these properties in turn are dependent on the 3D geometric and connectivity properties of the pore space. The determination of the pore-size distribution in carbonate rocks remains challenging; extreme variability in carbonate depositional environments and susceptibility to a range of post-depositional processes results in complex pore structures comprising length scales from tens of nanometers to several centimeters. To increase understanding of the role of pore structure on connectivity, conductivity, permeability, and recoveries requires one to probe the pore-scale structure in carbonates in a continuous range across over seven decades of length scales (from 10 nm to 10 cm) and to integrate information at these different scales. Here, a multi-scale digital core approach is used to improve prediction of petrophysical properties, such as permeability and capillary pressure, from sedimentary facies. The purpose is to establish a rock-typing system that reflects the 3D pore structure and can be confidently distributed at the field-scale.

An integrated petrographic, petrophysical, and 3D pore-scale study of core from the Shuaiba reservoir in Al Shaheen, Qatar, has been performed on a large set of core samples using 3D micro-CT imaging at resolutions down to 3 microns. Further experimental analysis via scanning electron microscopy (SEM) techniques has been undertaken to probe the pore-scale structure to scales of 100 nm. The 3D pore space geometry (pore and throat sizes) and topology (pore interconnectivity) were quantified, allowing for the definition of a 3D pore-scale reservoir rock-typing (3DRRT) scheme for the imaged samples. This rock typing was then coupled with petrophysical (capillary pressure, porosity, permeability) measurements undertaken both in the laboratory and directly on the digital image data. The direct enumeration of the 3D connectivity of specific pore types within core material allows for a much better prediction of the resultant porosity-permeability, and capillary pressure relationships. The identified rocks types from the 3DRRT scheme can be integrated with a facies distribution scheme and used to refine the reservoir geological model.
ABSTRACT: The understanding of petrophysical and multiphase flow properties is essential for the assessment and exploitation of hydrocarbon reservoirs. These properties are in turn dependent on the 3D geometric and connectivity properties of the pore space. The determination of the pore-scale distribution in carbonate rocks remains challenging; extreme variability in carbonate depositional environments and susceptibility to a range of post-depositional processes results in complex pore structures comprising length scales from tens of nanometers to several centimeters. To increase understanding of the role of pore structure on connectivity, conductivity, permeability, and recoveries requires one to probe the pore-scale structure in carbonates in a continuous range across over seven decades of length scales (from 10 nm to 4 cm) and to integrate information at these different scales. Here, a multi-scale digital core approach is used to improve prediction of petrophysical properties, such as permeability and capillary pressure, from sedimentary facies. The purpose is to establish a rock-typing system that reflects the 3D pore structure and can be confidently distributed at the field-scale. An integrated petrographic, petrophysical, and 3D pore-scale study of core from the Shuaiba reservoir in Al Shaheen, Qatar, has been performed on a large set of core samples using 3D micro-CT imaging at resolutions down to 3 microns. Further experimental analysis via scanning electron microscopy (SEM) techniques has been undertaken to probe the pore-scale structure to scales of 100 nm. The 3D pore space geometry (pore and throat sizes) and topology (pore interconnectivity) were quantified, allowing for the definition of a 3D pore-scale reservoir rock typing (3DRRT) scheme for the imaged samples. This rock typing was then coupled with petrophysical (capillary pressure, porosity, permeability) measurements undertaken both in the laboratory and directly on the digital image data. The direct enumeration of the 3D connectivity of specific pore types within core material allows for a much better prediction of the resultant porosity-permeability and capillary pressure relationships. The identified rock types from the 3DRRT scheme can be integrated with a facies distribution scheme and used to refine the reservoir geological model.

INTRODUCTION: DIGITAL CORE TECHNOLOGY

Digital core technology has focused on the direct comparison of predictions with data collected from conventional core analysis methods. However, the limitations in the ability to capture the full range of petrophysical and multiphase flow properties (permeability tensor, formation factor, resistivity index, relative permeability, and drainage capillary pressure) are in good agreement with experimental core measurements. The determination of the pore-size distribution in carbonate rocks remains challenging; extreme variability in carbonate depositional environments and susceptibility to a range of post-depositional processes results in complex pore structures comprising length scales from tens of nanometers to several centimeters. To increase understanding of the role of pore structure on connectivity, conductivity, permeability, and recoveries requires one to probe the pore-scale structure in carbonates in a continuous range across over seven decades of length scales (from 10 nm to 4 cm) and to integrate information at these different scales. Here, a multi-scale digital core approach is used to improve prediction of petrophysical properties, such as permeability and capillary pressure, from sedimentary facies. The purpose is to establish a rock-typing system that reflects the 3D pore structure and can be confidently distributed at the field-scale. An integrated petrographic, petrophysical, and 3D pore-scale study of core from the Shuaiba reservoir in Al Shaheen, Qatar, has been performed on a large set of core samples using 3D micro-CT imaging at resolutions down to 3 microns. Further experimental analysis via scanning electron microscopy (SEM) techniques has been undertaken to probe the pore-scale structure to scales of 100 nm. The 3D pore space geometry (pore and throat sizes) and topology (pore interconnectivity) were quantified, allowing for the definition of a 3D pore-scale reservoir rock typing (3DRRT) scheme for the imaged samples. This rock typing was then coupled with petrophysical (capillary pressure, porosity, permeability) measurements undertaken both in the laboratory and directly on the digital image data. The direct enumeration of the 3D connectivity of specific pore types within core material allows for a much better prediction of the resultant porosity-permeability and capillary pressure relationships. The identified rock types from the 3DRRT scheme can be integrated with a facies distribution scheme and used to refine the reservoir geological model.

OBJECTIVES

- Gauge applicability and quality of 3D imaging techniques to better understand pore structure of reservoir carbonates.
- Undertake study on samples from different facies associations: platform, margin, and basinial.
- Develop techniques for integrating pore-scale information at multiple scales (nm to plug scales).
- Derive petrophysical properties (e.g., F, Saturation exponent, permeability, recovery, relative permeability) from 3D image data.
- Compare to CCAL/SCAL data.

CHALLENGE:

- Understanding and cataloging 3D pore structure in a heterogeneous reservoir carbonate.
- Probing and characterizing structure from nanometer to plug scale.
- Correlating range of geological facies types to 3D pore-scale reservoir rock types.

IMAGE QUALITY CONTROL & CALIBRATION: INTEGRATE MULTIPLE SCALES:

Example: Plug to pore-scale integration (1/2 inch plug correlated to 2 micron resolution information). Required for higher energy facies

Example: Centimeter to nanometer calibration/mapping: Integrate SEM and μ-CT data. Required for mixed skeletal grainstone/packstone

Example: 3D imaging at the nanoscale: Integration of FIBSEM and micro-CT data. Required for lower energy muddy facies

Conclusion: Ability to integrate & catalog multiple length-scale information in 3D

Example: Mixed skeletal grainstone/packstone imaged in 3D from plug to nanometer scale
Integrating petrographic, petrophysical, and 3D pore scale measurements of core material from the Shuaiba reservoir in Al Shaheen, Qatar.

**CHARACTERIZE STRUCTURE & SIMULATE PETROPHYSICAL PROPERTIES**

- 3D Image & Reconstruction
- Phase identification
- Structural characterization. Grain shape & texture. Mineralogy. Direct enumeration of microporosity. Porograin interconnectivity and network reconstructions. 3D imaging software

**INTEGRATING PETROGRAPHIC, PETROPHYSICAL, & 3D PORE-SCALE MEASUREMENTS: Facies Type 1**

**Micro-skeletal Packstone:**

<table>
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<tr>
<th>Porosity</th>
<th>29.7</th>
<th>31.8</th>
<th>37.7</th>
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<td>macro</td>
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<td>20.9</td>
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<td>23.1</td>
</tr>
<tr>
<td>MCP</td>
<td>36.0</td>
<td>33.5</td>
<td>37.1</td>
</tr>
</tbody>
</table>

**Shuaiba depositional facies and environment**

- 6 General Facies Associations derived
- 15 Overall Facies types identified
- 9 Facies types considered in this study; Geological facies types correlated to 3D reservoir rock typing (3D RRT) from 3D imaging and Digital Core technology.
- 3 examples shown.

**INTEGRATING PETROGRAPHIC, PETROPHYSICAL, & 3D PORE-SCALE MEASUREMENTS: Facies Type Example 1**

**Mixed skeletal grainstone/packstone**

Poorly cemented peloidal grainstones. Bivalve (B) and echinoderm debris (E) is common and often has a micritic coating. Calcite cement (C) is often associated with echinoderm debris. The porosity (blue) is dominated by moldic pores, but a minor amount of inter- and intragranular pores are also present.

**CONCLUSIONS:**

- 3D imaging via different techniques (micro-CT, SEM, FIBSEM) enables one to probe 3D pore structure in a heterogeneous reservoir carbonate across several orders of magnitude in scale.
- Image registration enables one to couple information at multiple scales; from nanometer to plug scale.
- Illustrated study of samples from different facies; geological facies types correlated to 3D pore-scale reservoir rock types.
- Derived petrophysical properties (e.g., F, Saturation exponent, permeability, recovery, relative permeability) from 3D image data.
- Good comparison to CCAL/SCAL data.

**RECENT RELATED REFERENCES**

- A closer look at pore geometry, *Digital Review*, Spring 2006, p. 4-15