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

Rob Sok[1], Mark Knackstedt[1], Abid Ghous[1], Christoph Arns[1], Søren Frank[2], Frans van Buchem[2], Torben Rasmussen[2], Jens Larsen[2], and Ramdas Narayanan[3]

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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.

Integrating petrographic, petrophysical, and 3D pore scale measurements of core material from the Shuaiba reservoir in Al Shaheen, Qatar.

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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.

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.

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 basinal.
- 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.

INTRODUCTION: DIGITAL CORE TECHNOLOGY

Digital core technology, 3D imaging and visualization of core material at the pore scale and subsequent analysis of petrophysical and multiphase flow properties can give important insight to understanding properties of reservoir core material. Historically, digital core technology has focused on the direct comparison of predictions with data collected from conventional core analysis. Results show that predictions of petrophysical and multiphase properties from 3D image data (permeability tensor, formation factor, resistivity index, relative permeability, and drainage capillary pressure) are in good agreement with experimental core measurements.

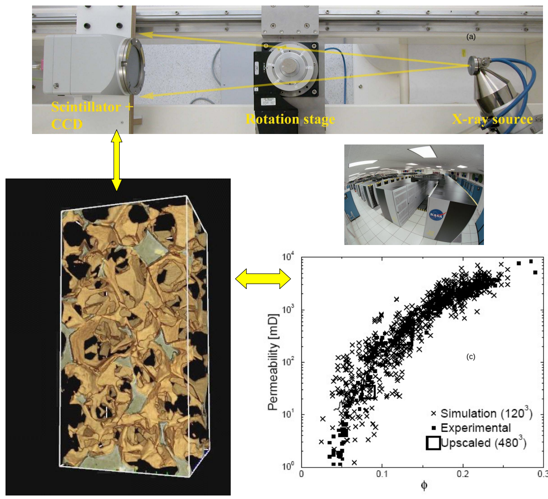
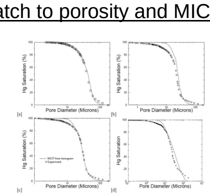
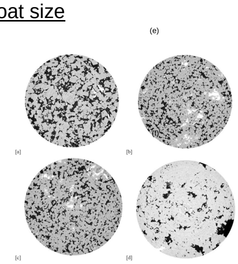


IMAGE QUALITY CONTROL & CALIBRATION:

Example: SIMPLE GRAINSTONE: Single pore-length scale

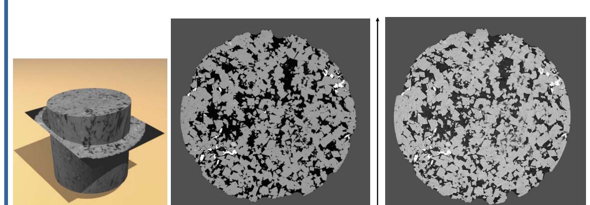
1. Match to porosity and MICP throat size





	ϕ_{exp}	ϕ_{image}	Dolomite	Calcite	Anhydrite
A	27.8%	28.3%	98.6%	0.0%	0.8%
B	19.1%	19.5%	85.9%	1.4%	7.2%
C	18.6%	18.1%	88.3%	4.9%	5.1%
D	12.8%	12.0%	90.2%	6.6%	2.1%

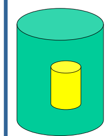
2. Direct Visual Calibration: 2D microscopy to 3D slice from image



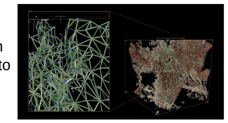
Slice of tomogram, 2.8 μm per voxel   6mm FOV   SEM, 1.3 μm per pixel

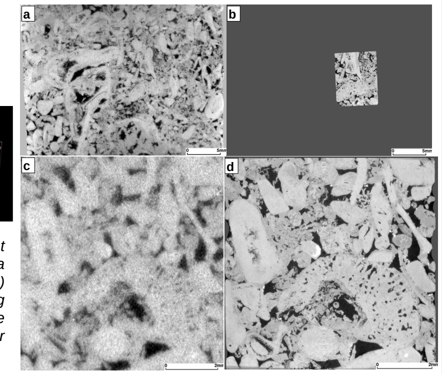
IMAGE QUALITY CONTROL & CALIBRATION: INTEGRATE MULTIPLE SCALES:

Example: Plug to pore-scale integration (1 ½ inch plug correlated to 2 micron resolution information): Required for higher energy facies



- Image same sample at multiple scales.
- Integrate information from higher resolution image into data at larger field of view
- Example: fracture/matrix

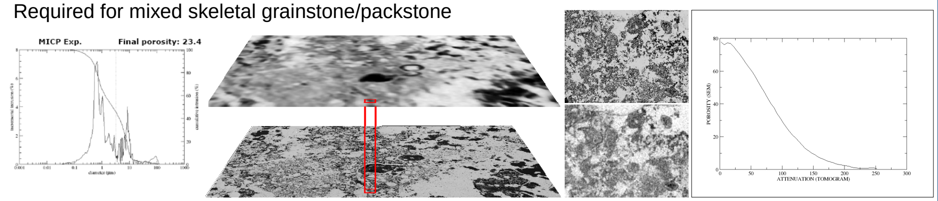




(Right) Example of the alignment of two 3D images at different resolutions. (a) shows an image of a slice from a tomogram of a carbonate plug obtained at the full plug scale (20 microns per voxel). (b) shows the spatial position of the subset of the 5mm subset of the plug now imaged at 2.5 microns per voxel. Bottom row shows slices from the same region of the carbonate imaged at (c) low and (d) higher resolutions.

Example: Centimeter to nanometer calibration/mapping: Integrate SEM and μ-CT data

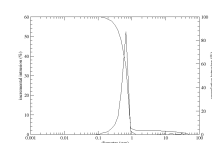
Required for mixed skeletal grainstone/packstone



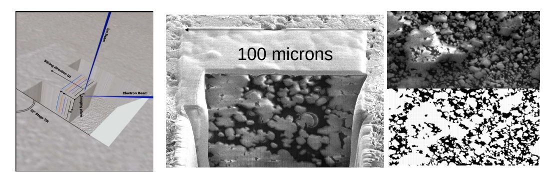
Left: MICP curve for packstone exhibiting pore sizes from 50 microns to 50 nm. Middle: Schematic and example of direct mapping from 3D slice at 2.8 micron resolution to 2D SEM at 250 nm resolution. (Right) Correlation between x-ray attenuation and porosity in the SEM is good.

Example: 3D imaging at the nanoscale: Integration of FIBSEM and micro-CT data

Required for lower energy muddy facies

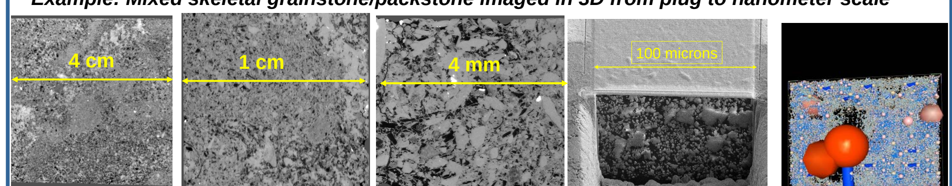


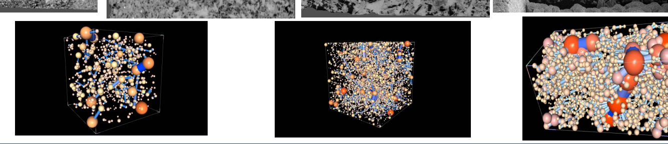
Left: Too tight for μ-CT. Right: FIB Tomography enables one to probe scales down to 10 nm



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

Example: Mixed skeletal grainstone/packstone imaged in 3D from plug to nanometer scale

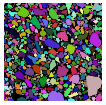


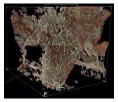


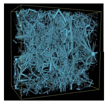
Integrating petrographic, petrophysical, and 3D pore scale measurements of core material from the Shuaiba reservoir in Al Shaheen, Qatar.

CHARACTERIZE STRUCTURE & SIMULATE PETROPHYSICAL PROPERTIES

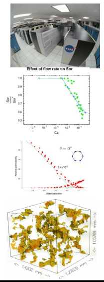
3D Image & Reconstruction + Phase identification

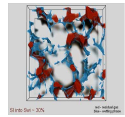






Structural characterization. Grain shape & texture. Mineralogy. Direct enumeration of microporosity. Pore/grain interconnectivity and network reconstructions. 3D imaging software





- •Permeability
- •Resisitivity (F & RI)
- •Capillary pressure
- •Relative Permeabilities
- •Residual Saturations
- •Two and three phase flow

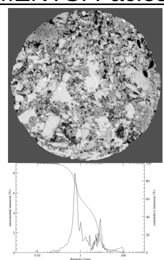
Shauaiba depositional facies and environment

- 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.

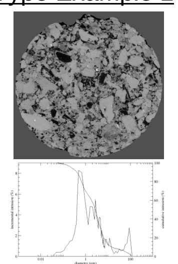
INTEGRATING PETROGRAPHIC, PETROPHYSICAL, & 3D PORE-SCALE MEASUREMENTS: Facies Type Example 1

Mixed skeletal grainstone/packstone

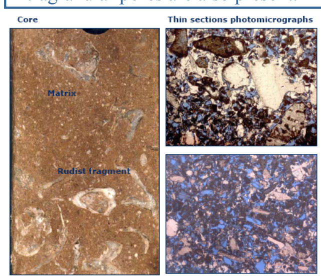
Poorly cemented peloidal grainstones. Bivalve (B) and echinoderm debris (E) is common and often has a micritic coating. Calcite cement (C) is often associated with echinoderm debris. The porosity (blue) is dominated by moldic pores, but a minor amount of inter- and intragranular pores are also present.

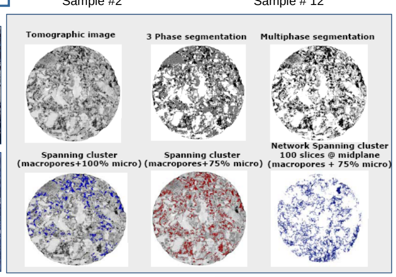


Sample #2

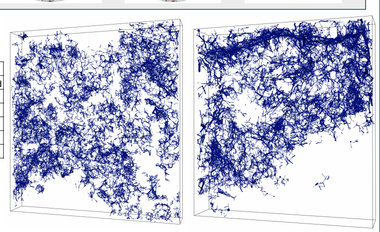


Sample # 12





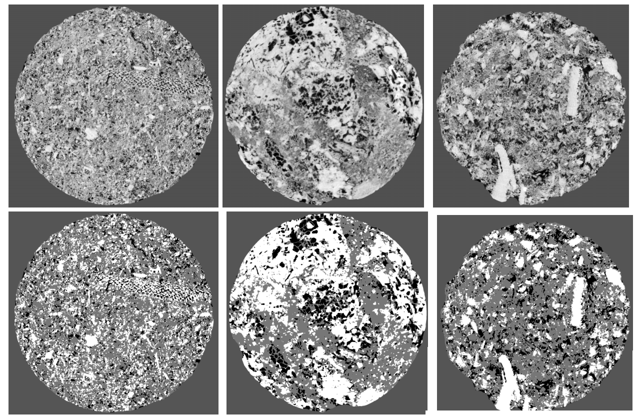
	MOQ2		MOQDCL12	
		Volume weighted		Volume weighted
<Z>	3.5	7.4	4.0	8.7
<R_pore>	17.8	29.6	13.4	27.2
<R_throat>	9.1	10.7	6.5	13.2
<R_p>/<R_t>	2.0	2.8	2.0	2.1
<L_throat>	94	138	76	122

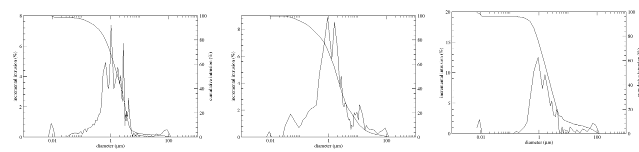


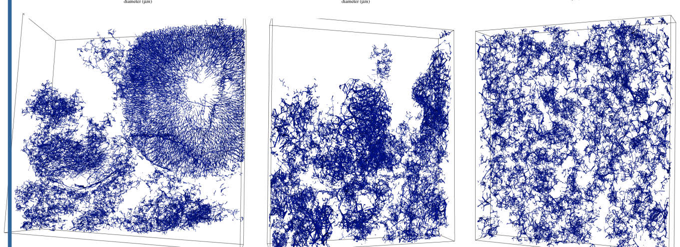
INTEGRATING PETROGRAPHIC, PETROPHYSICAL, & 3D PORE-SCALE MEASUREMENTS: Facies Type 2

Micro-skeletal Packstone:

Porosity:	29.7	31.8	37.7
macro	8.8	10.6	14.7
micro	20.9	21.3	23.1
MICP	36.0	33.5	37.1

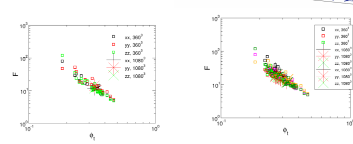






Archie's cementation exponent in 3 orthogonal directions

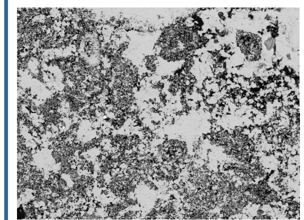
Sample	4	11
m_x	2.3	2.2
m_y	2.2	2.4
m_z	2.2	2.2

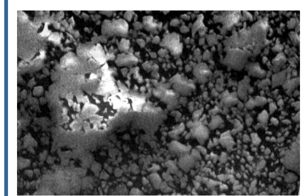


	MOQ4		MOQ11		MOQDCL13	
		Volume weighted		Volume weighted		Volume weighted
<Z>	3.2	4.6	3.16	5.92	3.4	7.5
<R_pore>	13.4	16.7	18.64	33.16	8.1	13.0
<R_throat>	6.25	6.88	9.52	12.44	4.16	4.91
<R_p>/<R_t>	2.15	2.42	1.96	2.67	1.8	2.66
<L_throat>	72.74	86.46	89.87	137.57	42.6	67.41

INTEGRATING PETROGRAPHIC, PETROPHYSICAL & 3D PORE-SCALE MEASUREMENTS: Example 3

Basinal Facies: Mudstone

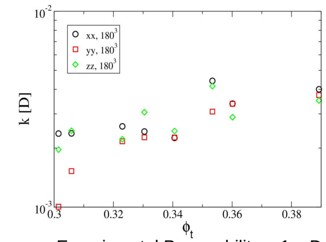




Left: Upper: SEM at 1 micron resolution ;

Left, Lower FIBSEM slice at 80 nm resolution.

Below: Permeability from 3D FIBSEM image



Experimental Permeability = 1 mD

Good permeability prediction in tight mudstones from FIBSEM

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

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•Pore level validaton of representative pore networks obtained from micro-CT images, **Society of Core Analysts, 2007**.

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•Probing pore systems in carbonates, **SPWLA Annual, 2008**.

•Carbonate petrophysical parameters derived from 3D images, **AAPG Annual Convention, 2008.**

•Image registration: Enhancing and calibrating X-ray micro-CT imaging, **Society of Core Analysts, 2008**.

•Wettability effects on the pore scale distribution of fluids, **Society of Core Analysts, 2008**.