Modeling Electrical Resistivity in Carbonates Using Micro-CT Scans and Assessing the Influence of Microporosity with MICP

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Micro-CT: Video demonstration of 3-D Core Plug Tomograms on page 5 is not available.
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Abstract

Understanding the complex relationships between resistivity, porosity and pore structure is of fundamental importance to accurately inverse from down-hole log data to permeability and pore fluids. This is especially important in carbonates, where various depositional and diagenetic processes produce a wide range of pore sizes and complex pore structures. This heterogeneity also results in complex electrical behavior, especially in microporous rocks. The purpose of this study is to investigate the influences of microporosity and pore size and number on both electrical and hydraulic behavior with the goal to better understand resistivity logs. These influences are assessed with two different approaches: (A) Micro-CT imaging of pore networks and subsequent resistivity modeling is used to evaluate the influence of the number of pores and (B) MICP measurements are used to investigate pore size controls.

(A) Two pairs of samples, each with similar porosities (2x 16% and 2x 27%) but different grain sizes and formation factors, were imaged using high-resolution micro-CT scans. The coarse-grained samples were imaged at 23µm resolution and the microporous samples at 1.6µm resolution (voxel size). The resultant 3D-images (tomograms) were filtered and segmented, then used for pore network analysis and finite element resistivity modeling. The most interesting result is that resistivity decreases with increasing total number of pores per volume. This result corroborates the hypothesis by Verwer et al. (2011) that the “apparent cross-sectional area”, which increases with pore count, is the second most important factor controlling resistivity and the cementation factor m, after the total porosity. The modeling results for formation factor and resistivity correlate well with laboratory measurements.
(B) Resistivities of 12 samples with low porosity (1-10%) and permeability (<0.001-0.785mD) were measured under variable pressures. Mercury Injection Capillary Pressure (MICP) measurements were then used to assess the pore (throat) size distribution. The most arresting finding is the trend of increasing cementation factor with increasing average pore size. Rocks with smaller pore sizes (average < 0.1µm) show cementation factors between 1.4 and 2.1, whereas rocks with larger pore sizes (average > 0.1µm) have cementation factors of 2.4 and higher. This trend is in contrast to what has been proposed by previous modeling studies.

References


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Motivation:

![Plot showing formation factor vs. porosity with cementation factor superimposed in color. Samples imaged with Micro-CT for this study are highlighted. Notice: Samples with similar porosities can have very different cementation factors.]

Fewer pores

![Plot showing pore shape parameters related to pore size/pore count. Fewer pores means higher cementation factor. Does absolute pore count control cementation factor? This will be further investigated quantitatively using Micro-CT scans and MICP measurements.]

Test Verwer et al’s (2011) hypothesis that samples with a lower cementation factor for a given porosity have a higher number of pores.

Higher number of pores = Smaller pores
Small pores facilitate the flow of electrical charge (low resistivity), but high capillary pressures hinder the flow of large water molecules (high permeability).

Approach: Assess influences of pore count on electrical resistivity with two independent approaches: Micro-CT Scanning and MICP measurements.

![Diagram of Micro-CT setup: X-Ray Source, Scintillator + CCD, Rotation Stage + Plug. 3-dimensional pore network modeling and pore network statistics.]

Core Plug

![Diagram of Core Plug setup: Laboratory resistivity measurements. Pore throat/size analysis, pore size distribution and pore count.]

MICP

Few large pores
Which has lower resistivity?
Many small pores
**Micro-CT Scanning**

**Tools / Technique**
- X-Ray Source
- Scintillator
- Rotation Stage
- CCD
- Sun Constellation cluster, vayu
- ANU
- NCI
- DigitalCore

Filtering / Segmenting
- Pore network statistics: Pore Count
- Finite element resistivity modeling

**Drisht 3D volume visualization**

To analyze the samples on pore count to find reasons for these differences in resistivity, we imaged them using high-resolution micro-CT scanners at the Australian National University, Canberra. The tomograms were filtered and segmented into phases (example below). Then pore network analysis and finite element resistivity modeling was applied to the segmented tomogram, using the cluster computing facilities at ANU. Finally the tomograms were visualized at

**Segmentation Example: Grainstone (27% Porosity)**

- **Filtered tomogram**
  - Voxel size: 23 microns
- **2-Phase Segmentation**
  - Macroporosity: 4.16%
- **Microporosity Segmentation**
  - Microporosity: 21.93%

**Aims:**
- Create pore network
- Model Resistivity
- Calculate Pore Count

**Samples**

- Two pairs of samples with similar porosities but different resistivities
- What is the reason for the different resistivities?
- Pore count?

**Results**

Plot showing the two pairs of samples with their relative pore count. It is evident that samples with less pores have higher resistivities and cementation factors.

Electrical resistivity in carbonate rocks is not so much dependent on pore throat diameter or tortuosity but rather on pore structure and number of pore connections!

**More Pores = Lower Resistivity**
Key Results

- Micro-CT: Resistivity decreases with increasing number of pores per volume
- MICP: Resistivity decreases with decreasing average pore size (increasing number of pores per volume)
- BOTH independent approaches reveal a decrease in Electrical Resistivity with increasing pore count. This result corroborates the hypothesis by Verwer et al. (2011) that the “apparent cross-sectional area”, which increases with pore count, is the second most important factor controlling resistivity, after the total porosity

Micro-CT: Video demonstration of 3-D Core Plug Tomograms

Video showing the well connected Macroporosity in the Ooid Grainstones and the unconnected Macropores in the Skeletal Wackestones

Rock Solid Phase
Macroporosity
Micro-porosity
MICP (Mercury Injection Capillary Pressure)

**Tools / Technique**

Characterizes a material’s porosity by applying various levels of pressure to a sample immersed in mercury. The pressure required to intrude mercury into the sample’s pores is inversely proportional to the size of the pores.

**Aims:**
- Get Pore Size Distribution
- Inverse from pore size to pore count
- Capability to measure pore diameters from 0.003 to ~1000 μm

**Samples**

12 mixed carbonate-siliciclastic samples with low porosities (1-10%) and permeabilities (<0.001-0.785mD)

What is the reason for the different resistivities? Pore size?

**Results**

Plot of porosity vs. formation factor with cementation factor color coded. New samples marked with X-es. The results complement the Verwer et al. dataset into the realm of low porosities (to the left).

**Average Pore Diameter vs. Porosity (Cementation Factor superimposed in color)**

Plot of Average Pore Diameter vs. Porosity with Cementation Factor superimposed in color. Lower Pore Diameter means more pores at similar porosities. Samples with more pores tend to have lower Cementation Factors

Smaller Pores = More Pores = Lower Resistivity
Conclusions

Previous studies have assumed that resistivity is greatly influenced by the total number of pores and pore connections.

Here we quantified and tested those assumptions.

Both approaches confirm Verwer et al.’s (2011) hypothesis that increased pore count lowers resistivity.

More Pores = More Pathways

More Pores/Pathways = Lower Resistivity

Micro-CT Scanning

Micro-CT scans reveal the 3-dimensional pore structure and the fact that - at equal porosities - samples with higher cementation factor have less pores.

MICP

Average Pore Diameter vs. Cementation factor

Samples analyzed with MICP show clear trend of increasing cementation factor with increasing pore size (less pores at equal porosities).

Explanation: Electrical Resistivity & Pore Structure

Samples with larger pore sizes (e.g. grainstones) have higher electrical resistivity and cementation factor than samples dominated by smaller pore sizes (e.g. wackestones).

In natural rocks many more pores (and pore connections) need to exist in rocks with smaller pore sizes than in rocks with larger pores in order to maintain equal porosity.

This results in fewer pore connections for rocks dominated by larger pores and hence conduction of electrical current is retarded. For samples dominated by many small pores the flow of electrical charge is facilitated by the dense pore network.

Abstract:

Understanding the complex relationships between resistivity, porosity and pore structures is of fundamental importance to accurately infer from down-hole log data to permeability and pore fluids. This is especially important in carbonate, where various depositional and diagenetic processes produce a wide range of pore sizes and complex pore structures. This heterogeneity also results in complex electrical behavior, especially in microporous rocks. The purpose of this study is to investigate the influences of microporosity and pore size and number on both electrical and also hydraulic behavior with the goal to better understand resistivity logs. These influences are assessed with two different approaches: (A) Micro-CT imaging of pore networks and subsequent resistivity modeling is used to evaluate the influence of the number of pores and (B) MICP measurements are used to investigate pore size controls.

(A) Two pairs of samples, each with similar porosities (2x 16% and 2x 27%) but different grain sizes and formation factors, were imaged using high-resolution micro-CT scans. The coarse grained samples were imaged at 23µm resolution and the microporous samples at 1.5µm resolution (voxel size). The resultant 3D images (volumegrams) were filtered and segmented, then used for pore network analysis and finite element resistivity modeling. The most interesting result is that resistivity decreases with increasing total number of pores per volume. This result corroborates the hypothesis by Verwer et al. (2011) that the “apparent cross-sectional area”, which increases with pore count, is the most important factor controlling resistivity and the cementation factor m, after the total porosity. The modeling results for formation factor and resistivity correlate well with laboratory measurements.

(B) Resistivities of 12 samples with low porosity (1.10%) and permeability (<0.001- 0.78Dm3/s) were measured under variable pressures. Mercury Injection Capillary Pressure (MICP) measurements were then used to assess the pore (throat) size distribution. The most arresting finding is the trend of increasing cementation factor with increasing average pore size. Rocks with smaller pore sizes (average < 0.1µm) show cementation factors between 1.4 and 2.1, whereas rocks with larger pore sizes (average > 0.1µm) have cementation factors of 2.4 and higher. This trend is in contrast to what has been proposed by previous modeling studies.

Electrical Resistivity & Archie’s Law

\[ F = F_0 \left(\frac{R_s}{R_w}\right)^m \]

Where,

- \( F \) = formation resistivity factor
- \( F_0 \) = resistivity of fully saturated rock (100% saturation)
- \( R_w \) = resistivity of pore fluid
- \( R_s \) = resistivity of fully saturated rock

Controlled by:
1) Total porosity
2) Number of pores
3) Tortuosity

References:


