Improved Oil-in-Place Estimates in Clay- and Pyrite-Bearing Shales*

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Abstract

Subsurface electromagnetic (EM) measurements, namely galvanic resistivity, EM induction, EM propagation, and dielectric dispersion, exhibit frequency dependence due to the interfacial polarization (IP) of clay minerals, clay-sized particles, and conductive minerals. Existing oil-in-place estimation methods based on subsurface EM measurements do not account for dielectric permittivity, dielectric dispersion, and dielectric permittivity anisotropy arising from the IP effects. The conventional interpretation methods generate inaccurate oil-in-place estimates in clay- and pyrite-bearing shales because they separately interpret the multi-frequency effective conductivity and permittivity using empirical models.

We introduce a new inversion-based method for accurate oil-in-place estimation in clay-and pyrite-bearing shales. The inversion algorithm is coupled with an electrochemical model that accounts for the frequency dispersion in effective conductivity and permittivity due to the above-mentioned IP effects. The proposed method jointly processes the multi-frequency effective conductivity and permittivity values computed from the subsurface EM measurements. The proposed method assumes negligible invasion, negligible borehole rugosity, and lateral and vertical homogeneity effects.

The successful application of the new interpretation method is documented with synthetic cases and field data. Water saturation estimates in shale formations obtained with the new interpretation method are compared to those obtained with conventional methods and laboratory measurements. Conventional interpretation of multi-frequency effective conductivity and permittivity well logs in a clay- and pyrite-rich shale formation generated water saturation estimates that varied up to 0.5 saturation units, as
a function of the operating frequency of the EM measurement, at each depth along the formation interval. A joint interpretation of multifrequency conductivity and permittivity is necessary to compute the oil-in-place estimates in such formations. Estimated values of water saturation, average grain size, and surface conductance of clays in that formation are in the range of 0.4 to 0.7, 0.5 micrometer to 5 micrometer, and $5 \times 10^{-7}$ S to $9 \times 10^{-7}$ S, respectively. The proposed method is a novel technique to integrate effective conductivity and permittivity at various frequencies. In doing so, the method generates frequency-independent oil-in-place estimates, prevents under-estimation of hydrocarbon saturation, and identifies by-passed zones in shales.

References Cited


Improved Oil-in-Place Estimates in Clay- and Pyrite-Bearing Shales

Yifu Han and Siddharth Misra
University of Oklahoma

Presenter: Siddharth Misra
Outline

- Introduction and Motivation
- Multi-frequency conductivity-permittivity model
- Model predictions
- Multi-frequency conductivity-permittivity inversion
- Interpretation of Synthetic and Subsurface Data
- Conclusions
Introduction: Definition

Conductivity

\[ \sigma \]

Frequency independent
No phase, Real Number

Permittivity

\[ \varepsilon^*(\omega) = \varepsilon_r^*(\omega)\varepsilon_0 \]

Complex relative permittivity

\[ \varepsilon_r'(\omega) - i\varepsilon_r''(\omega) \]

Conductivity measurement

\[ (\sigma + \omega\varepsilon_r'\varepsilon_0) + i(\omega\varepsilon_r'\varepsilon_0) \]

Relative permittivity measurement

\[ \varepsilon_r' - i\left(\varepsilon_r'' + \frac{\sigma}{\omega\varepsilon_0}\right) \]
Introduction: Definition

Polarization

Dispersion
Introduction: Downhole EM Tools

Galvanic
100 Hz – 1 kHz

Induction
10 – 50 kHz

Propagation
400 kHz – 2 MHz

Permittivity
20 MHz – 2 GHz
Introduction: Downhole EM Tools

Effects on EM log measurements

- Invasion
- Borehole
- Tool eccentricity
- Bed boundary
- Resistivity Anisotropy

- Interfacial polarization
- Frequency dispersion
Introduction: Pyrites and Clays
Introduction: Polarization

Frequency dispersions of effective conductivity and permittivity

Clay Double-layer
Metallc IP
Maxwell-Wagner
Orientation

\[ \sigma (\omega) \]
\[ \varepsilon_r' (\omega) \]

Laterolog
RAB
AIT
ARC
DPT
EPT

35, 280 Hz
1.5 kHz
26, 52 kHz
0.4, 2 MHz
25 MHz
1.1 GHz

Anderson et al., 2007
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Orientation polarization is the only mechanism dominant around 1 GHz for hydrocarbon-bearing porous geomaterials.
Introduction: Polarization

Interfacial polarization of conductive mineral grains – Metallic IP

Placencia-Gomez et al., 2013

Metallic IP effects are negligible beyond 1 MHz

Width of view = 1.38 mm
Introduction: Polarization

Interfacial polarization of clay particles – Membrane Polarization

Membrane Polarization effects are negligible beyond 1 MHz

Revil et al., 2012
Motivation

Frequency dispersion in effective conductivity and permittivity

Wang and Poppitt, 2013
Motivation

Frequency dispersion in conductivity and permittivity

\[ s_w = \frac{(\varepsilon^*_r,\text{eff})^\alpha - (1 - \phi)(\varepsilon^*_r,\text{m})^\alpha - \phi(\varepsilon^*_r,\text{hy})^\alpha}{(\varepsilon^*_r,\text{w})^\alpha - (\varepsilon^*_r,\text{hy})^\alpha} \]

CRIM Formula

\[ S_w = \sqrt[n]{\frac{\sigma_{\text{eff}}}{\sigma_w \phi^m}} \]

Archie’s equation
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Wang and Poppitt, 2013
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Conductivity-Permittivity Interpretation

1. Downhole EM Measurements
   - Voltage, Current, Phase, Amplitude

2. EM Modeling and Inversion
   - Conductivity, Permittivity, Anisotropy, Azimuth, Dip

3. Petrophysical estimation
   - Water Saturation
   - Brine conductivity
   - Clay surface conductance

Archie’s equation

\[ s_w = \frac{n}{\sqrt{\sigma_{\text{eff}} / \sigma_w \phi_m}} \]

CRIM

\[ s_w = \frac{(\varepsilon_{r,\text{eff}}^\alpha - (1 - \phi)(\varepsilon_{r,m}^\alpha) - \phi(\varepsilon_{r,\text{hy}}^\alpha)}{(\varepsilon_{r,w}^\alpha - (\varepsilon_{r,\text{hy}}^\alpha))^\alpha} \]
Conductivity-Permittivity Model

Misra et al., 2016
Conductive inclusion

Nonconductive inclusion

Misra et al., 2016
Conductivity-Permittivity Model

Alteration in electromigration
Account for charge accumulation and electrodiffusion

Misra et al., 2016
**Conductivity-Permittivity Model**

**Input Parameters**
- Volume fraction of pyrite grains
- Bulk conductivity of pyrite
- Relative permittivity of pyrite
- Diffusion coefficient of pyrite
- Radius of pyrite grains
- Volume fraction of clay
- Relative permittivity of clay
- Surface conductance of clay
- Radius of spherical clay grains
- Volume fraction of sand
- Surface conductance of sand
- Radius of sand grains
- Bulk conductivity of brine
- Relative permittivity of brine
- Diffusion coefficient of brine
- Relative permittivity of hydrocarbon
- Water saturation

**PS Model**
Model Predictions

Metallic Nature and Shape of Conductive Inclusions

Conductive Inclusions (5%)
+ Silica grains (70%)
+ Brine (0.1-S/m)

Graphite (G)
Pyrite (P)
Chalcopyrite (C)
Low-conductivity material (X)
Model Predictions

Grain Size of Conductive Inclusions

Conductive Inclusions (5%)
+ Silica grains (70%)
+ Brine (0.1-S/m)

Spheres

<table>
<thead>
<tr>
<th>Spherical inclusion</th>
<th>Sheet-like inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 pyrite</td>
<td>2</td>
</tr>
<tr>
<td>P2 pyrite</td>
<td>20</td>
</tr>
<tr>
<td>P3 pyrite</td>
<td>200</td>
</tr>
<tr>
<td>P4 pyrite</td>
<td>2000</td>
</tr>
</tbody>
</table>
Model Predictions

Brine Conductivity and Conductive Inclusion Shape

Conductive Inclusions (5%) + Silica grains (70%) + Brine (0.1-S/m)

- **P1**: 200 μm
- **P2**: 20 μm
- **P3**: 1 mm
Conductivity-Permittivity Inversion

Measurements

Conductivity-Permittivity Inversion

Model response

Known Parameters

- Volume fraction of pyrite grains
- Volume fraction of sand
- Bulk conductivity of pyrite
- Surface conductance of sand
- Relative permittivity of pyrite
- Radius of sand grains
- Diffusion coefficient of pyrite
- Relative permittivity of brine
- Volume fraction of clay
- Relative permittivity of clay

Estimated Parameters

- Water saturation
- Bulk conductivity of brine
- Surface conductance of clay
- Radius of spherical clay grains
- Radius of pyrite grains

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## Interpretation of Synthetic Data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Parameter values for Synthetic Data 1</th>
<th>Parameter values for Synthetic Data 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume fraction of pyrite grains</td>
<td>%</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Bulk conductivity of pyrite</td>
<td>S/m</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Relative permittivity of pyrite</td>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Diffusion coefficient of pyrite</td>
<td>m²/s</td>
<td>10⁻⁶</td>
<td>10⁻⁶</td>
</tr>
<tr>
<td>Radius of pyrite grains</td>
<td>µm</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Volume fraction of clay</td>
<td>%</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Relative permittivity of clay</td>
<td></td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Surface conductance of clay</td>
<td>S</td>
<td>10⁻⁶</td>
<td>5 × 10⁻⁶</td>
</tr>
<tr>
<td>Radius of spherical clay grains</td>
<td>µm</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Volume fraction of sand</td>
<td>%</td>
<td>19</td>
<td>45</td>
</tr>
<tr>
<td>Surface conductance of sand</td>
<td>S</td>
<td>10⁻⁹</td>
<td>10⁻⁹</td>
</tr>
<tr>
<td>Radius of sand grains</td>
<td>µm</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Bulk conductivity of brine</td>
<td>S/m</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>Relative permittivity of brine</td>
<td></td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Diffusion coefficient of brine</td>
<td>m²/s</td>
<td>10⁻⁹</td>
<td>10⁻⁹</td>
</tr>
<tr>
<td>Relative permittivity of hydrocarbon</td>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Water saturation</td>
<td>%</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>
Interpretation of Synthetic Data

Synthetic Data 1

- $s_w$: Water saturation
- $C_w$: Water conductivity
- $\lambda_c$: Permeability
- $r_c$: Representative elementary volume
- $r_i$: Interfacial radius
- Error vs. iteration

Parameter Values:
- $s_w = 0.1$
- $C_w = 0.1 \text{ S/m}$
- $\lambda_c = 10^{-6} \text{ S}$
- $r_c = 1 \mu\text{m}$
- $r_i = 100 \mu\text{m}$
Interpretation of Synthetic Data

Synthetic Data 2

\[
s_w = 0.6 \\
C_w (S/m) = 3 \\
\lambda_c (S) = 5 \times 10^{-6} \\
r_c (\mu m) = 0.3 \\
r_f (\mu m) = 30 \\
\text{error}
\]

iteration#

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Interpretation of Synthetic Data

Synthetic Data 1

Relative permittivity vs. Frequency (Hz)

Synthetic data
Modeled data based on inverted data

Conductivity (S/m) vs. Frequency (Hz)

Synthetic Data 2

Relative permittivity vs. Frequency (Hz)

Synthetic data
Modeled data based on inverted data

Conductivity (S/m) vs. Frequency (Hz)
Interpretation of Subsurface Data

Wang and Poppitt, 2013

Permittivity
Propagation
Induction
Interpretation of Subsurface Data

- $s_w$: 0.84
- $c_w$: 17.7 S/m
- $\lambda_c$: 3.8e-6 S

![Graphs showing iterative changes in $s_w$, $c_w$, and $\lambda_c$ over iterations.](image)
Interpretation of Subsurface Data

![Graph showing relative permittivity and conductivity vs. frequency](image)

- **Relative permittivity** vs. **Frequency (Hz)**
  - Synthetic data
  - Modeled data based on inverted data

- **Conductivity (S/m)** vs. **Frequency (Hz)**
  - Synthetic data
  - Modeled data based on inverted data
Conclusions

• Conductivity and permittivity of clay-bearing and conductive-mineral-bearing samples depend on:
  – Grain size of conductive inclusions
  – Metallic nature of conductive inclusions
  – Brine conductivity
  – Frequency of the applied EM field

• In contrast to EM induction and EM propagation measurements, galvanic resistivity measurements are:
  – Highly sensitive to laminations of clays and conductive minerals
  – Non-sensitive to disseminated spherical inclusions of clays and conductive minerals

• Dielectric dispersion measurements at operating frequencies higher than 100 MHz are unsusceptible to the effects of interfacial polarization of clays and pyrite grains.
Conclusions

• We developed an inversion scheme to jointly process the subsurface galvanic resistivity (< 1 kHz), EM induction (10 – 100 kHz), EM propagation (400 kHz – 10 MHz), and dielectric dispersion (10 MHz – 1 GHz) logs.

• We presented a proof-of-concept exercise to assess water saturation, brine conductivity, surface conductance of clays, average grain size of clays, and average grain size of pyrite inclusions.

• The proposed joint inversion improves the accuracy of petrophysical interpretation of EM measurements by eliminating the effects of interfacial polarization of clays and pyrite inclusions.
Thank You