InnovationS in near-surface geophysics: going beyond state-of-the-art imaging

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Near-surface geophysics: twisting reality?

Binley et al., 2015, WRR
A revolution in space
A historical perspective in images

Geonics ®

CHAR project, ULiege
A historical perspective in images

Nguyen, 2005

CHAR project, ULiege
Advances in modeling physical phenomena to improve imaging

Klotzsche, et al., 2010
Full waveform inversion brings high resolution

Klotzsche, et al., 2010
Mapping surveys

Challenges: maintaining the depth of investigation while reducing the loop

Auken et al., 2019
Mapping surveys: 2 days to image 1.6 km² down to 70 m with a 25 m resolution

Auken et al., 2019, Geophysics
Then in time...
Data processing: making sense out of noise

Voisin et al., 2017, JWARP
Data processing: making sense out of noise

Voisin et al., 2017, JWARP
4D imaging at Hanford, WA

A critical boundary directing flow towards river

Paleochannels incised into the Ringold unit suspected to channel flow towards the river

Courtesy of Prof. Lee Slater
ERT 3D + time

Johnson et al., 2015, WRR
Relation to state variables...
Petrophysics: the power to quantify...or not

Jougnot et al., 2018
Petrophysics: testing hypothesis

Jougnot et al., 2018
And understanding field limitations

Benoit et al., 2019
Biogeosystems: the next frontier...

- Pumping of contaminated water
- Biological treatment in the bioremediation unit
- Reinjection of the treated water amended with nutrients (nitrogen source) and electron acceptors ($O_2$) in the periphery

Started in mid-2008, ended in mid 2011

Caterina et al., 2017
...but requires fundamental studies

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**Graph Details**

- **X-Axis**: Frequency (Hz)
- **Y-Axis**: Phase (mrad)

**Graph Legend**

- Growth medium
- Suspension (1h)
- Suspension (3h)

**Data Points**

- 0.04 mrad

**Relevant Information**

- *Phage growth medium*
- *Bacillus subtilis RL5260*

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*Pilawski, 2019*
Tackling biogeosystems...

- Growth medium mixed with sand
- Suspension mixed with sand (1h)
- Suspension mixed with sand (3h)
- Growth medium
- Suspension (1h)
- Suspension (3h)

Pilawski, 2019

316 Hz  631 Hz

Phase (mrad)

0.1 mrad

0.04 mrad

Frequency (Hz)

Growth medium mixed with sand
Suspension mixed with sand (1h)
Suspension mixed with sand (3h)
Growth medium
Suspension (1h)
Suspension (3h)
Process oriented imaging

Water conductivity increases with temperature... 2% changes per °C

\[ \Delta T = \frac{1}{m_f} \left( \frac{\sigma_{b,TL}}{\sigma_{b,B}} \frac{\sigma_{f,B}}{\sigma_{f,25}} - 1 \right) + 25 - T_{init} \]

Robert et al., GELMON
Process oriented

Wildermeersch et al., 2014
Process oriented imaging

Hermans et al., 2015
Data integration
Earth Sciences modeling = dealing with uncertainty

We can rely on stochastic modeling based on a prior distribution of geological model parameters to generate realistic subsurface models.

Hermans et al., 2015, WRR
Geophysics provide dense information but indirect and uncertain information.

Global comparison of all the models
Not necessary to match any data
Inversion introduces a strong bias (smoothing), so what could we do?

Lopez et al., 2019

Collected data using PyGIMLi’s Refraction module (Rucker et al., 2017).

Inversion
Instead, we could define features of geophysical data \( f(d) \) that inform on the prior:

\[
p(s|d) \approx p(s|f(d))
\]
Approach to test the features

• Uniform sampling of a structural prior, e.g. orientation $s = 0.5 \pi$

• Realization of a facies distribution, e.g.

• From facies to geophysical data

• Design features of geophysical data
Exploring the prior falsification potential of:

Histogram of travel times
Joint probability distribution for discrete $s$ with $+ = s_1$ along with posterior.

(a)

Testing the features of MDS on the histogram of travel times.
Data integration: geophysics as a fully integrated dataset

Prediction-focused approach

1) Definition of the prior and conceptual model and generation of n realizations of the aquifer

2) PCA

3) Canonical correlation analysis

4) Gaussian regression and sampling

5) Back transformation

6) Full posterior

Table 1: Parameters Used for the Heat Flow and Transport Simulations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Fixed/variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of ( \log_{10} K ) (m/s)</td>
<td>Variable</td>
<td>U(-4 -1)</td>
</tr>
<tr>
<td>Variance ( \log_{10} K ) (m/s)</td>
<td>Variable</td>
<td>U(0.05 1.5)</td>
</tr>
<tr>
<td>Range (m)</td>
<td>Variable</td>
<td>U(1 10)</td>
</tr>
<tr>
<td>Anisotropy ratio</td>
<td>Variable</td>
<td>U(0.5 10)</td>
</tr>
<tr>
<td>Orientation</td>
<td>Variable</td>
<td>U(-4/4)</td>
</tr>
<tr>
<td>Porosity</td>
<td>Variable</td>
<td>U(0.05 0.40)</td>
</tr>
<tr>
<td>Gradient (%)</td>
<td>Variable</td>
<td>U(0 0.167)</td>
</tr>
<tr>
<td>( \log_{10} K ) (m/s) – upper layer</td>
<td>Fixed</td>
<td>10^-3</td>
</tr>
<tr>
<td>Longitudinal dispersivity (m)</td>
<td>Fixed</td>
<td>1</td>
</tr>
<tr>
<td>Transverse dispersivity (m)</td>
<td>Fixed</td>
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</tr>
<tr>
<td>Solid thermal conductivity (W/mK)</td>
<td>Fixed</td>
<td>3</td>
</tr>
<tr>
<td>Water thermal conductivity (W/mK)</td>
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<tr>
<td>Solid specific heat capacity (J/kgK)</td>
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</tr>
<tr>
<td>Water specific heat capacity (J/kgK)</td>
<td>Fixed</td>
<td>4,189</td>
</tr>
</tbody>
</table>

Hermans et al., 2018
Data integration

Hermans et al., 2018
Conclusions and outlook

• Quantitative geophysics in the sense that we will be able to quantify for example a water content is a sweet dream far far away...

• However, qualitative information which is spatiotemporally distributed is probably more important for the studied processes to reduce the inherent subsurface uncertainty...

• In that sense, data density/quality improv’t, understanding fundamental “petro”physics, improved physical modeling, imaging and data integration methods lead the way forward.