Fractured Bedrock Hydrogeologic Characterization Using Digital Rock Physics*
Eric Goldfarb¹, Logan Shmidt¹, Ken Ikeda¹, Omar Alamoudi¹, Daniella Rempe¹, and Nicola Tisato¹

Search and Discovery Article #42398 (2019)**
Posted July 29, 2019

*Adapted from oral presentation given at 2019 AAPG Annual Convention and Exhibition, San Antonio, Texas, May 19-22, 2019
**Datapages © 2019 Serial rights given by author. For all other rights contact author directly. DOI:10.1306/42398Goldfarb2019

¹The University of Texas at Austin, Austin, TX (eric.goldfarb@utexas.edu)

Abstract

Bedrock groundwater systems in mountains are critical water resources, yet they are poorly understood. In part, this is due to sparse data on complex flowpaths. Mountainous environments are typically characterized by fractured and variably weathered bedrock with complex pore networks. The extent to which flow is partitioned between fractures in the bedrock, and rock matrix remains challenging to assess quantitatively. In this study, we use novel quantitative micro Computed Tomography (CT) to characterize the density, porosity, pore structure, and permeability of fractured argillaceous bedrock core from a forested montane hydrologic monitoring site.

By CT scanning a rock core, digital representations of the sample can be captured, and used to create digital rock physics models. One advantage of rock physics models is the ability to work with intact scanned cores. Most lab equipment for porosity and permeability testing cannot handle rocks larger than a few centimeters. By working with larger rock physics models, we are more likely to capture a representative elementary volume (REV) to be used in our analysis.

Density models can be created by scanning alongside objects of known density. Using these objects for calibration, CT attenuation can be converted to density at each voxel (3D pixel). A porosity model can be created by using an inverse relationship to density for each voxel. Effective medium theory is then used to create a velocity model of the rock. We used a finite difference method simulation to solve the wave equation at each node through the model of the fractured sample and computed wave-speeds. Fluid flow can also be simulated through the CT based models. Fluid flow modeling can quantify water flux partitioning between fractures and the rock matrix.

We compare the digital rock physics models to laboratory measurements of density, velocity, porosity, and pore structure. Pore information has been evaluated with helium pycnometry, mercury intrusion porosimetry, and laboratory nuclear magnetic resonance. Fluid flow simulations, porosity, and velocity data are compared to field scale measurements at our intensive monitoring site to improve understanding of fluid pathways at the hillslope and catchment scale.
References Cited


Lee, S.S., 2018, Spatial Patterns of Bedrock Weathering at the Hillslope Scale Inferred via Drilling and Multi-Scale Geophysical Methods: Master’s Thesis, The University of Texas at Austin, Austin, TX, 81 p.


Websites Cited


Fractured Bedrock Hydrogeologic Characterization Using Digital Rock Physics

Eric Goldfarb, Logan Schmidt, Ken Ikeda, Omar Alamoudi, Daniella Rempe, Nicola Tisato

The University of Texas at Austin
• For day to day consumption of water:
  • 37% of the U.S. population relies on groundwater
  • 50 million Americans rely on the Colorado River basin
  • No realistic maps of porosity or permeability of the USA

Source: Google Earth
• For day to day consumption of water:
  • 37% of the U.S. population relies on groundwater
  • 50 million Americans rely on the Colorado River basin
• No realistic maps of porosity or permeability of the USA

Problem:
How do we quantify the groundwater resources for a mountainous environment?

Source: Google Earth
A 1D model of regions contained in the “critical zone”

http://criticalzone.org/national/research/the-critical-zone-1national/
Goal: Characterise and quantify flow paths

- Where are unit boundaries?
- How porous is each unit?
- How permeable is each unit?
Surface topography does not necessarily tell us much about flow paths

Tools:

- Boreholes
- Sample collection
- Sledge hammer seismic survey
- Characterise seismic velocity for each unit


P Wave velocity inversion
P Wave velocity inversion

Field Results:

- Sledge hammer seismic data: P wave velocity
  - Soil: 350-600 m/s
  - Weathered bedrock: 600-1900 m/s
  - Fresh bedrock: >1900 m/s (almost all >2700 m/s)

What happens if we don’t have a data rich environment? (i.e. most environments?)

- P velocity $> 5$ km/s is probably not porous at all
- P velocity $< 500$ m/s is probably very porous
What happens if we don’t have a data rich environment? (i.e. most environments?)

• P velocity > 5 km/s is probably not porous at all
• P velocity <500 m/s is probably very porous
• And for in between....?
Ground truth:

A piece of unweathered shale bedrock.
Ground truth: Laboratory testing

Density: 2 653 kg/m³
Porosity: 1.01%
Ultrasonic Velocity: $V_p = 3 800$ m/s

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Quartz</th>
<th>Illite</th>
<th>Plagioclase</th>
<th>Chlorite</th>
<th>Carbonate</th>
<th>Kaolinite</th>
<th>Smectite</th>
<th>other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>25.1</td>
<td>14.7</td>
<td>24.4</td>
<td>20.3</td>
<td>1.3</td>
<td>1.9</td>
<td>10.0</td>
<td>~2</td>
</tr>
</tbody>
</table>
Preparing this rock was challenging. Every time we sawed it wet it would crumble.

It had to be cut with a saw dry, and slow. It created a lot of dust.

To grind the sample, it had to be done with kerosene as water would cause the clay to swell and the sample would crumble.

Total laboratory time for prep and testing: ~4 hours
Porosity: ????%
How to characterize an environment in a data rich way:
How to characterize an environment with a budget:
How to characterize an environment with Digital Rock Physics:
Click to View Movie
Relationship Between CT Number and Density for Several Materials

\[ \rho = 0.706(\text{CT#}) + 4.7 \]

\[ R^2 = 0.9963 \]
Relationship Between CT Number and Density for Several Materials

Density (kg/m$^3$)

- **Glass**
- **Quartz**
- **Borosilicate**

Fitted curve:

$$\rho = 0.706(\text{CT#}) + 4.7$$

$$R^2 = 0.9963$$

CT Number (Air value subtracted)
Relationship Between CT Number and Density for Several Materials

CT Number

Density, (Kg/m³)

\[ R^2 = 0.9963 \]

\[ 0.706(\text{CT#}) + 4.7 \]

Glass

Quartz

Air

Borosillicate
Lab measured density: 2653 kg/m³
CT estimated density: 2608 kg/m³

Difference: 1.7%
\[ \phi = \frac{\rho_{frame} - \rho_{voxel}}{\rho_{frame} - \rho_{fluid}} \]

\( \phi = \) porosity  
\( \rho_{frame} = \) frame density  
\( \rho_{voxel} = \) voxel density  
\( \rho_{fluid} = \) pore density
\[ \phi = \frac{\rho_{\text{frame}} - \rho_{\text{voxel}}}{\rho_{\text{frame}} - \rho_{\text{fluid}}} \]

\( \phi \) = porosity  \\
\( \rho_{\text{frame}} \) = frame density  \\
\( \rho_{\text{voxel}} \) = voxel density  \\
\( \rho_{\text{fluid}} \) = pore density

<table>
<thead>
<tr>
<th>Percentage (%)</th>
<th>Quartz</th>
<th>Illite</th>
<th>Plagioclase</th>
<th>Chlorite</th>
<th>Carbonate</th>
<th>Kaolinite</th>
<th>Smectite</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25.1</td>
<td>14.7</td>
<td>24.4</td>
<td>20.3</td>
<td>1.3</td>
<td>1.9</td>
<td>10.0</td>
<td>~2</td>
</tr>
</tbody>
</table>

\( \rho = 0.706(\text{CT#})+4.7 \)  
\( R^2 = 0.9963 \)

Lab measured porosity: 1.01%
CT estimated porosity: 1.03%

Difference: 1.9%
Relationship Between CT Number and Density for Several Materials:

- Glass:
  \[ \rho = 0.706 \times CT + 4.7 \]
  \[ R^2 = 0.9963 \]
- Quartz:
  \[ \rho = -0.03961 \times CT + 100 \]

CT Number
Density
Porosity
Quartz | Illite | Plagioclase | Chlorite | Carbonate | Kaolinite | Smectite | other
--- | --- | --- | --- | --- | --- | --- | ---
Percentage% | 25.1 | 14.7 | 24.4 | 20.3 | 1.3 | 1.9 | 10.0 | ~2

Effective Medium Theories for Multicomponent Poroelastic Composites

James G. Berryman

Abstract: It is demonstrated that effective medium theories for poroelastic composites such as rocks can be formulated easily by analogy to well-established methods used for elastic composites. An identity analogous to Eshelby's classic result has been derived previously for use in composites containing arbitrary ellipsoidal-shaped inclusions. This result is the starting point for new methods of estimation, including generalizations of the coherent potential approximation, differential effective medium theory, and two explicit schemes. Results are presented for estimating drained shear and bulk modulus, the Biot-Willis parameter, and Skempton's coefficient. Three of the methods considered appear to be quite reliable estimators, while one of the explicit schemes is found to have some undesirable characteristics. Furthermore, the results obtained show that the actual microstructure should be taken carefully into account when trying to decide which of these methods to apply in a given situation.


CE Database subject headings: Composite materials; Poroelasticity; Micromechanics; Poro media.

Effective bulk modulus with no porosity: 45.6 GPa
Effective shear modulus with no porosity: 28.4 GPa
Elastic Modulus for Each Voxel, when Porosity and End Members are Known

\[ v_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \]

\[ V_p = P \text{ wave velocity} \]
\[ K = \text{bulk modulus} \]
\[ \mu = \text{shear modulus} \]
\[ \rho = \text{density} \]
Finite Difference Method Solver: Sofi3D
Order in space: 8th
Order in time: 2nd
Source: 1Mhz Ricker

Lab measured $V_p$: 3 800 m/s  
CT estimated $V_p$: 3 526 m/s  
Difference: -6 %
Assumptions:
• all porosity is in fractures
• near planar fractures
Don’t Rock Physics models already explain this?
Don’t Rock Physics models already explain this?

- Not in the way we need them to...
- Consider adding porosity in a fracture, versus distributing it equally.

<table>
<thead>
<tr>
<th></th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>25.1</td>
</tr>
<tr>
<td>Illite</td>
<td>14.7</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>24.4</td>
</tr>
<tr>
<td>Chlorite</td>
<td>20.3</td>
</tr>
<tr>
<td>Carbonate</td>
<td>1.3</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>1.9</td>
</tr>
<tr>
<td>Smectite</td>
<td>10.0</td>
</tr>
<tr>
<td>other</td>
<td>~2</td>
</tr>
</tbody>
</table>
Assumptions
All increases in porosity is randomly distributed
Single-voxel-shaped pores added

Porosity:
1% (original)

Porosity:
3%

Porosity:
5%

Porosity:
10%

Porosity:
15%

Porosity:
22%

All slices
1cm x 1cm

Density:
0 1000 2000 3000 4000 Kg/m³
Assumptions
Two planes added
All increases in porosity is distributed near fracture planes
Single-voxel-shaped pores added
Results

P wave velocity as a function of porosity with several pore types

- MHS-Upper
- Voigt bound
- Reuss bound
- VRH bound
- Initial model

Porosity (%)
P wave velocity (m/s)
Results

P wave velocity as a function of porosity with several pore types

- MHS-Upper
- Voigt bound
- Reuss bound
- VRH bound
- Initial model
- Randomly assigned pore space
Results

Porosity: 1.01%

randomly assigned
Results

P wave velocity as a function of porosity with several pore types

- MHS-Upper
- Voigt bound
- Reuss bound
- VRH bound
- Initial model
- Randomly assigned pore space
- Planar pore space
Results

Porosity: 1.01%

randomly assigned planar
Results

P wave velocity as a function of porosity with several pore types

- MHS-Upper
- Voigt bound
- Reuss bound
- VRH bound
- Initial model
- Randomly assigned pore space
- Planar pore space
- Hybrid pore space
Results

Porosity: 1.01%

randomly assigned planar hybrid
Discussion:

- Better understanding of pore types

Porosity:
- Original: 1%
- Added as specks: 2%
- Added as fractures: 2%
- Added as hybrid: 2%
Discussion:

• Better understanding of pore types
• Different shaped pores possible
• Other ways to model fractures also possible

<table>
<thead>
<tr>
<th>Term</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical</td>
<td><img src="image" alt="Cylindrical" /></td>
</tr>
<tr>
<td>Discoidal</td>
<td><img src="image" alt="Discoidal" /></td>
</tr>
<tr>
<td>Spherical</td>
<td><img src="image" alt="Spherical" /></td>
</tr>
<tr>
<td>Tabular</td>
<td><img src="image" alt="Tabular" /></td>
</tr>
<tr>
<td>Ellipsoidal</td>
<td><img src="image" alt="Ellipsoidal" /></td>
</tr>
<tr>
<td>Equant</td>
<td><img src="image" alt="Equant" /></td>
</tr>
<tr>
<td>Irregular</td>
<td><img src="image" alt="Irregular" /></td>
</tr>
</tbody>
</table>

http://earthsci.org/mineral/rockmin/sed/sed.html
Discussion:

- Better understanding of pore types
- Different shaped pores possible
- Other ways to model fractures also possible

- Same type of modeling can be used with Resistivity

Figure 12. Line 2 surveys at Rivendell hillslope with Lines 10 and 11 intersecting. Seismic
Discussion:
• Better understanding of pore types
• Different shaped pores possible
• Other ways to model fractures also possible
• Identical modeling can be used with Resistivity
• Testing this many physical rocks would take MONTHS; however, a few additional samples would be helpful.
Conclusion
• Solving wave velocity from digital rocks is a big step.
• The next step is using digital rock physics to help us understand data poor environments, by creating new data from base case information.
• This type of modelling can extend with many types of geophysical methods.
• Mountainous environments are complex 3D systems that may never be fully mapped with physical samples.