Fractured Bedrock Hydrogeologic Characterization Using Digital Rock Physics*

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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.

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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

Maupin, M. A., Kenny, J. F., Hutson, S. S., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2014). US Geological Survey.

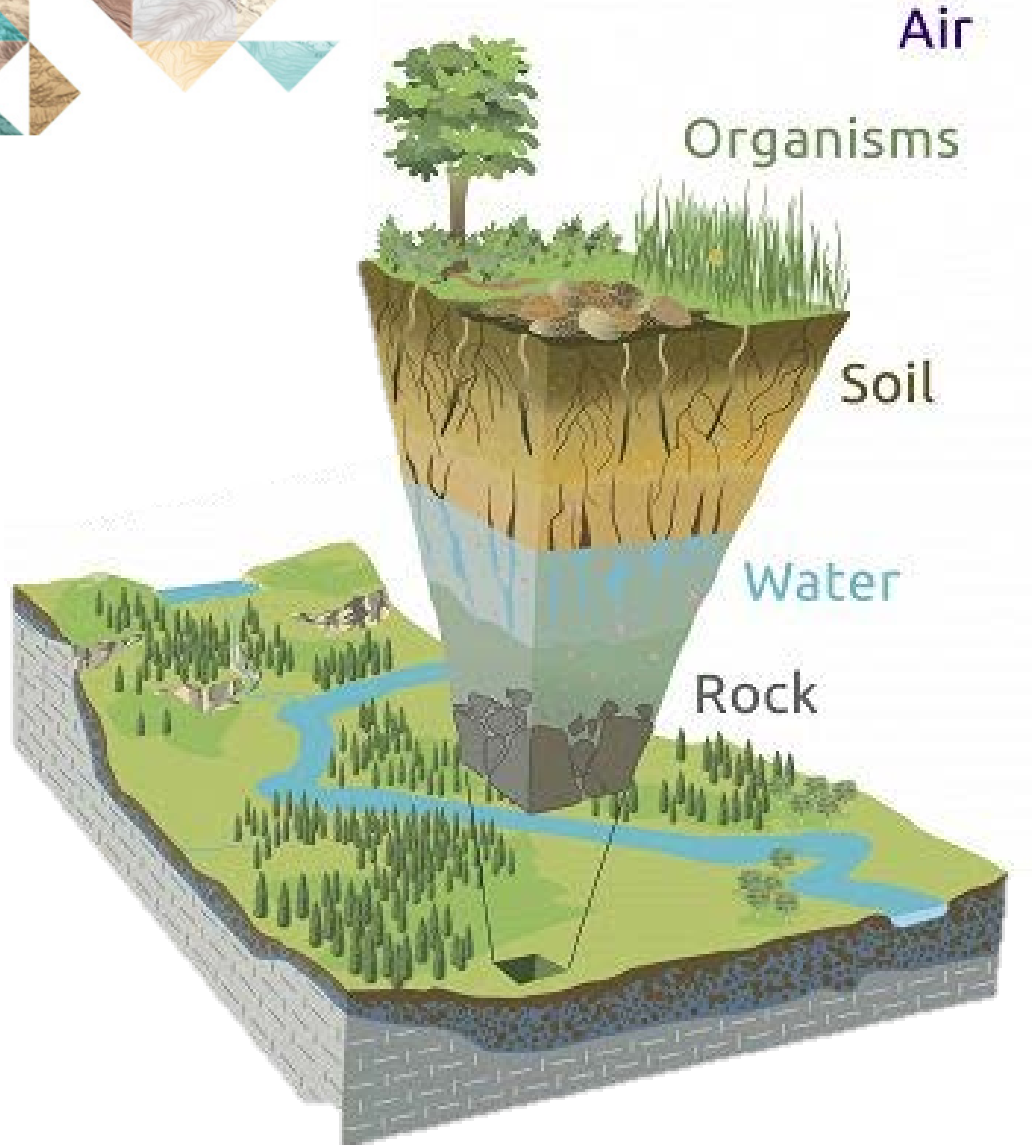
- For day to day consumption of water:
  - 37% of the U.S. population relies on groundwater
  - 50 million Americans rely on the Colorado River basin
- No realistic maps of porosity or permeability of the USA

Problem:

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

Source: Google Earth

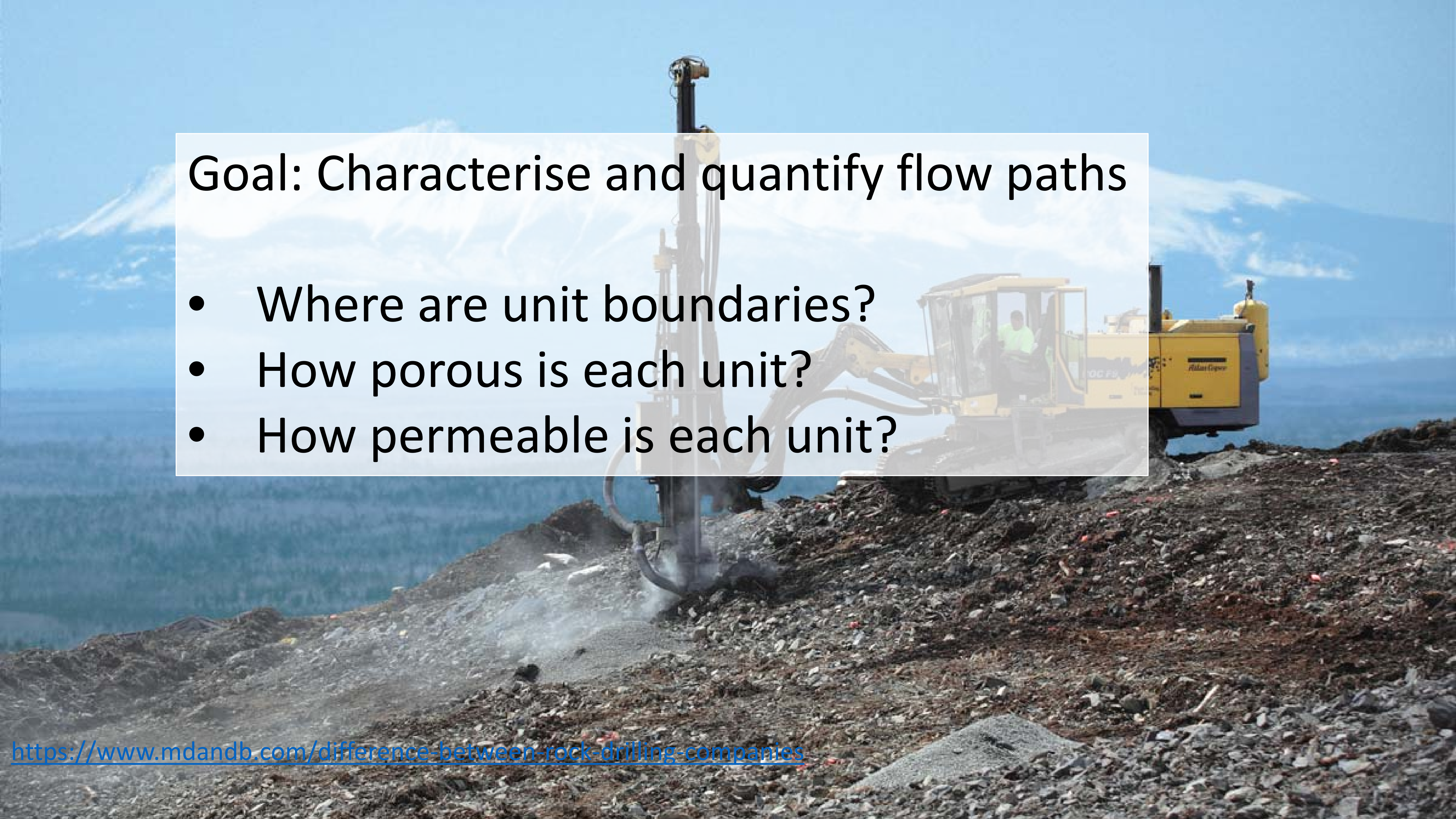
Maupin, M. A., Kenny, J. F., Hutson, S. S., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2014). US Geological Survey.



A 1D model of regions contained in the "critical zone"

http://criticalzone.org/national/research/the-critical-zone-1national/

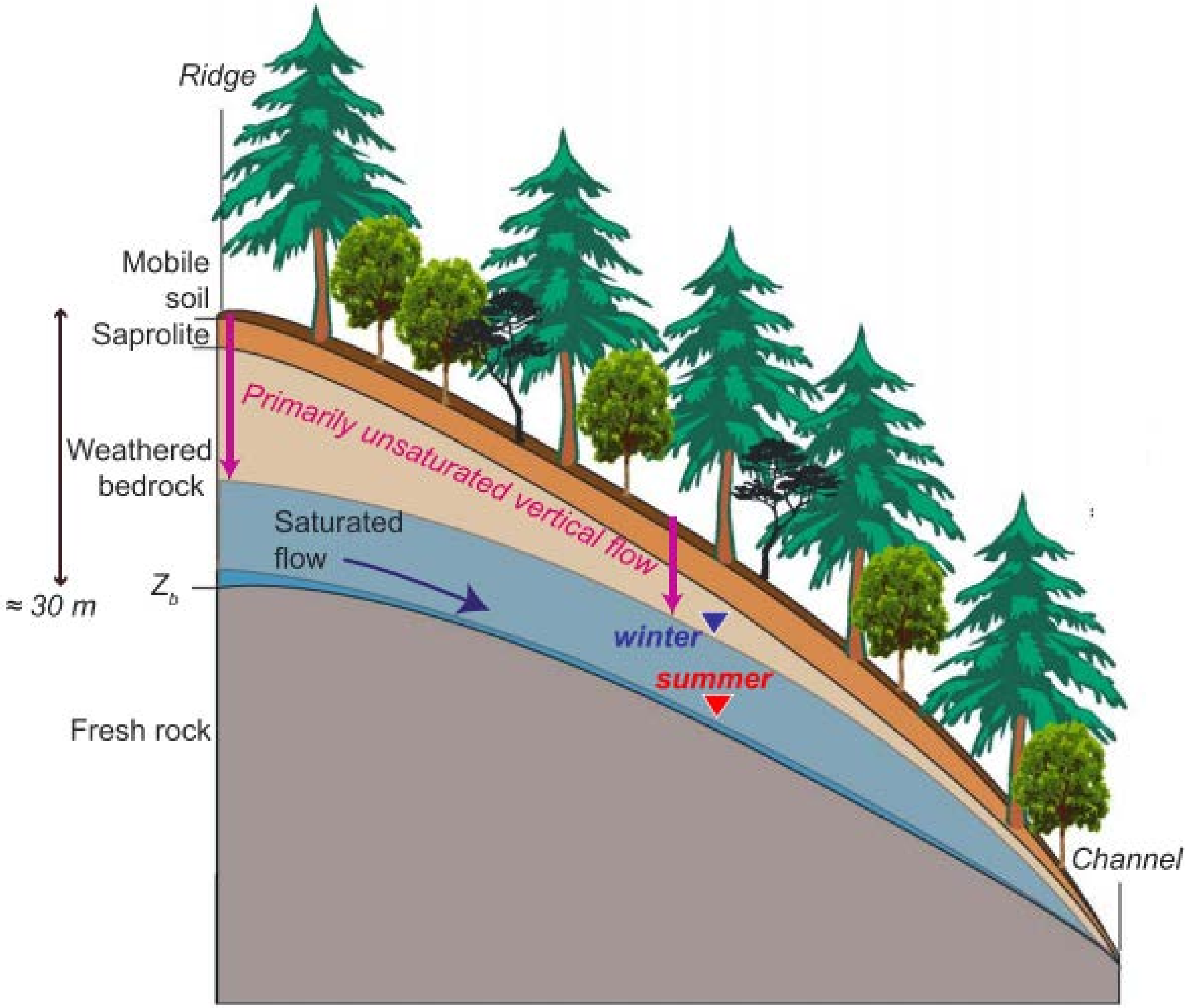
https://www.mdandb.com/difference-between-rock-drilling-companies



Goal: Characterise and quantify flow paths

- Where are unit boundaries?
- How porous is each unit?
- How permeable is each unit?

https://www.mdandb.com/difference-between-rock-drilling-companies

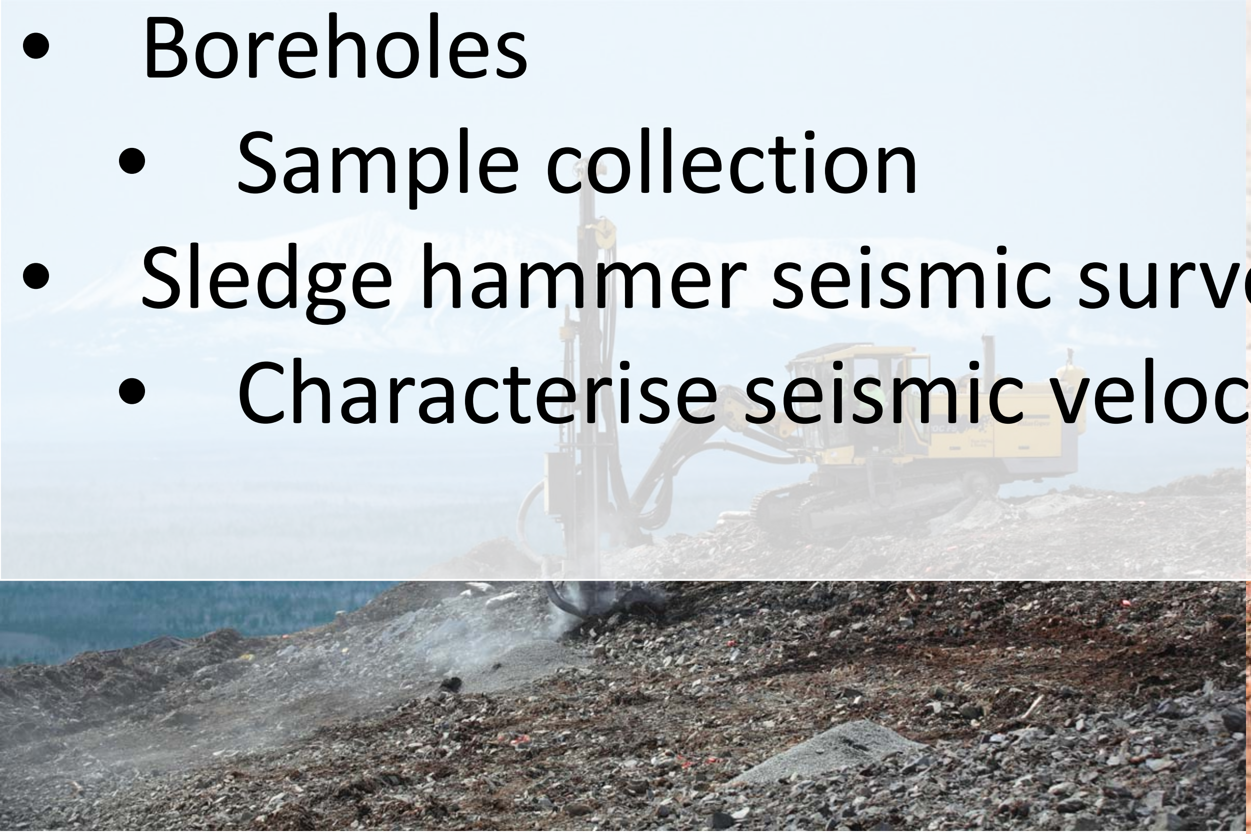


Surface topography does not necessarily tell us much about flow paths

Hahm, W. J., Rempe, D. M., Dralle, D. N., Dawson, T. E., Lovill, S. M., Bryk, A. B., & Dietrich, W. E. 2019. *Water Resources Research*.

Tools:

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



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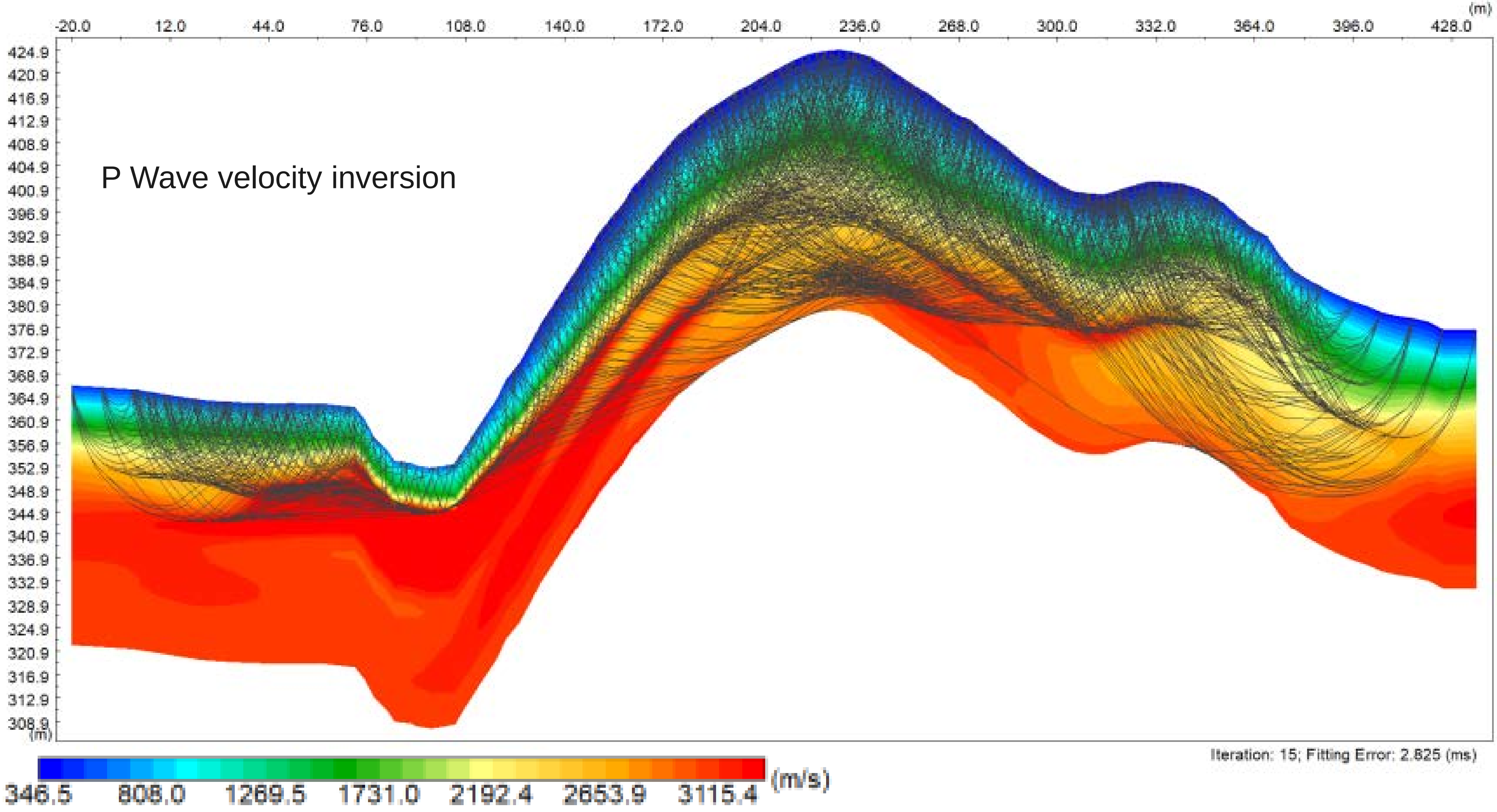

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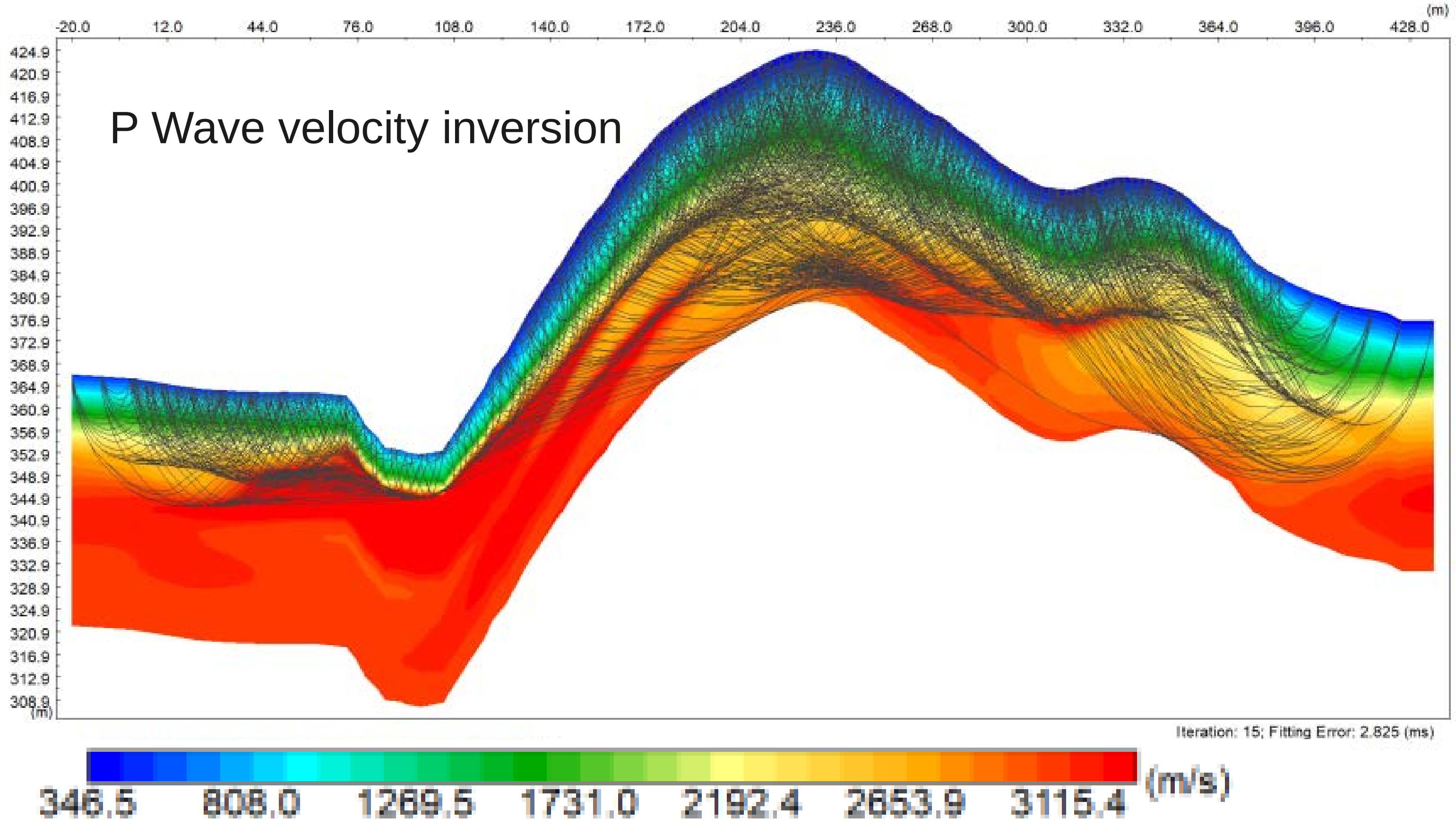

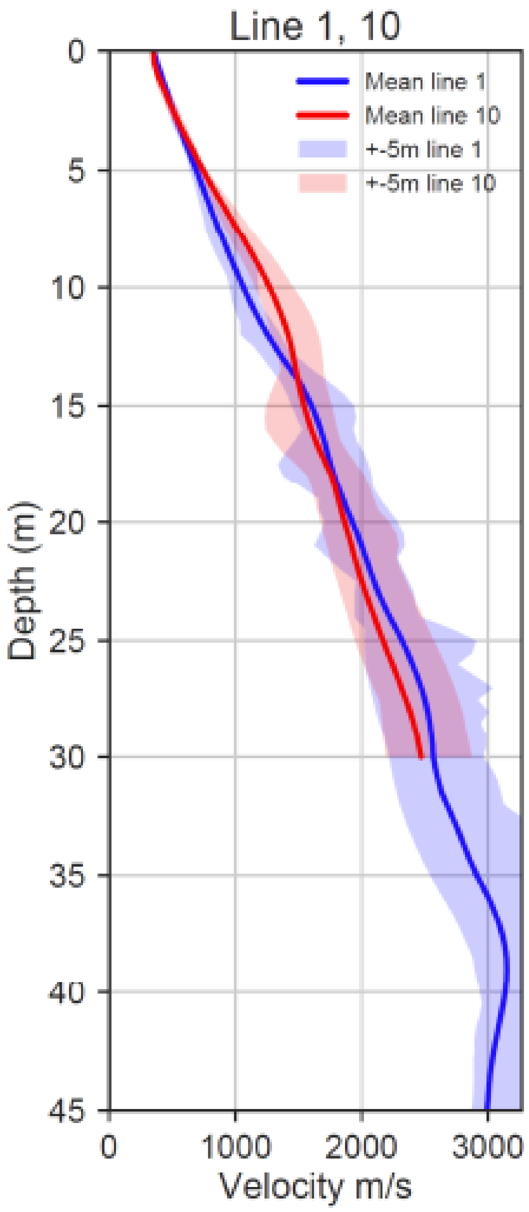

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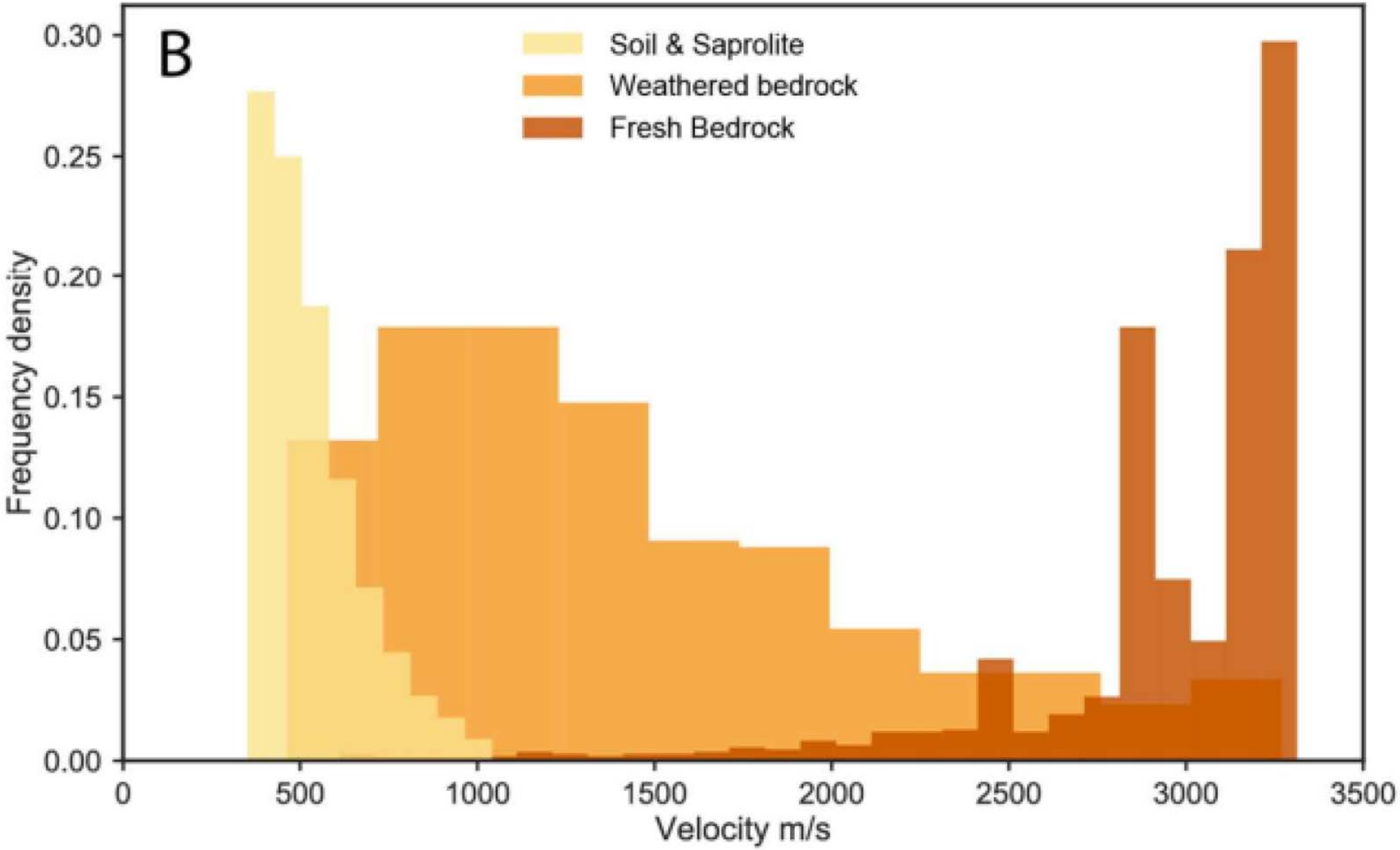

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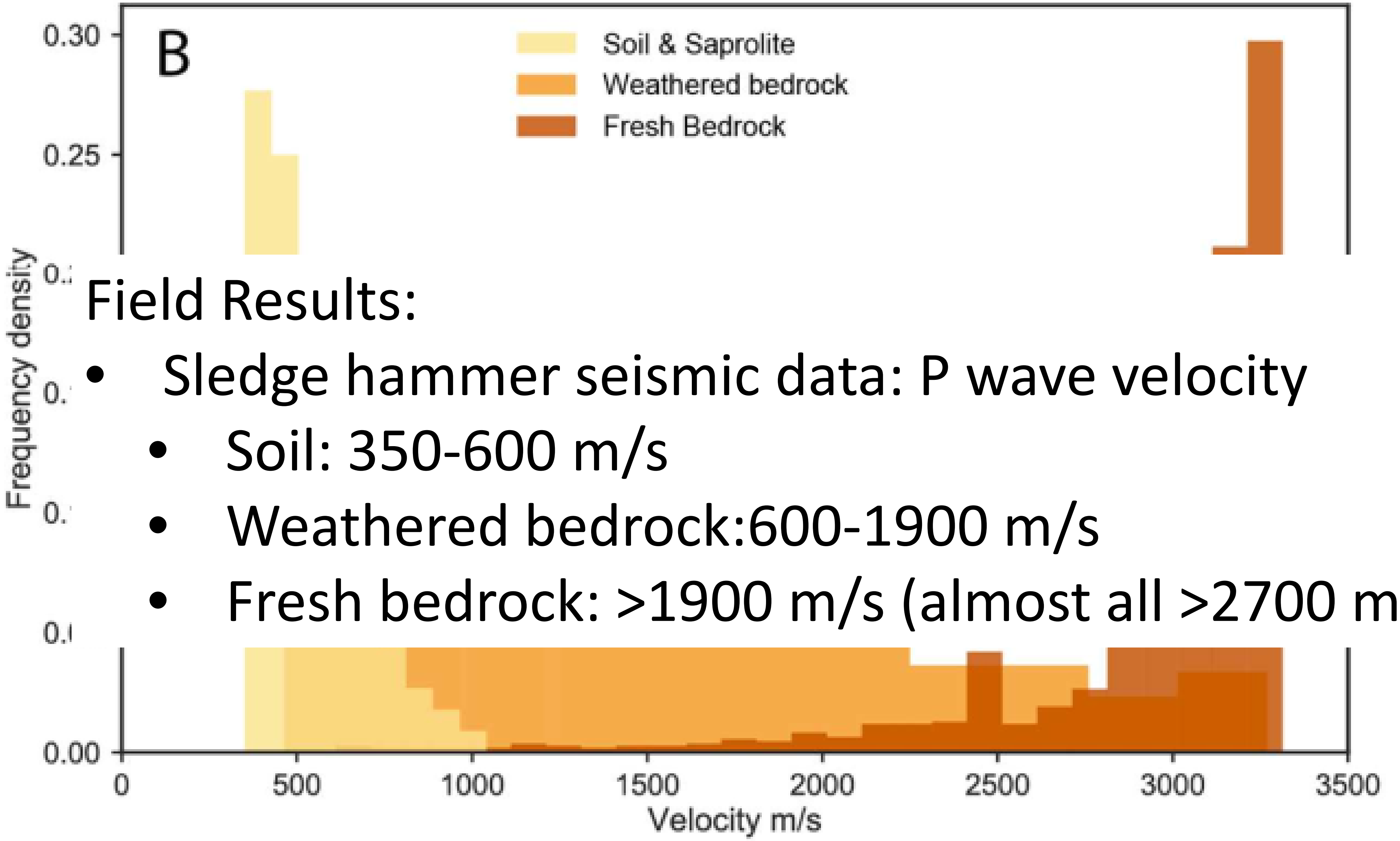
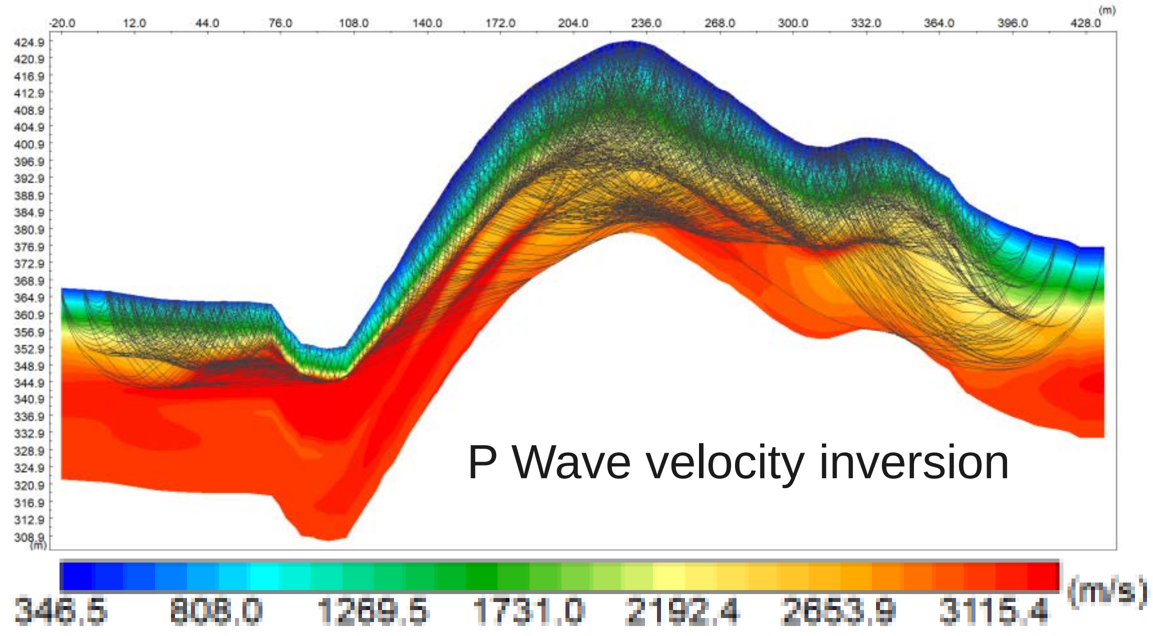
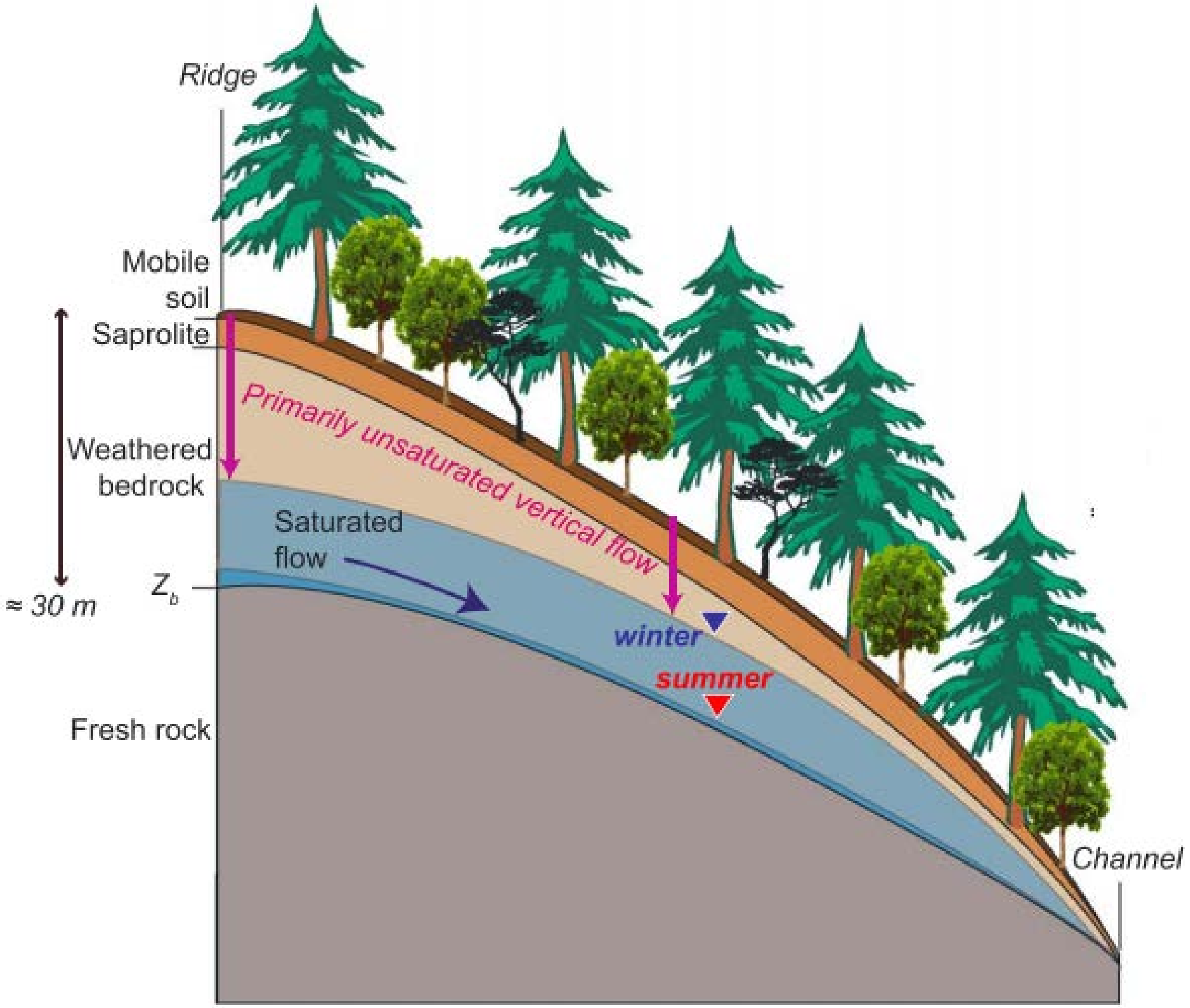


Field Results:

- 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)

Lee, Shawn S. *Master's Dissertation*. 2018.





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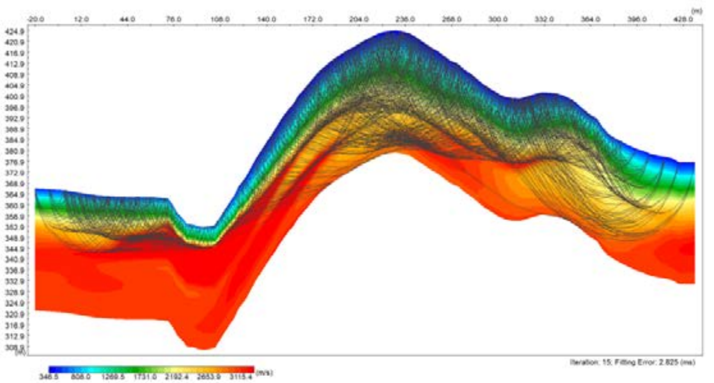
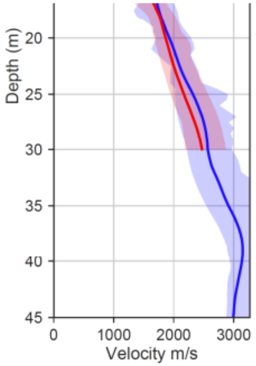
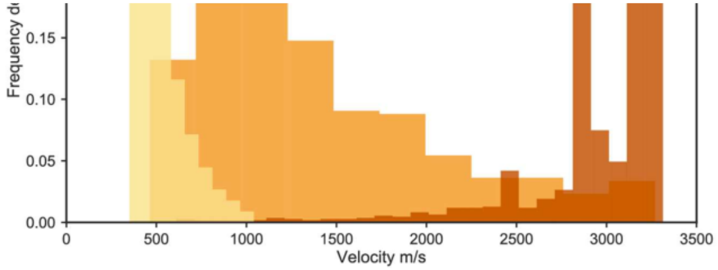
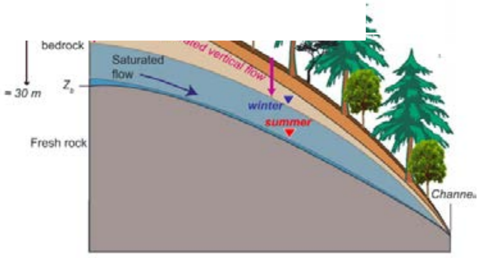
What happens if we don’t have a data rich environment? (i.e. most environments?)

- P velocity > 5 km/s is probably not porous at all
- P velocity <500 m/s is probably very porous



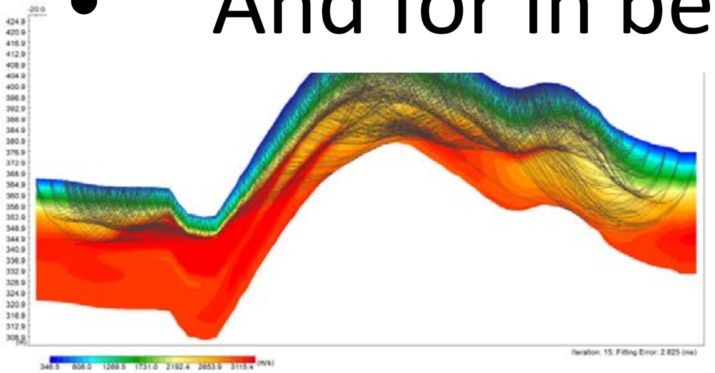


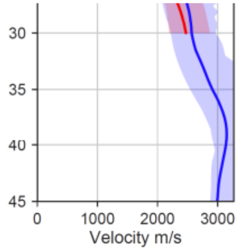


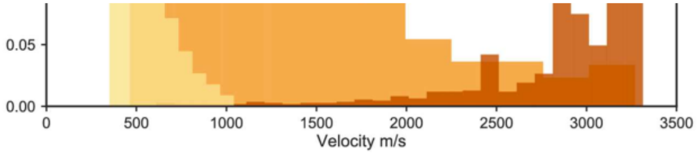


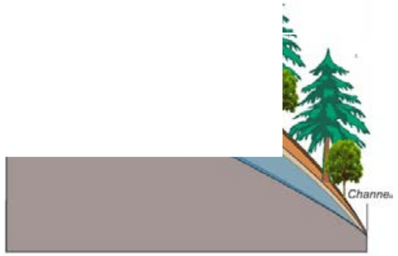
What happens if we don’t have a data rich environment? (i.e. most environments?)

- P velocity > 5 km/s is probably not porous at all
- P velocity <500 m/s is probably very porous
- And for in between….?



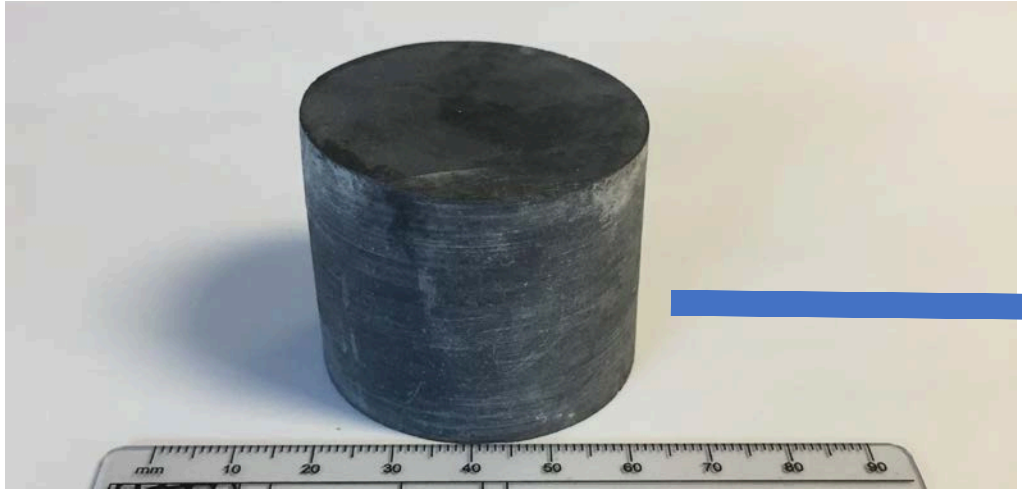


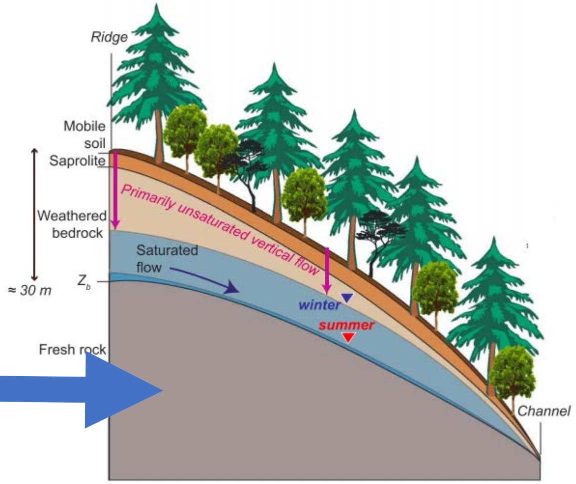


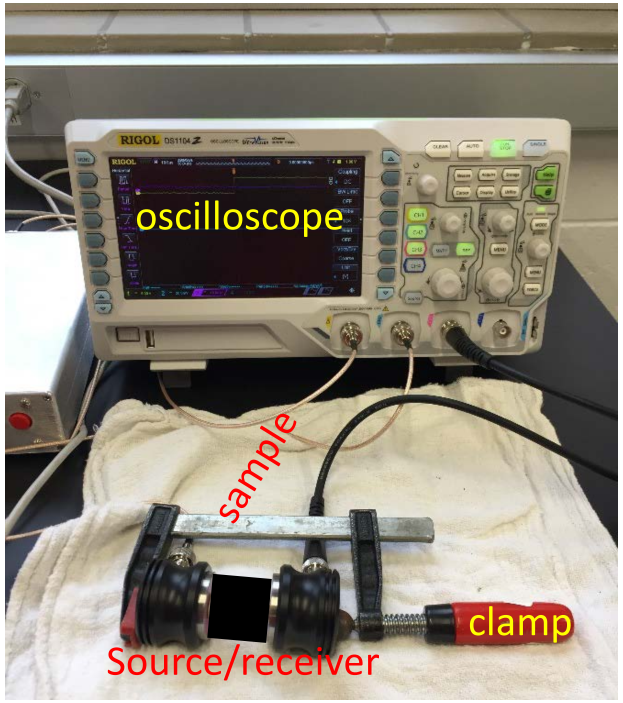


Ground truth:

A piece of unweathered shale bedrock.



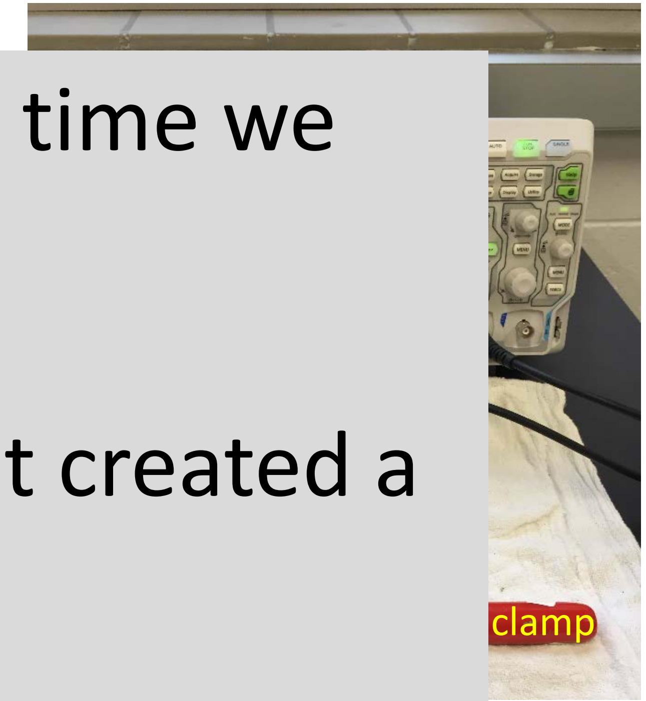




Ground truth: Laboratory testing

Density: 2 653 kg/m^3
Porosity: 1.01%
Ultrasonic Velocity: V_P =3 800 m/s

	Quartz	Illite	Plagioclase	Chlorite	Carbonate	Kaolinite	Smectite	other
Percentage%	25.1	14.7	24.4	20.3	1.3	1.9	10.0	~2



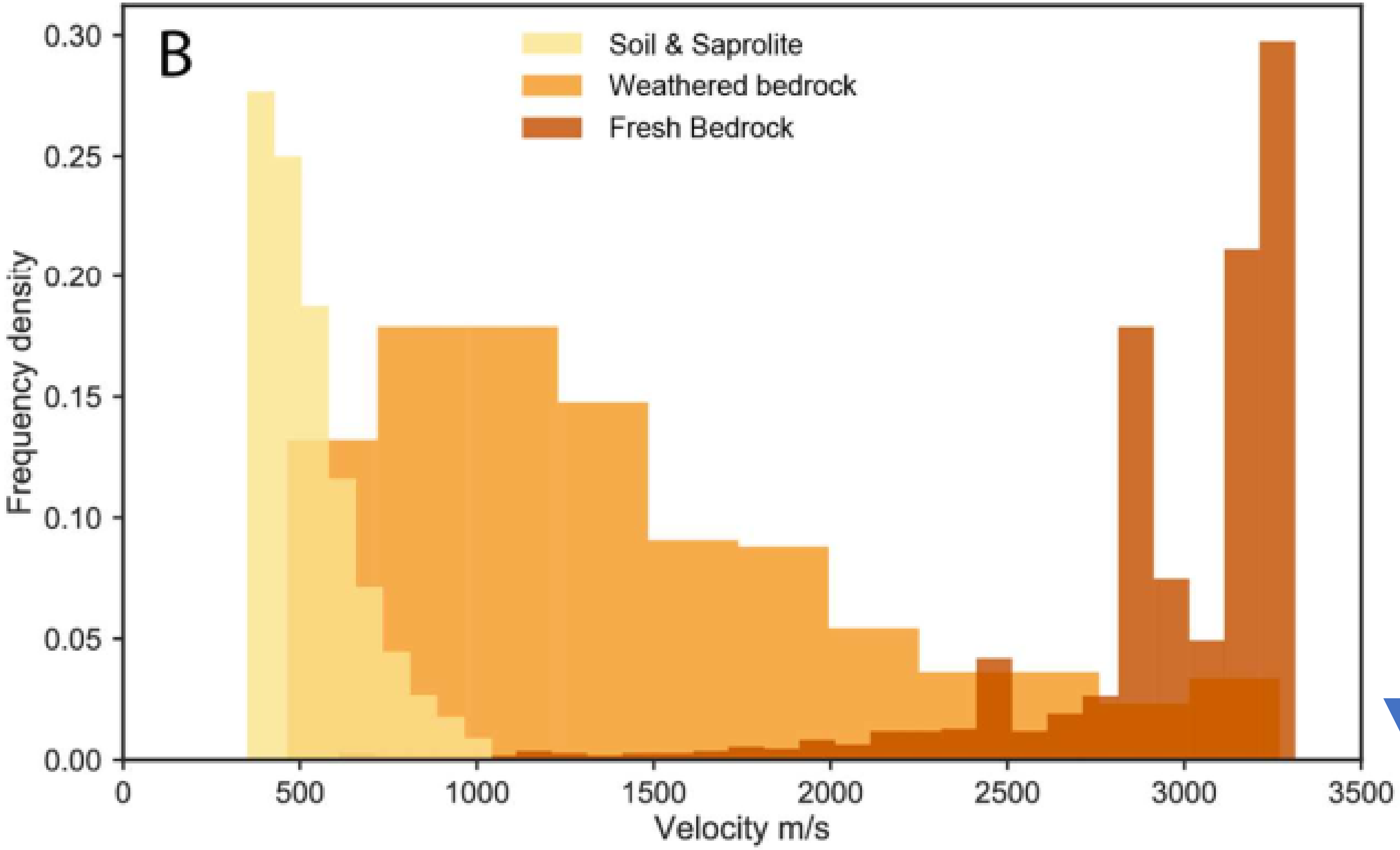
Preparing this rock was challenging. Every time we sawed it wet it would crumble.

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

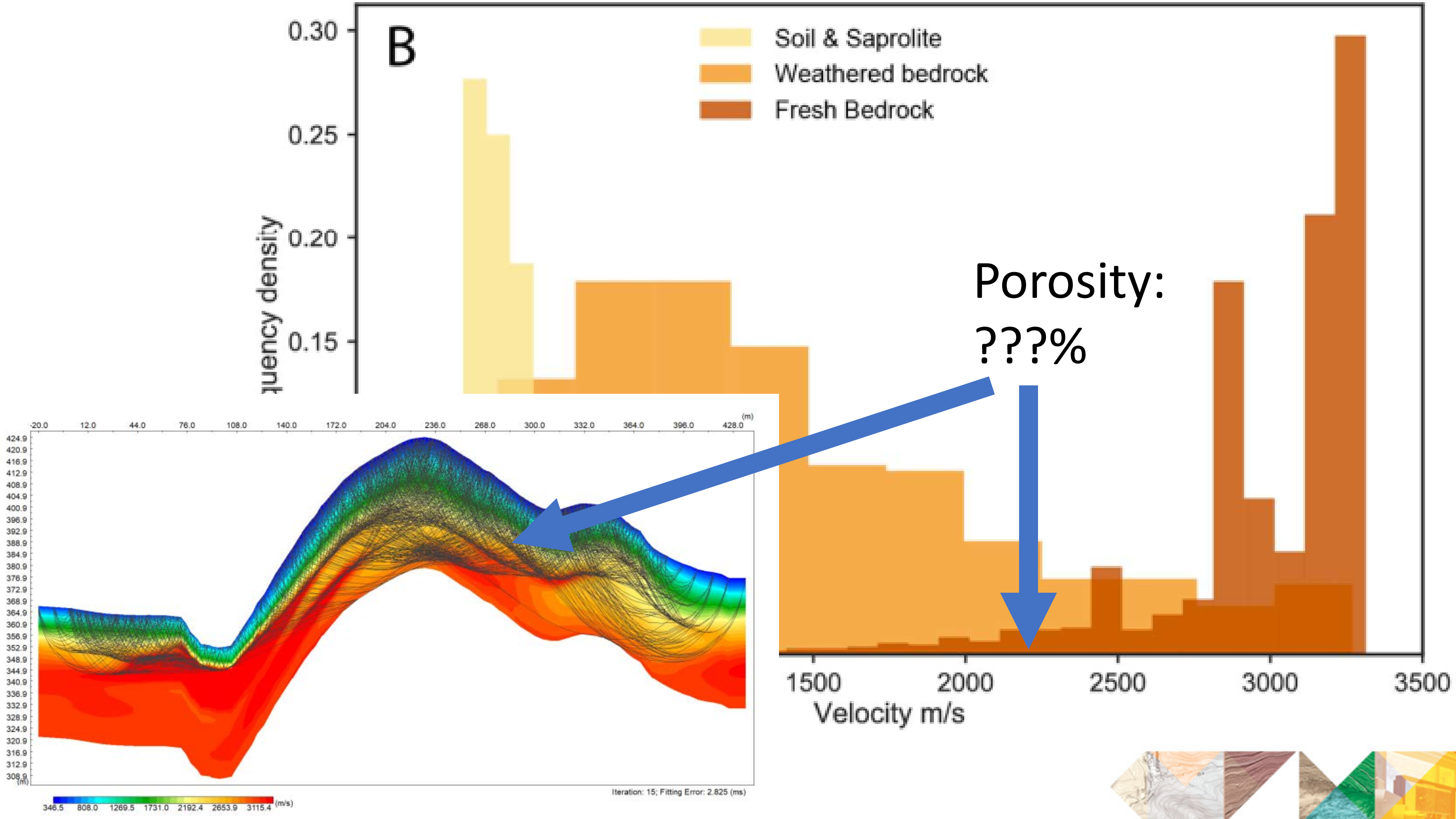
To grind the sample, it had to be done with kerosene as water would cause the clay to swell and the sample would crumble.

Total laboratory time for prep and testing: ~4 hours

Percer

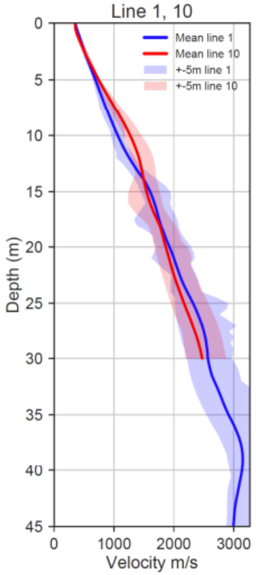


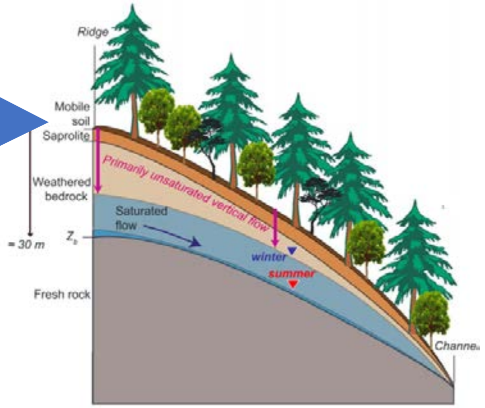
Porosity:
1.01%


B
Soil & Saprolite
Weathered bedrock
Fresh Bedrock
0.30
0.25
0.20
0.15
1500
2000
2500
3000
3500
Velocity m/s
Iteration: 15; Fitting Error: 2.825 (ms)

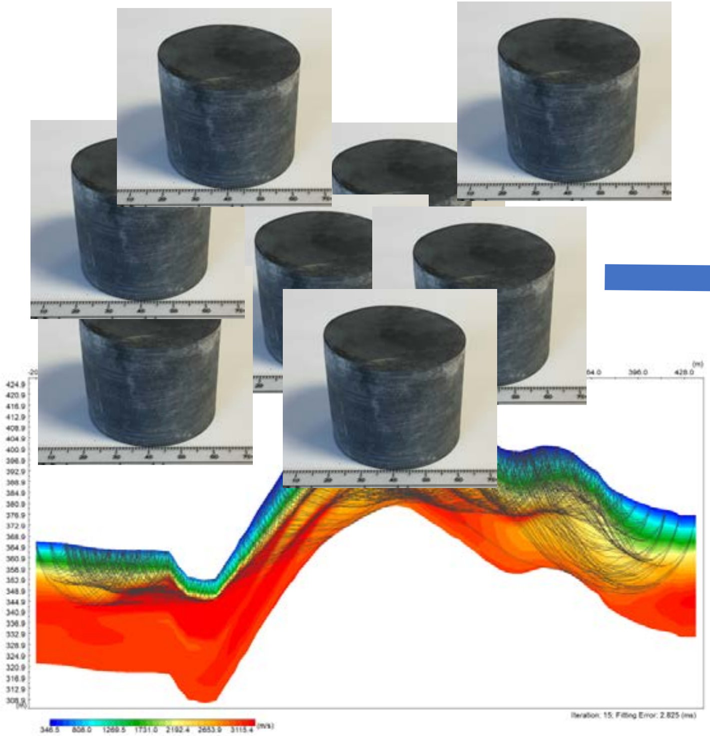
Porosity:
???%

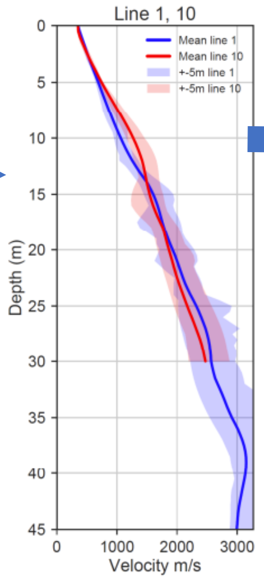
How to characterize an environment in a data rich way:

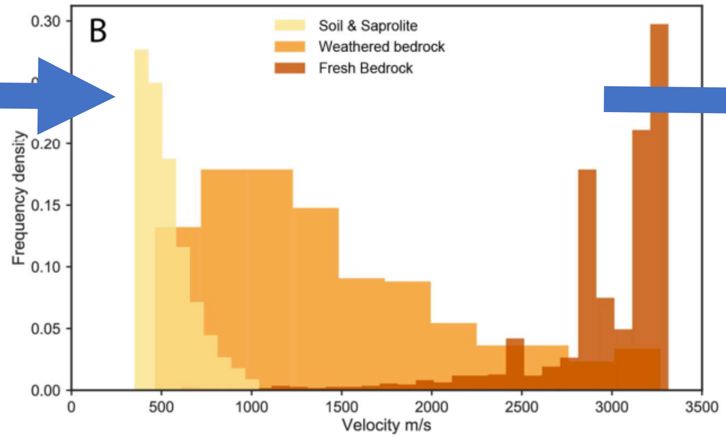


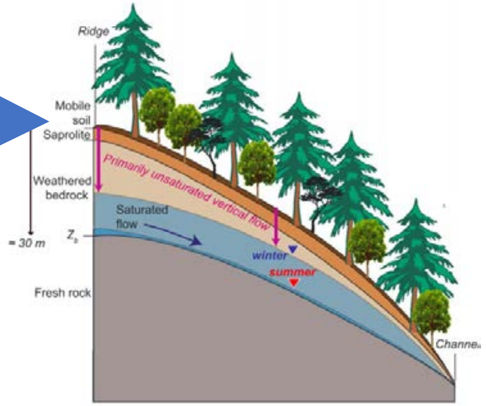


How to characterize an environment with a budget:

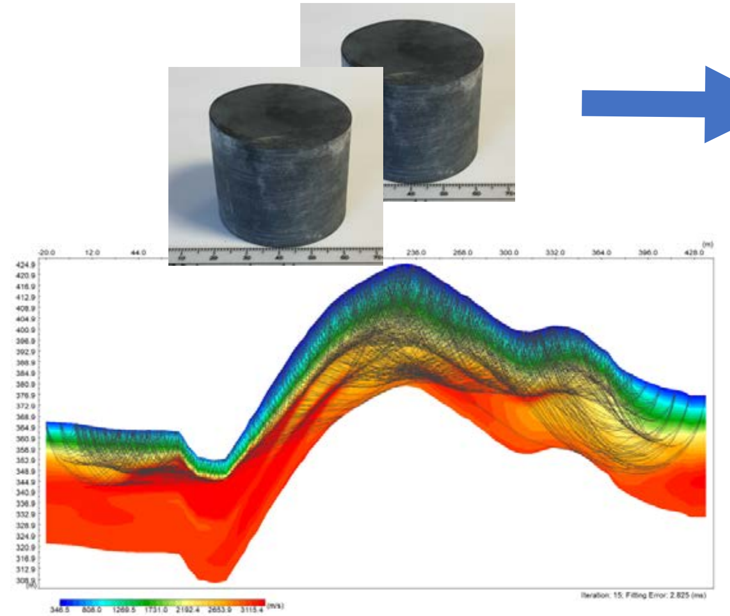




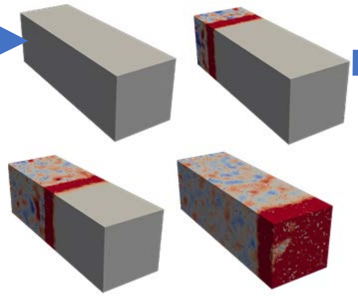


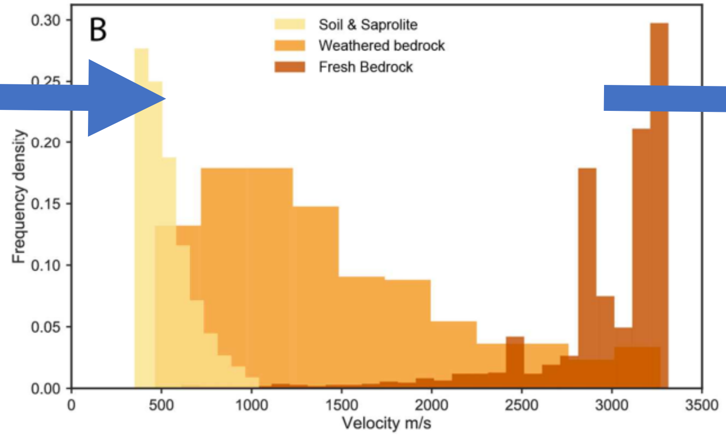


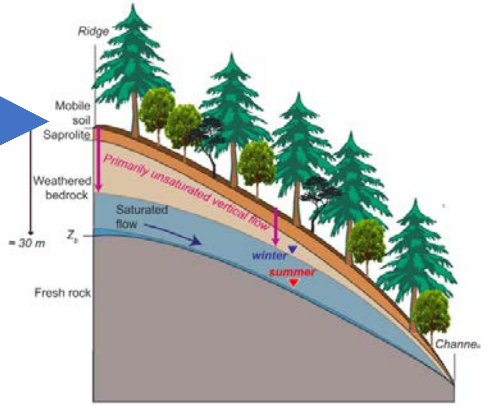
How to characterize an environment with Digital Rock Physics :

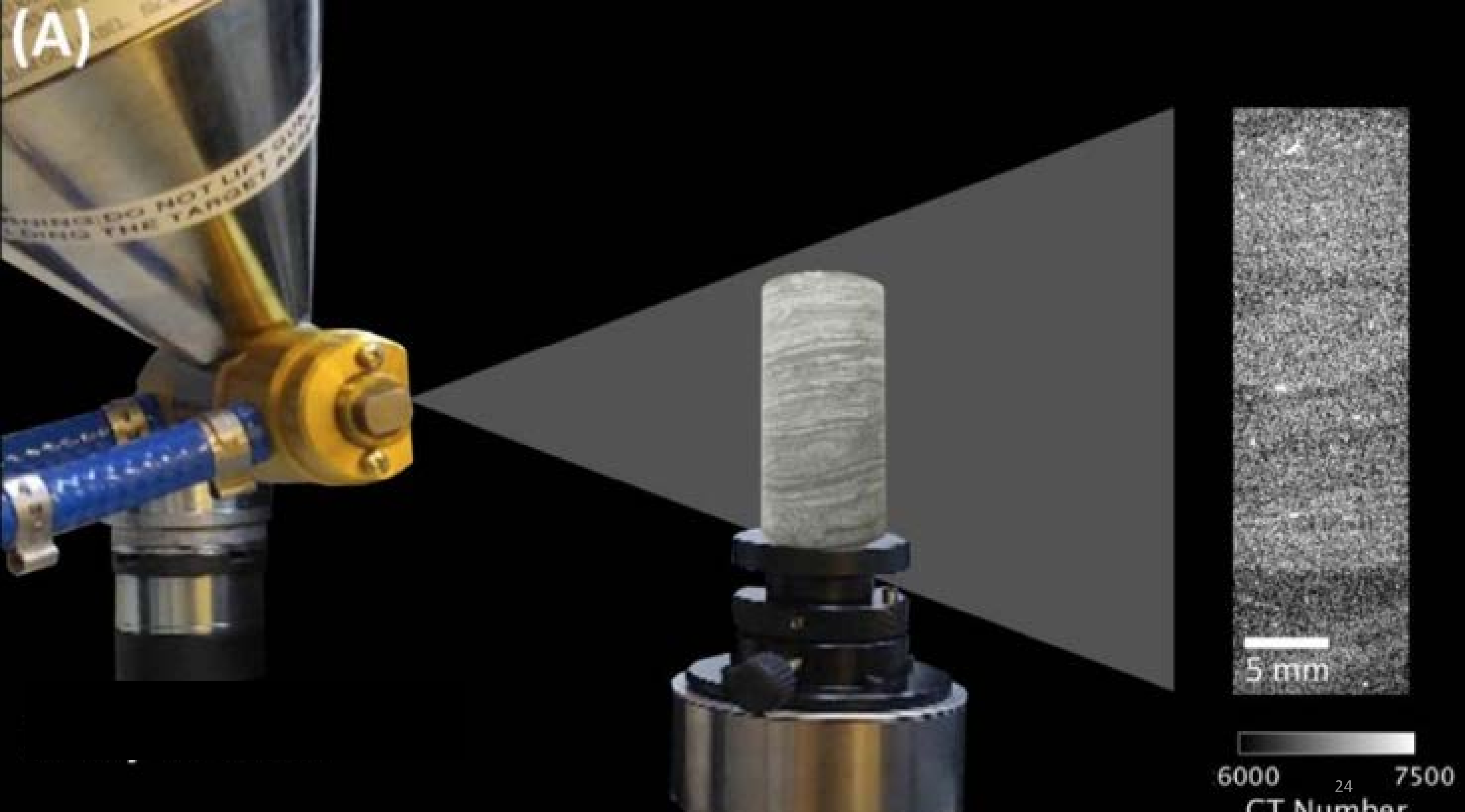


DRP









Ramos, Espinoza, Goldfarb, Tisato, Laubach, Torres-Verdín, 2018, *Geophysical Journal International*

Ramos, Espinoza, Goldfarb, Tisato, Laubach, Torres-Verdín. 2018. *Geophysical Journal International*

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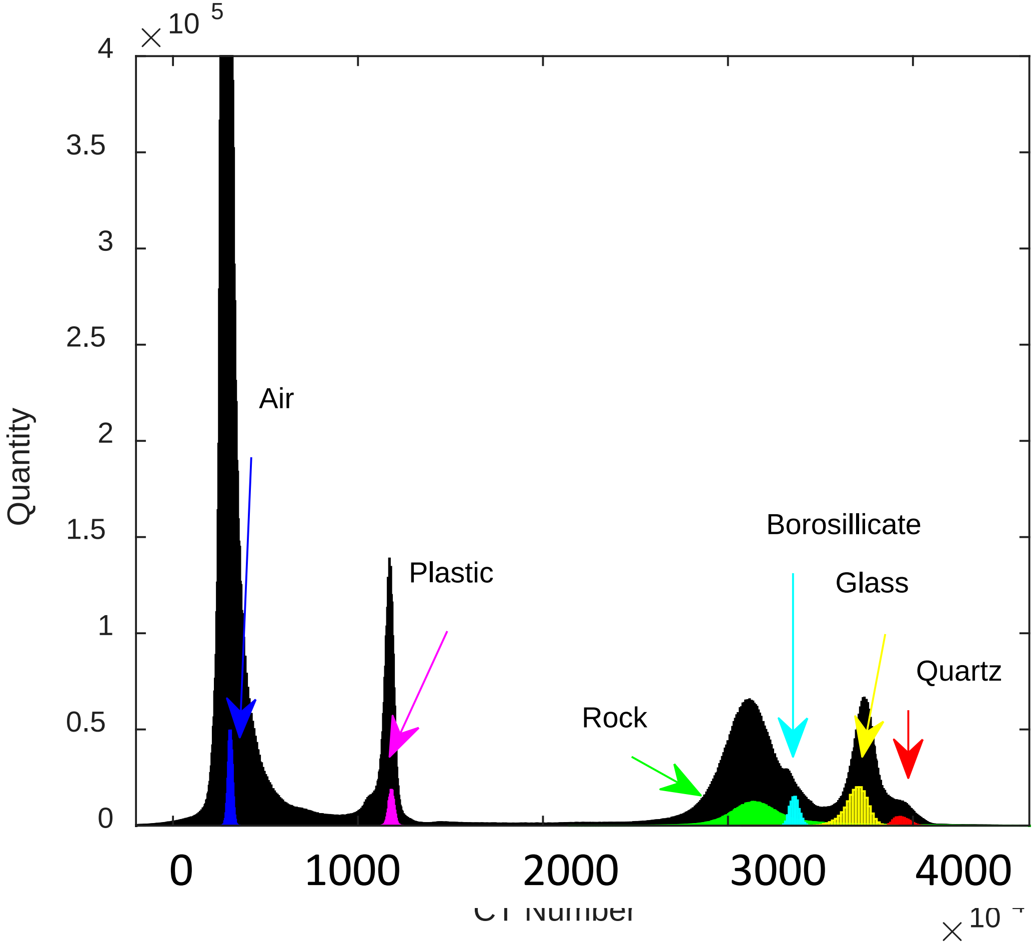
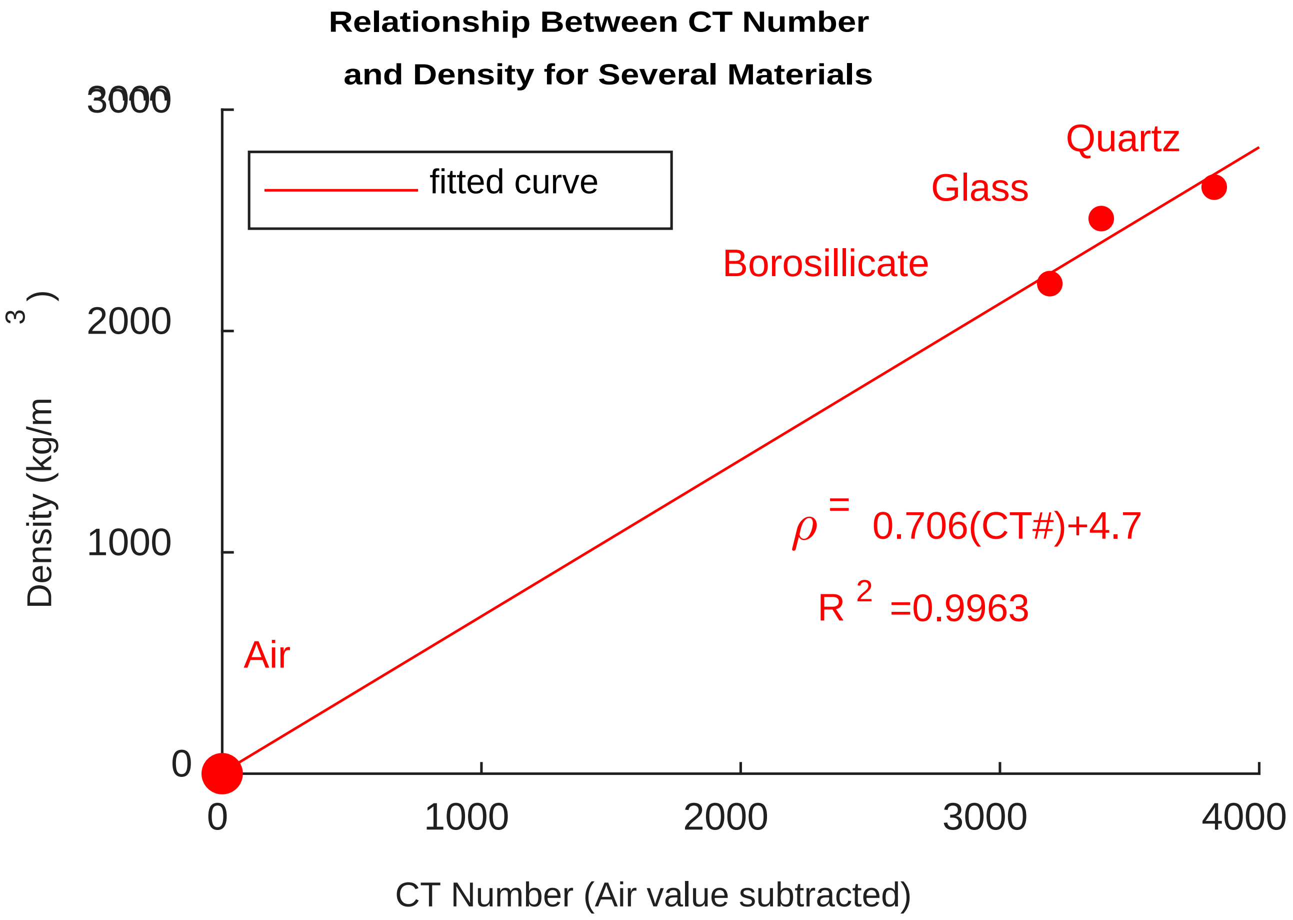
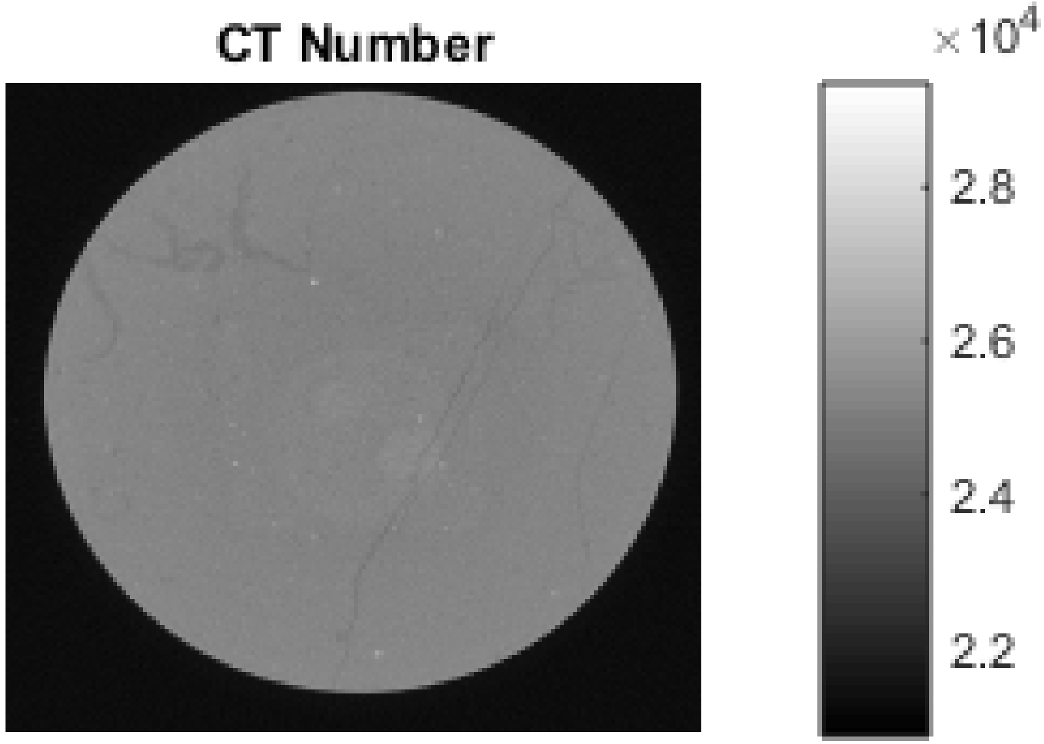
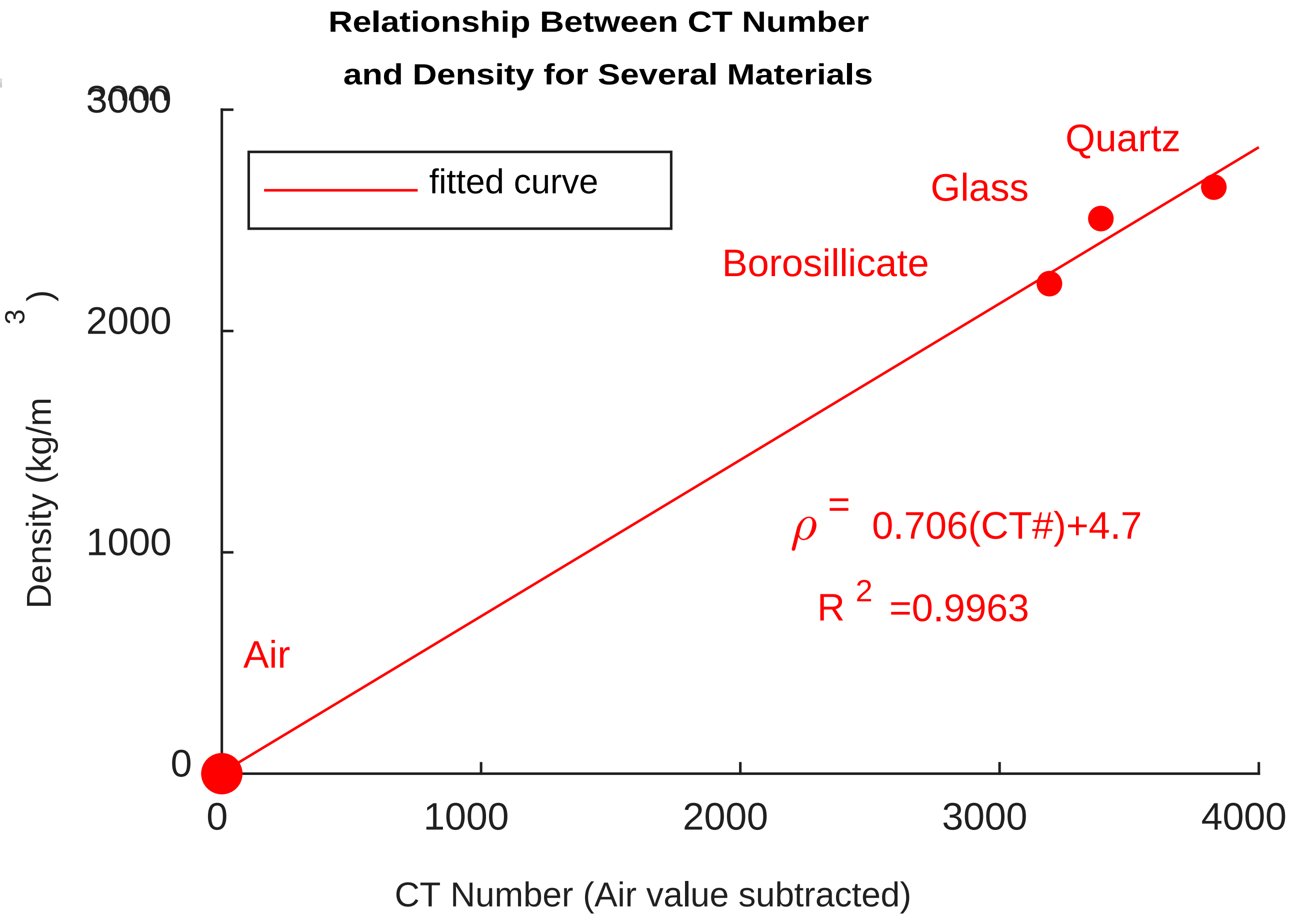


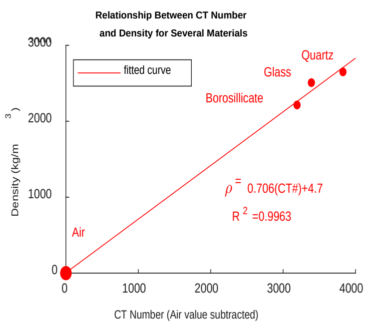
×10 5
4
3.5
3
2.5
2
1.5
1
0.5
0
Quantity
Air
Plastic
Rock
Borosillicate
Glass
Quartz
0
1000
2000
3000
4000
CT Number
×10 4



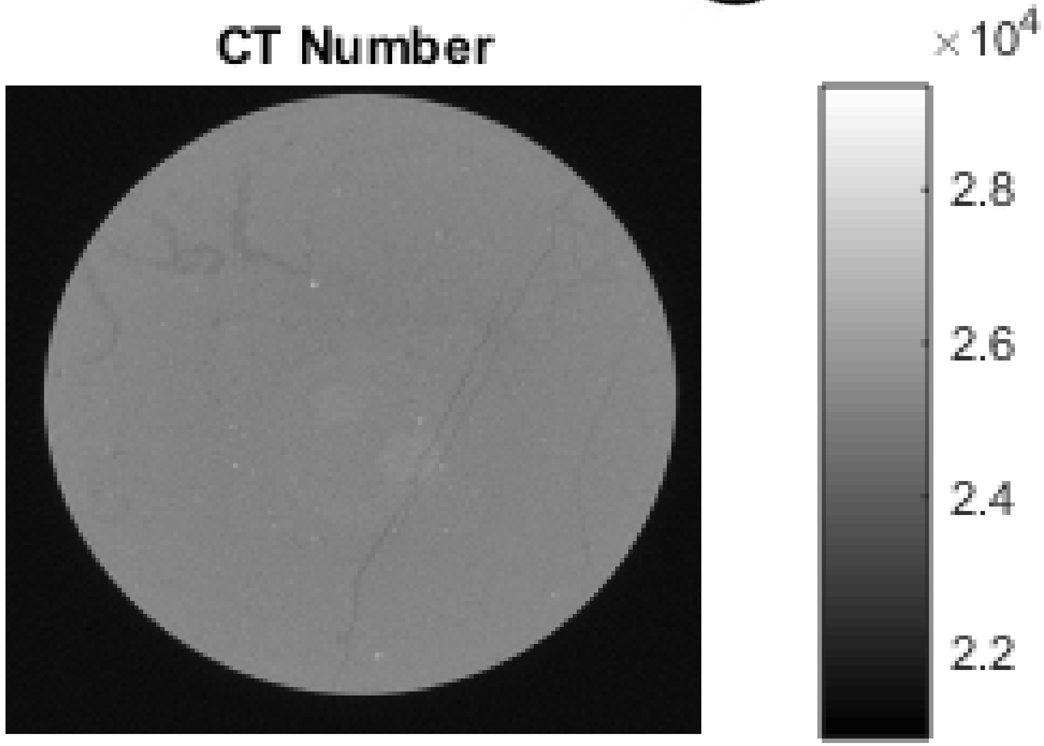
Relationship Between CT Number
and Density for Several Materials
3000
2000
1000
0
Density (kg/m 3)
fitted curve
Quartz
Glass
Borosillicate
Air
ρ = 0.706(CT#)+4.7
R 2 =0.9963
0
1000
2000
3000
4000
CT Number (Air value subtracted)


CT Number
×10^4
2.8
2.6
2.4
2.2

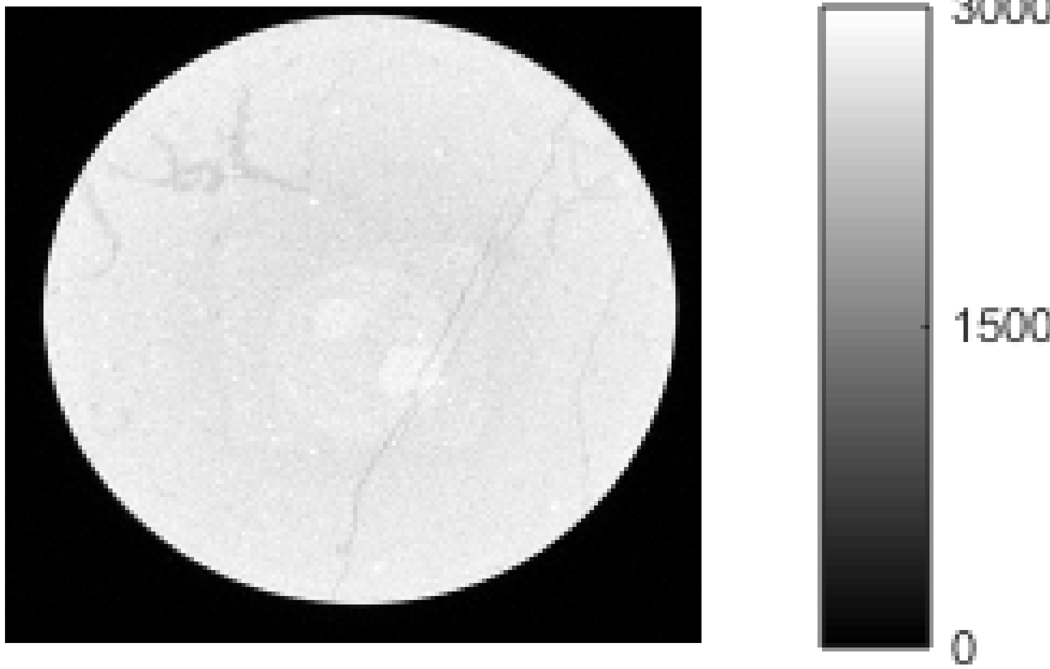

Relationship Between CT Number
and Density for Several Materials
fitted curve
Quartz
Glass
Borosillicate
Air
ρ = 0.706(CT#)+4.7
R 2 =0.9963
Density (kg/m 3)
3000
2000
1000
0
0
1000
2000
3000
4000
CT Number (Air value subtracted)



CT Number



Density, (Kg/m^3)



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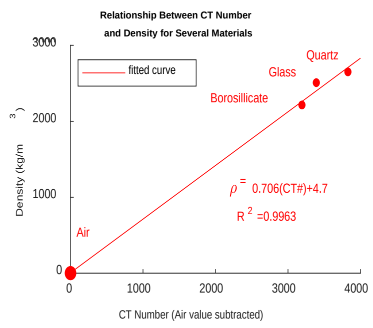

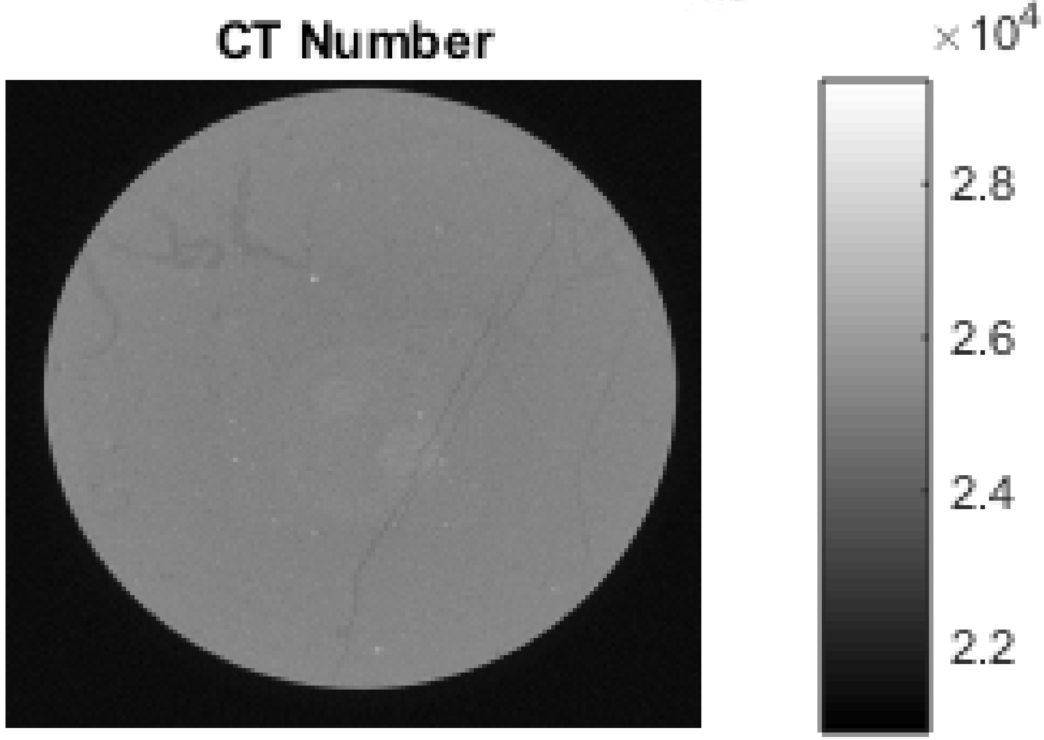

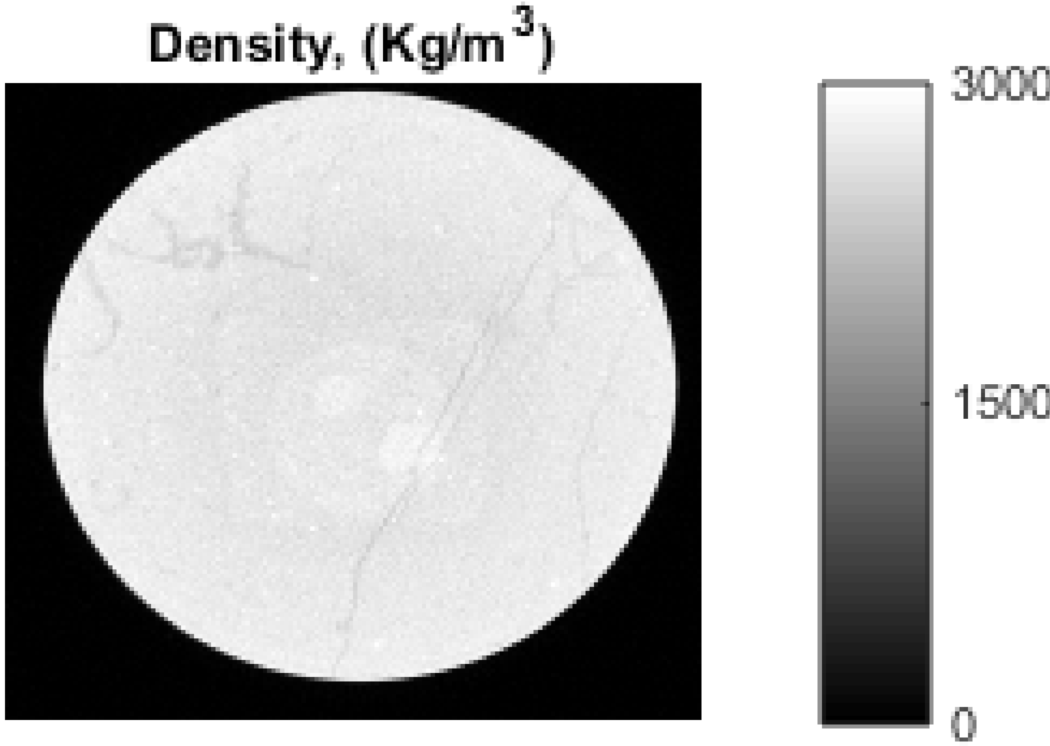

Lab measured density: 2 653 kg/m^3

CT estimated density: 2 608 kg/m^3

Difference:1.7%

$$\phi = \frac{\rho_{frame} - \rho_{voxel}}{\rho_{frame} - \rho_{fluid}}$$

ϕ = porosity
ρ_{frame} = frame density
ρ_{voxel} = voxel density
ρ_{fluid} = pore density

Savre, and Burke. *SPWLA 4th Annual Logging Symposium*. 1963.

	Quartz	Illite	Plagioclase	Chlorite	Carbonate	Kaolinite	Smectite	other
Percentage%	25.1	14.7	24.4	20.3	1.3	1.9	10.0	~2

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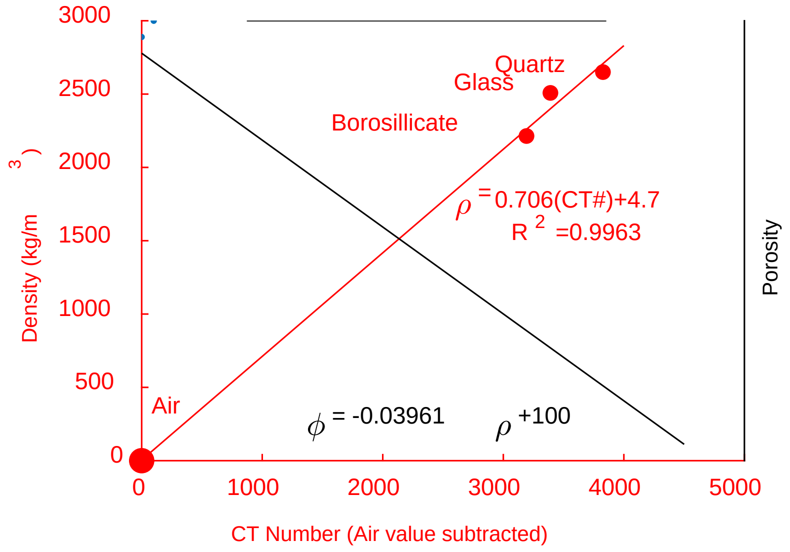
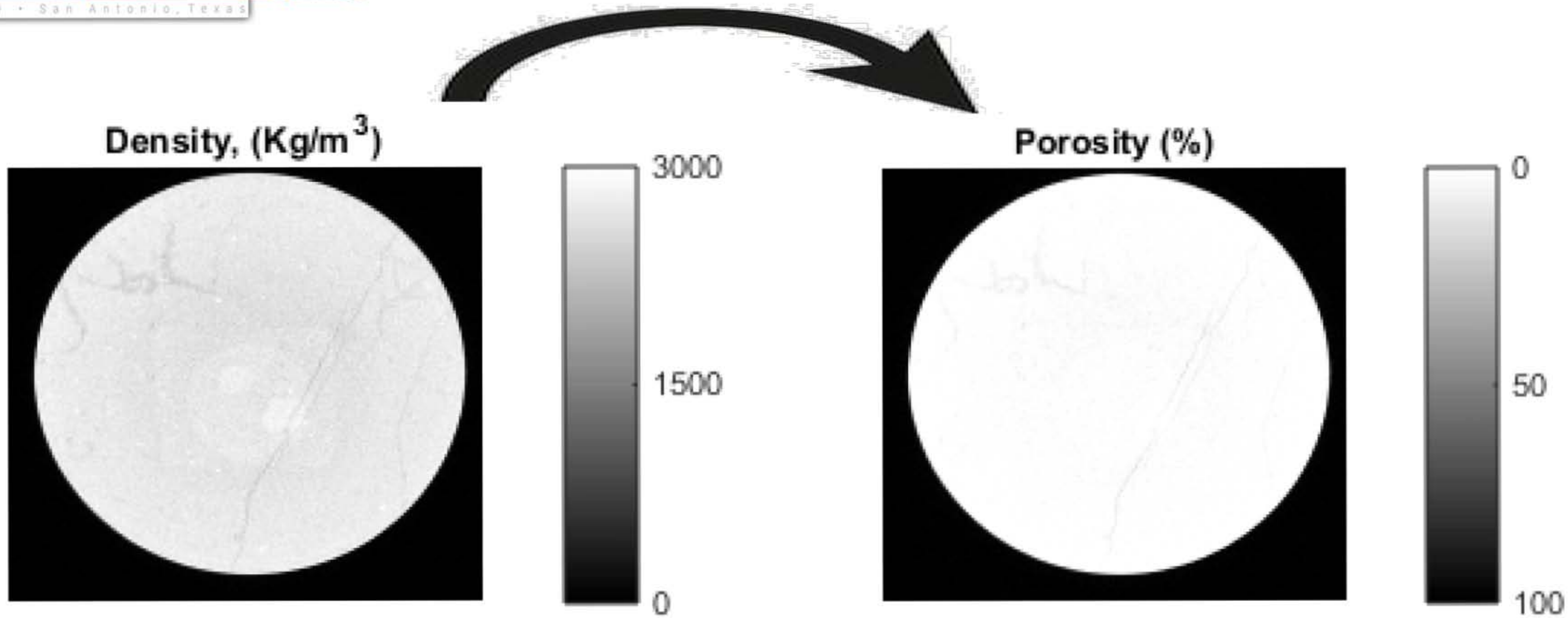
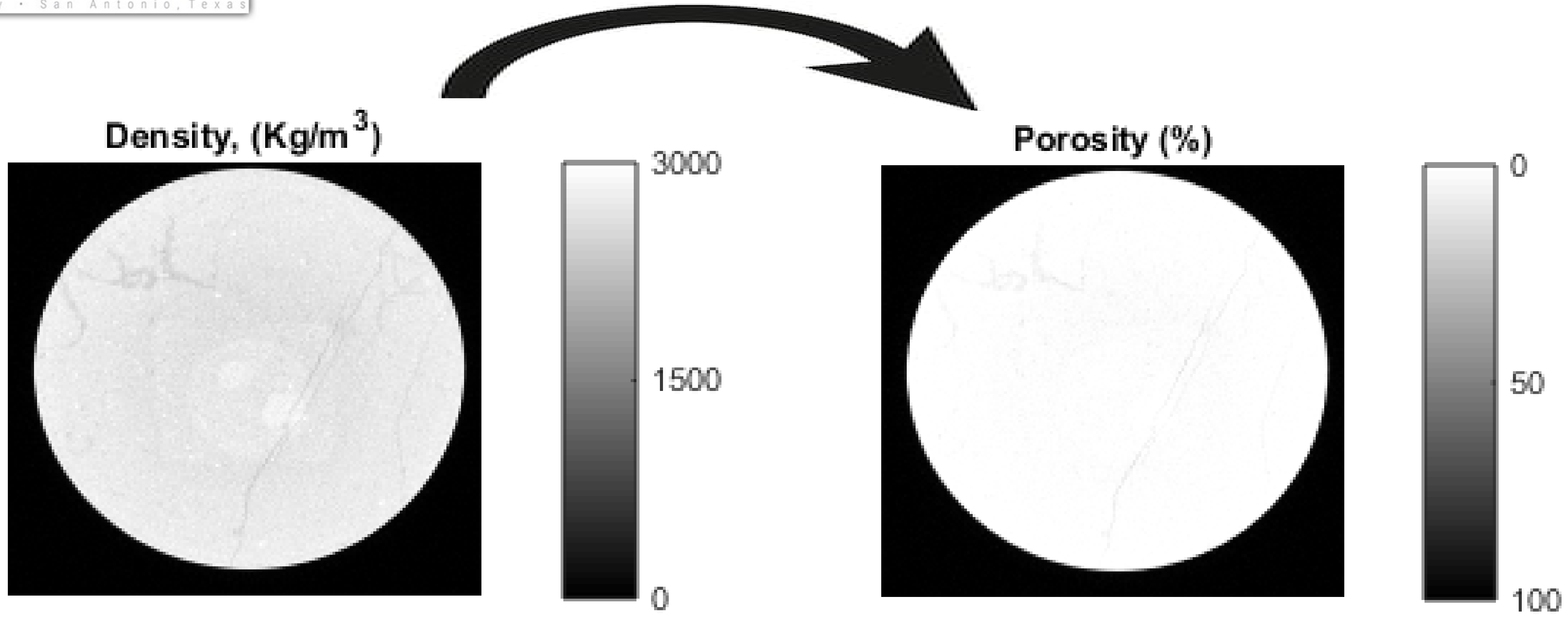
ρ_{voxel} = voxel density
ρ_{fluid} = pore density



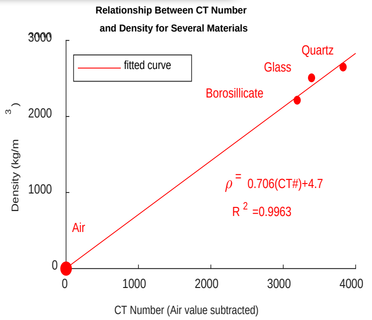
Savre, and Burke. *SPWLA 4th Annual Logging Symposium*. 1963.

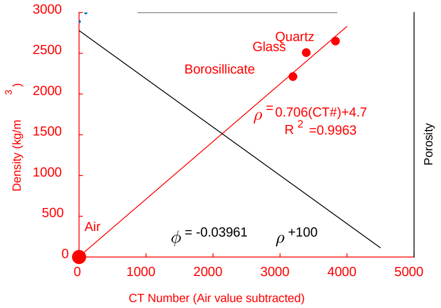

Density, (Kg/m3)
3000
1500
0
Porosity (%)
0
50
100



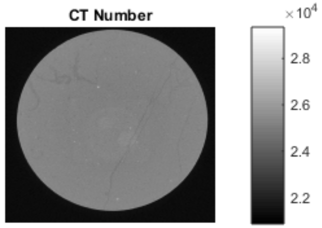
Lab measured porosity: 1.01%
CT estimated porosity: 1.03%

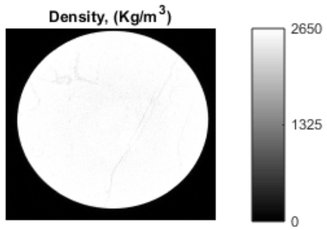
Difference:1.9%

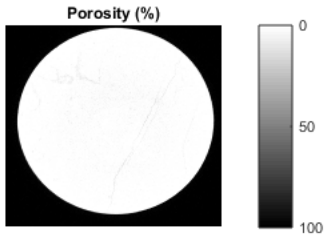


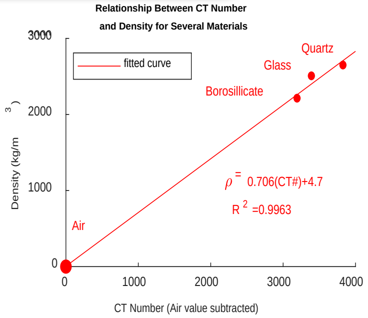


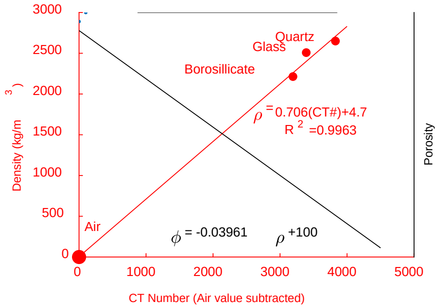
CT Number → Density → Porosity



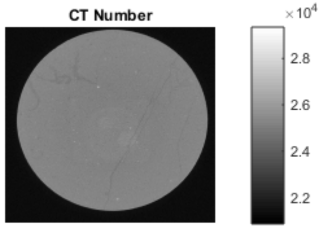


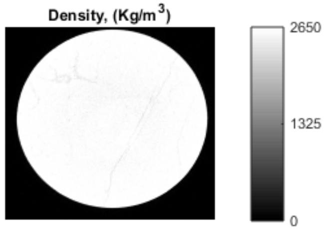


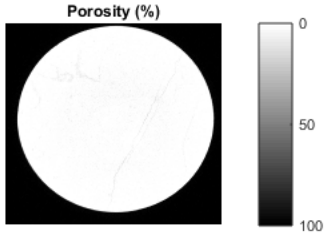




CT Number — Density — Porosity — Elastic Moduli — Velocity Simulation







	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[1]

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.

DOI: 10.1061/(ASCE)0733-9399(2006)132:5(519)

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

Berryman, James G. *Engineering Mechanics*. 2006

	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[1]

Effective bulk modulus with no porosity : 45.6 GPa
Effective shear modulus with no porosity 28.4 GPa

Abstr
to well
use in
includi
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.

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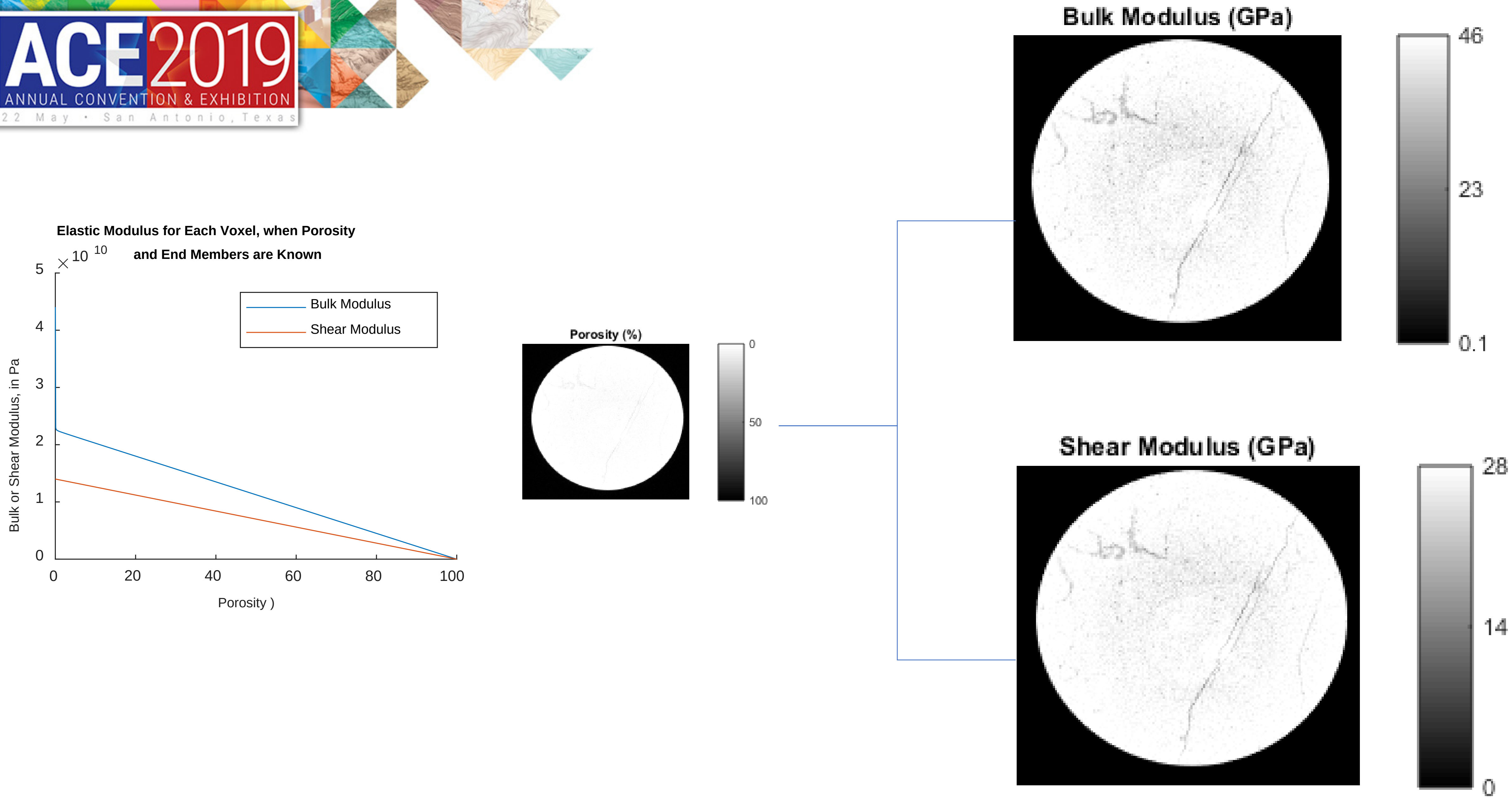
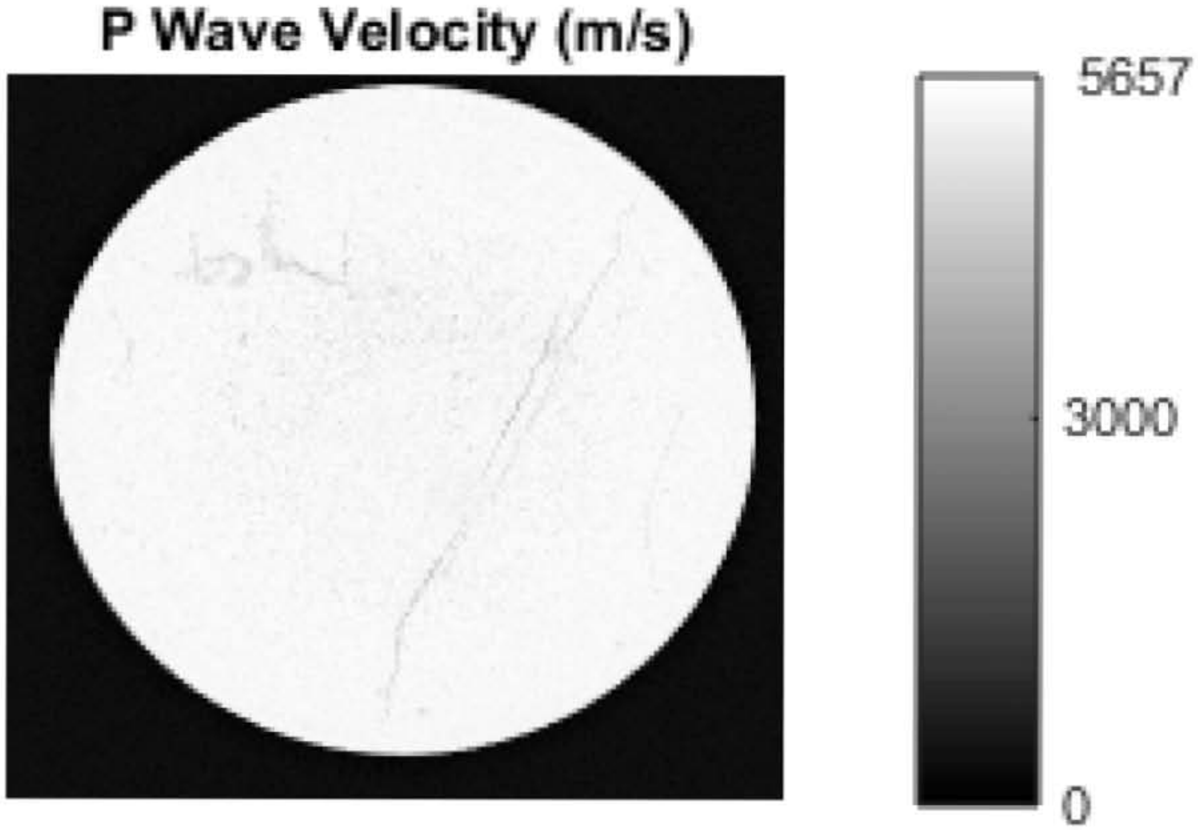
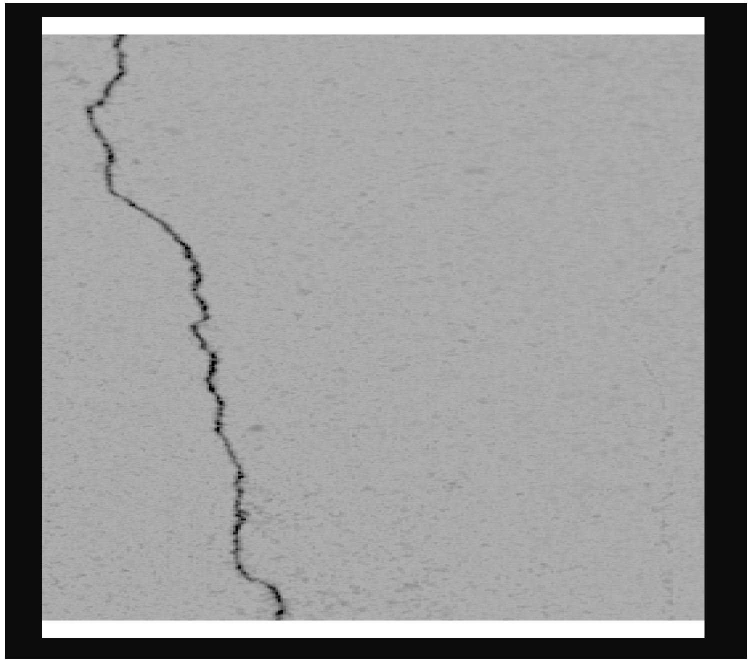


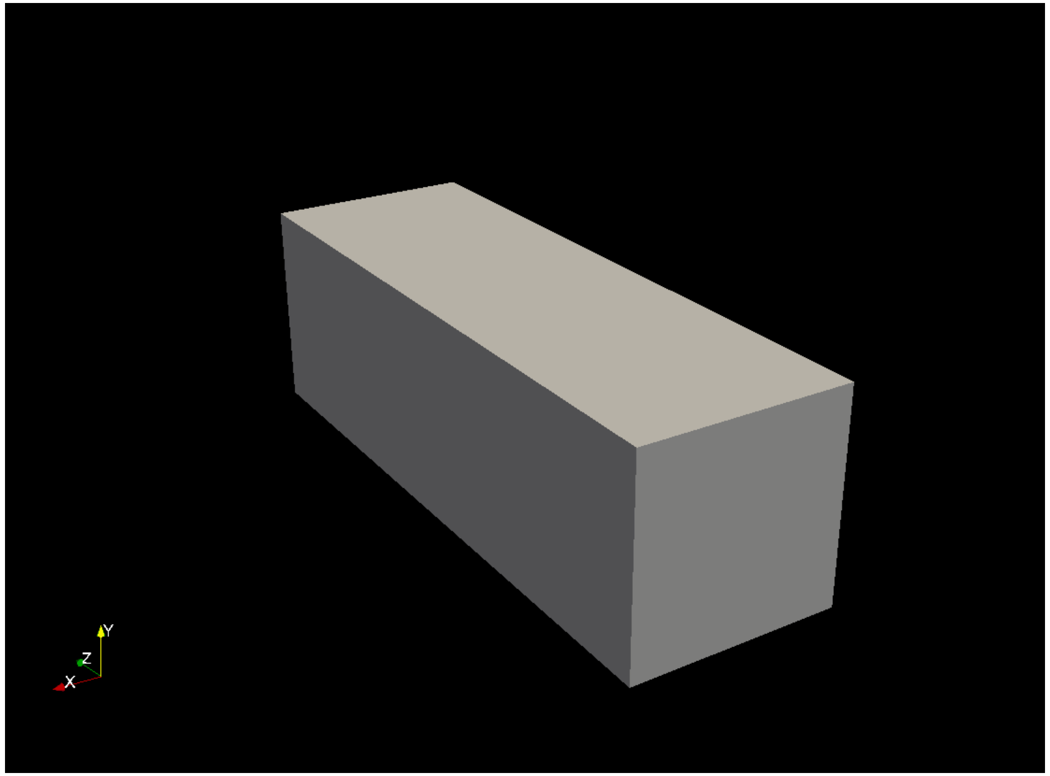
Goldfarb, Ikeda, Nicola Tisato. *SEG Technical Program Expanded Abstracts 2017*.

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

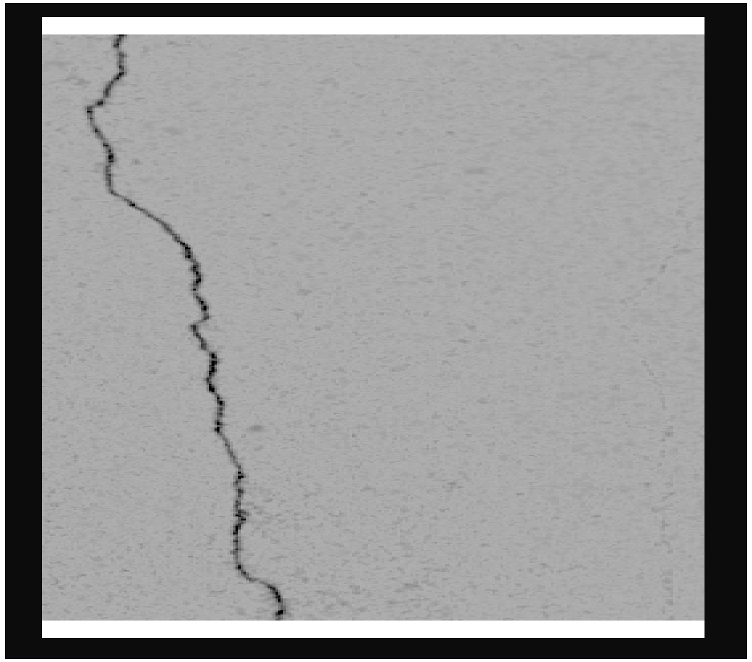
Vp = P wave velocity
K = bulk modulus
μ = shear modulus
ρ = density







Bohlen, Thomas. "Parallel 3-D viscoelastic finite difference seismic modelling." *Computers & Geosciences* 28.8 (2002): 887-899.



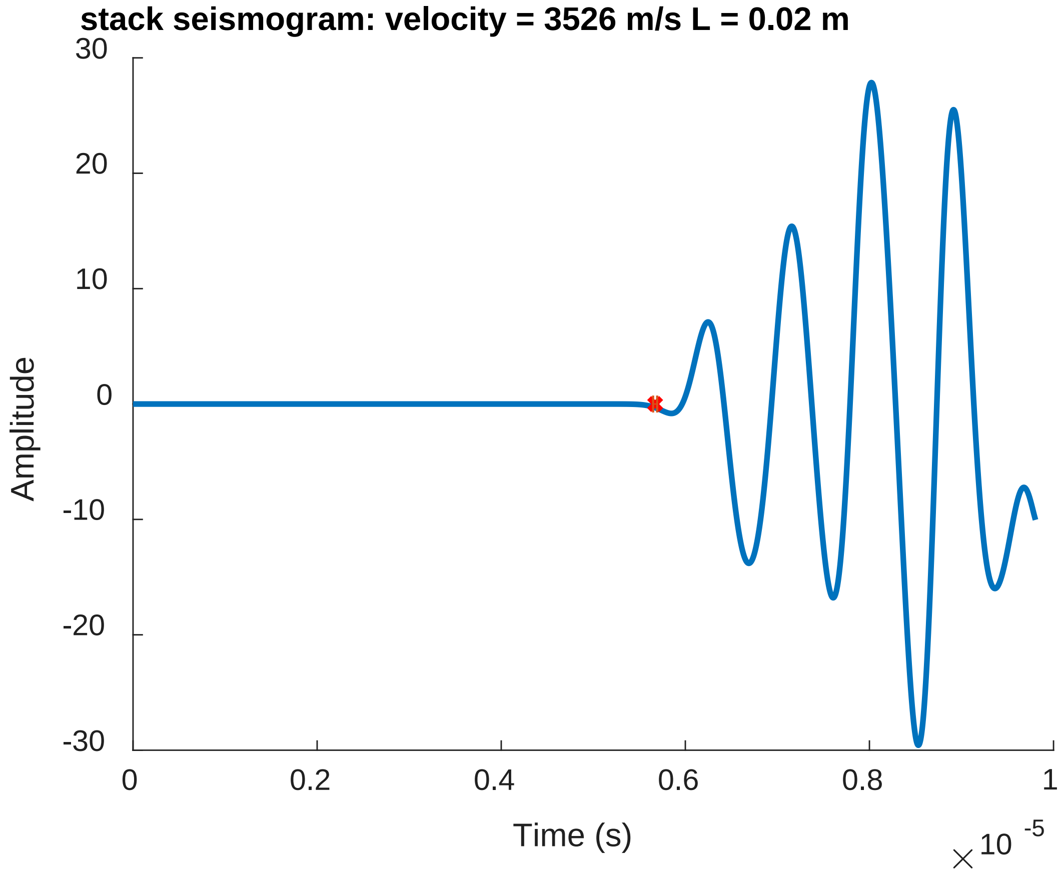
Finite Difference Method Solver:Sofi3D

Order in space: 8^{th}

Order in time: 2^{nd}

Source: 1Mhz Ricker

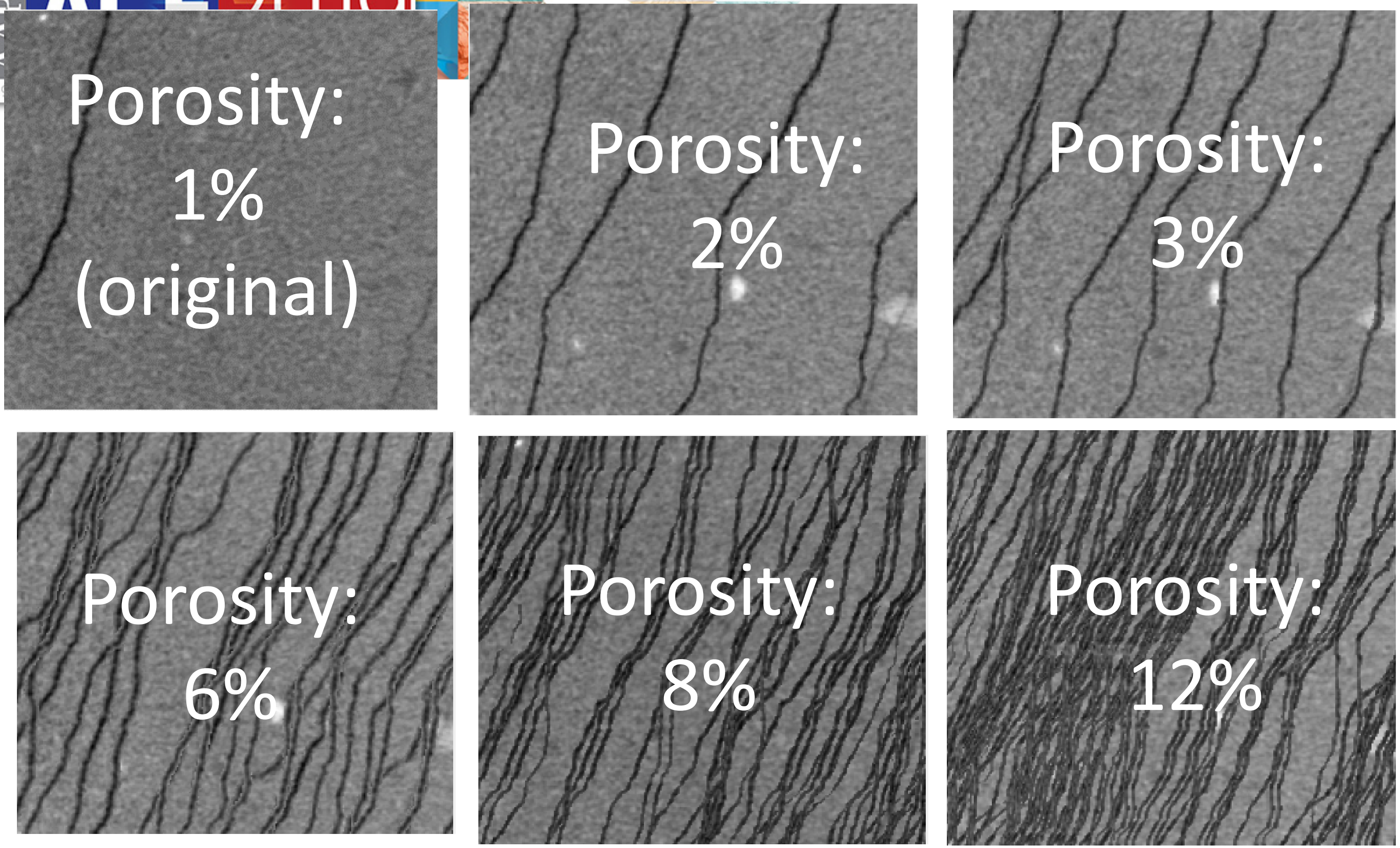
Bohlen, Thomas. "Parallel 3-D viscoelastic finite difference seismic modelling." *Computers & Geosciences* 28.8 (2002): 887-899.



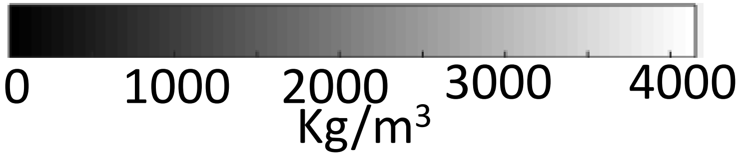
Lab measured Vp: 3 800m/s

CT estimated Vp: 3 526 m/s

Difference: -6 %



All slices
1cm x 1cm



Assumptions:

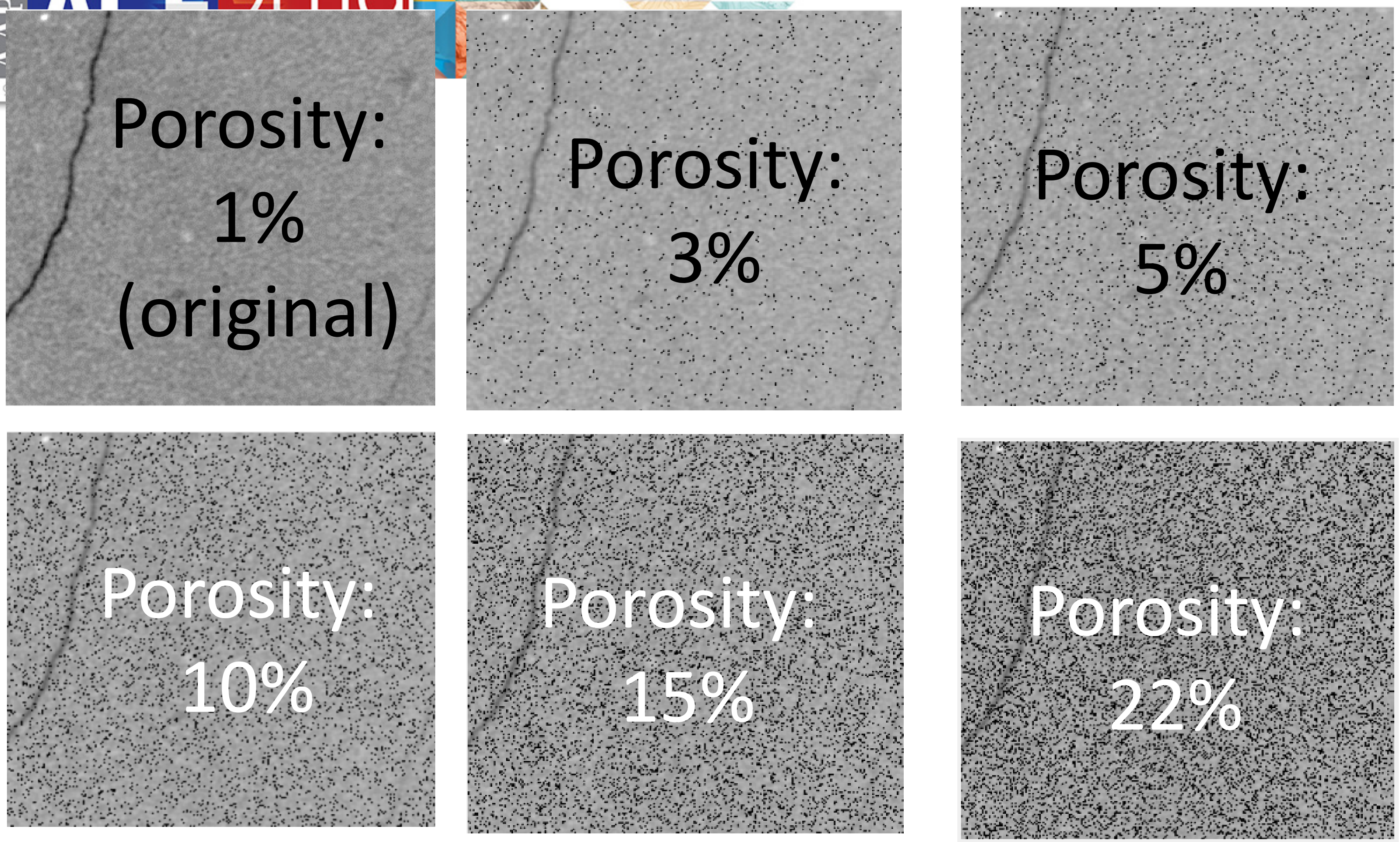
- all porosity is in fractures
- near planar fractures

Don’t Rock Physics models already explain this?

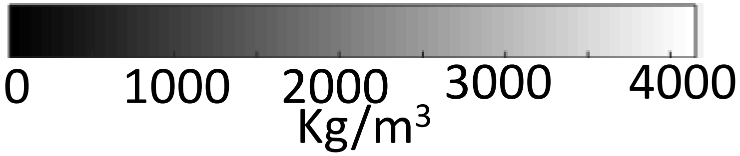
Don’t Rock Physics models already explain this?

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

	Quartz	Illite	Plagioclase	Chlorite	Carbonate	Kaolinite	Smectite	other
Percentage%	25.1	14.7	24.4	20.3	1.3	1.9	10.0	~2



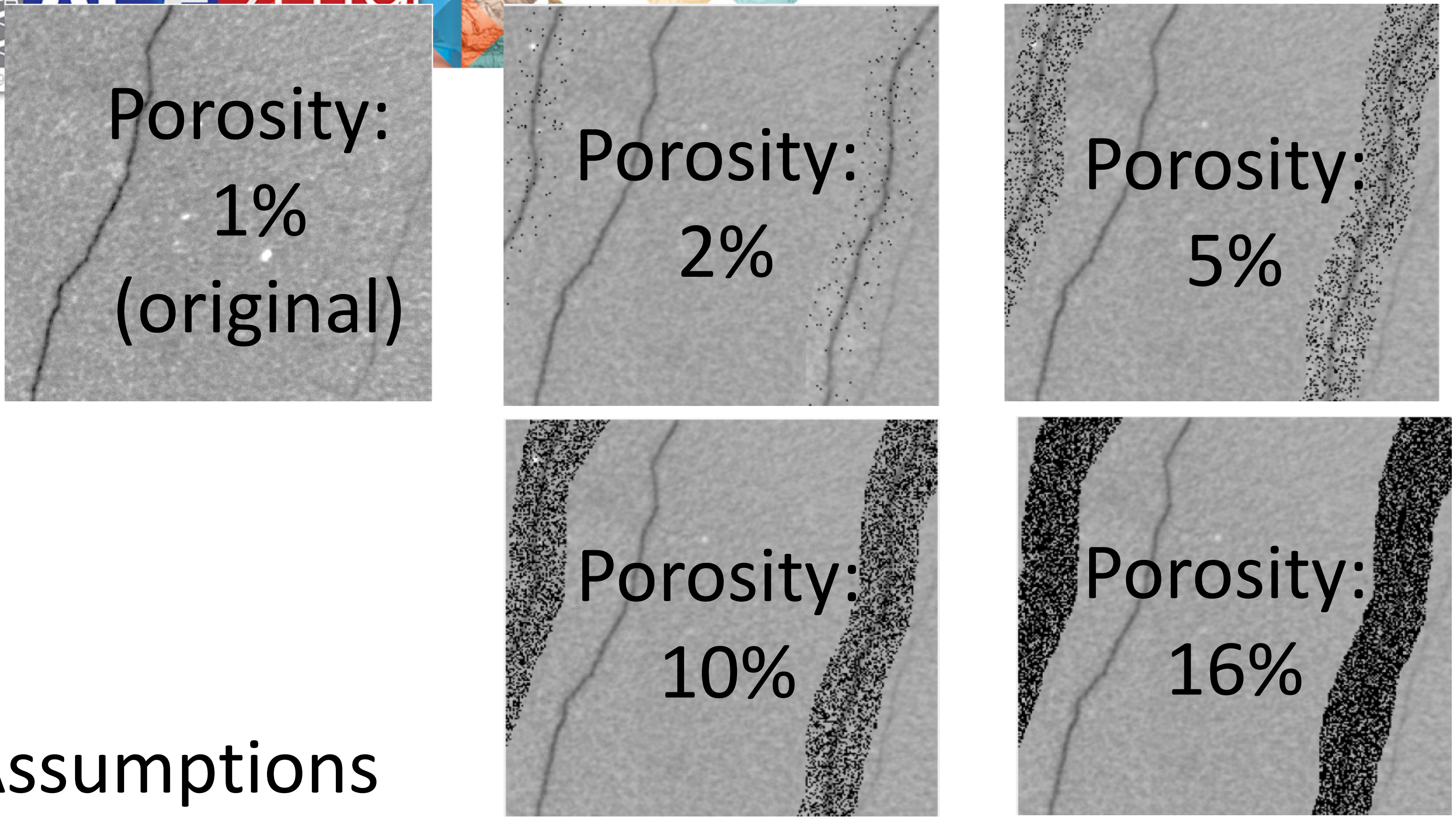
All slices
1cm x 1cm



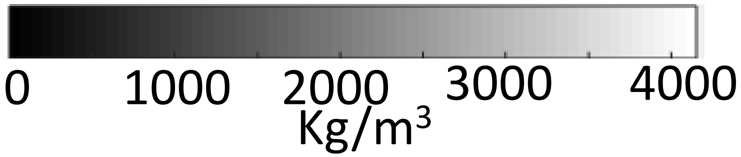
Assumptions

All increases in porosity is randomly distributed

Single-voxel-shaped pores added



All slices
1cm x 1cm



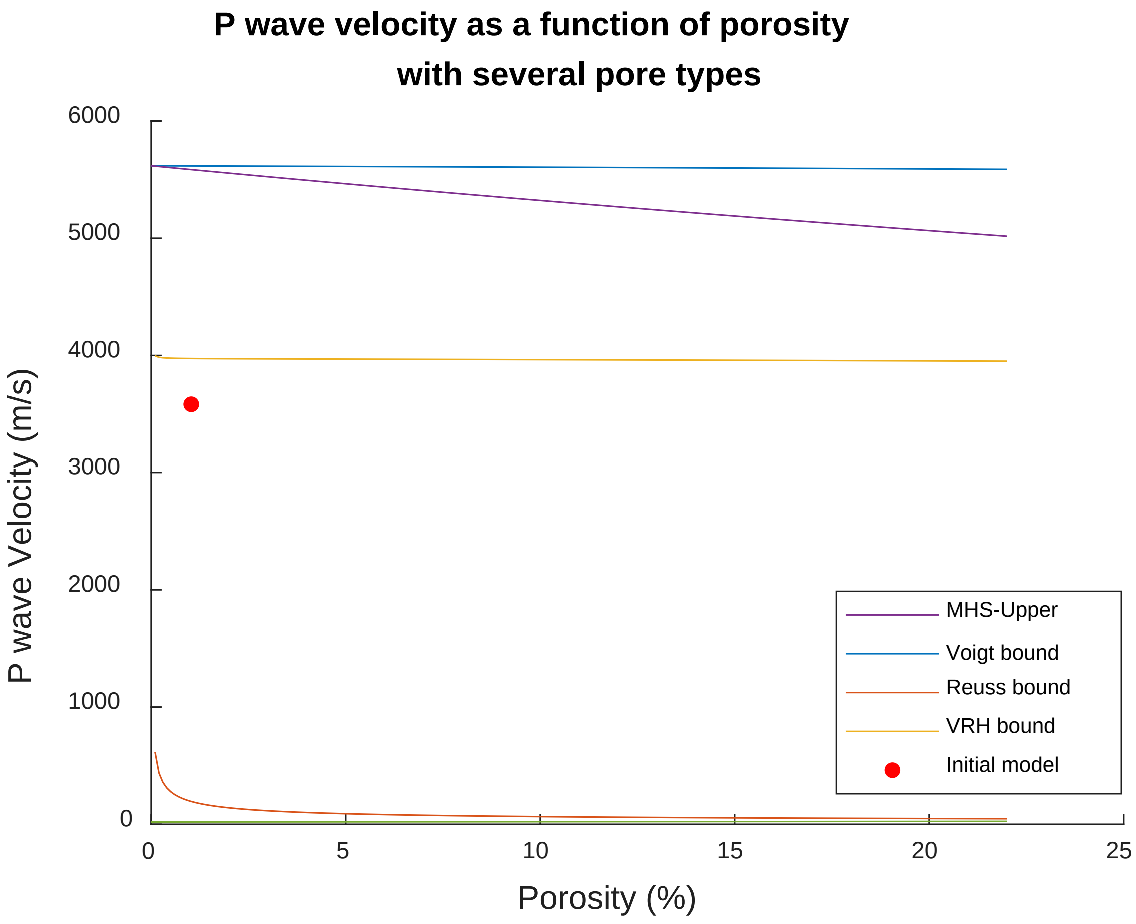
Assumptions

Two planes added

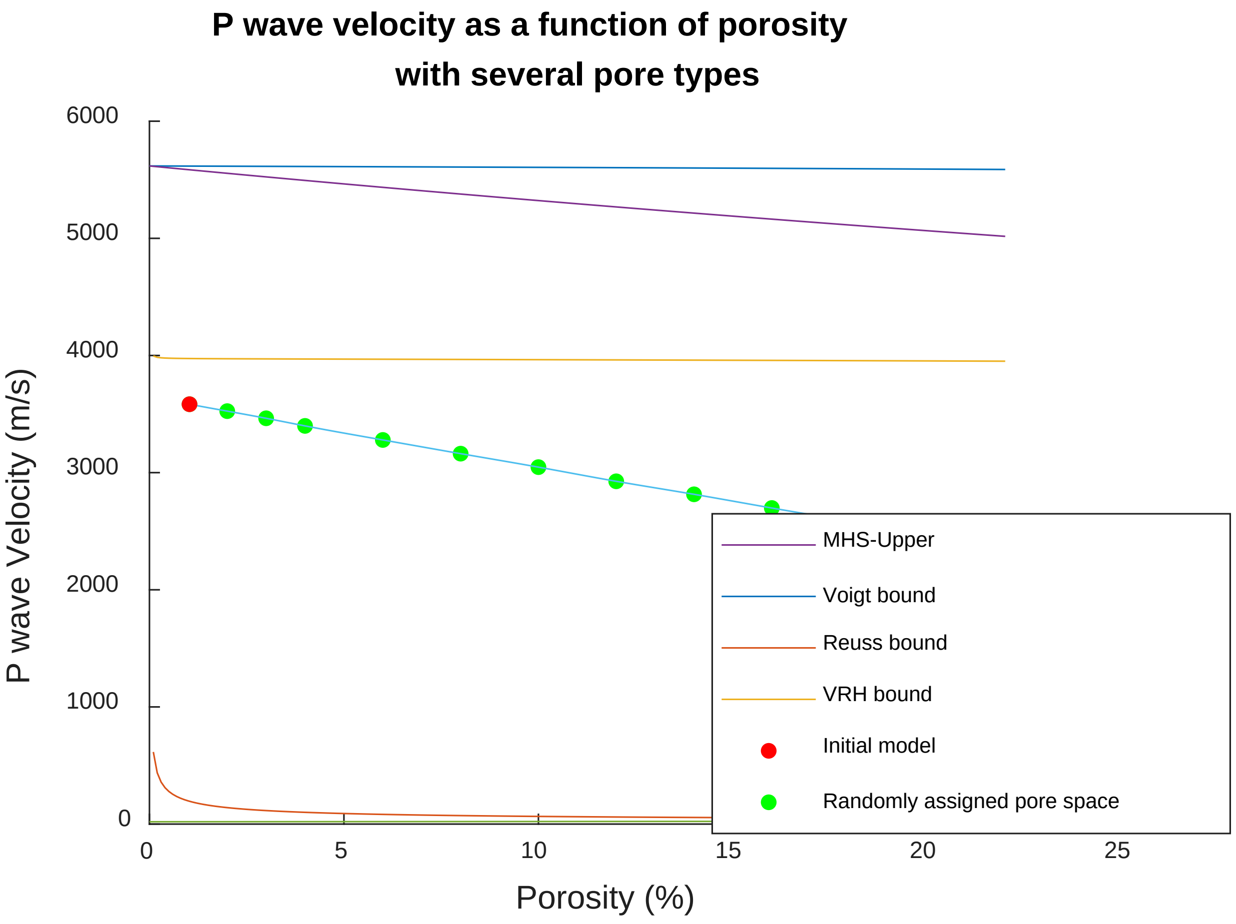
All increases in porosity is distributed near fracture planes

Single-voxel-shaped pores added

Results


P wave velocity as a function of porosity
with several pore types
P wave Velocity (m/s)
Porosity (%)
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
MHS-Upper
Voigt bound
Reuss bound
VRH bound
Initial model

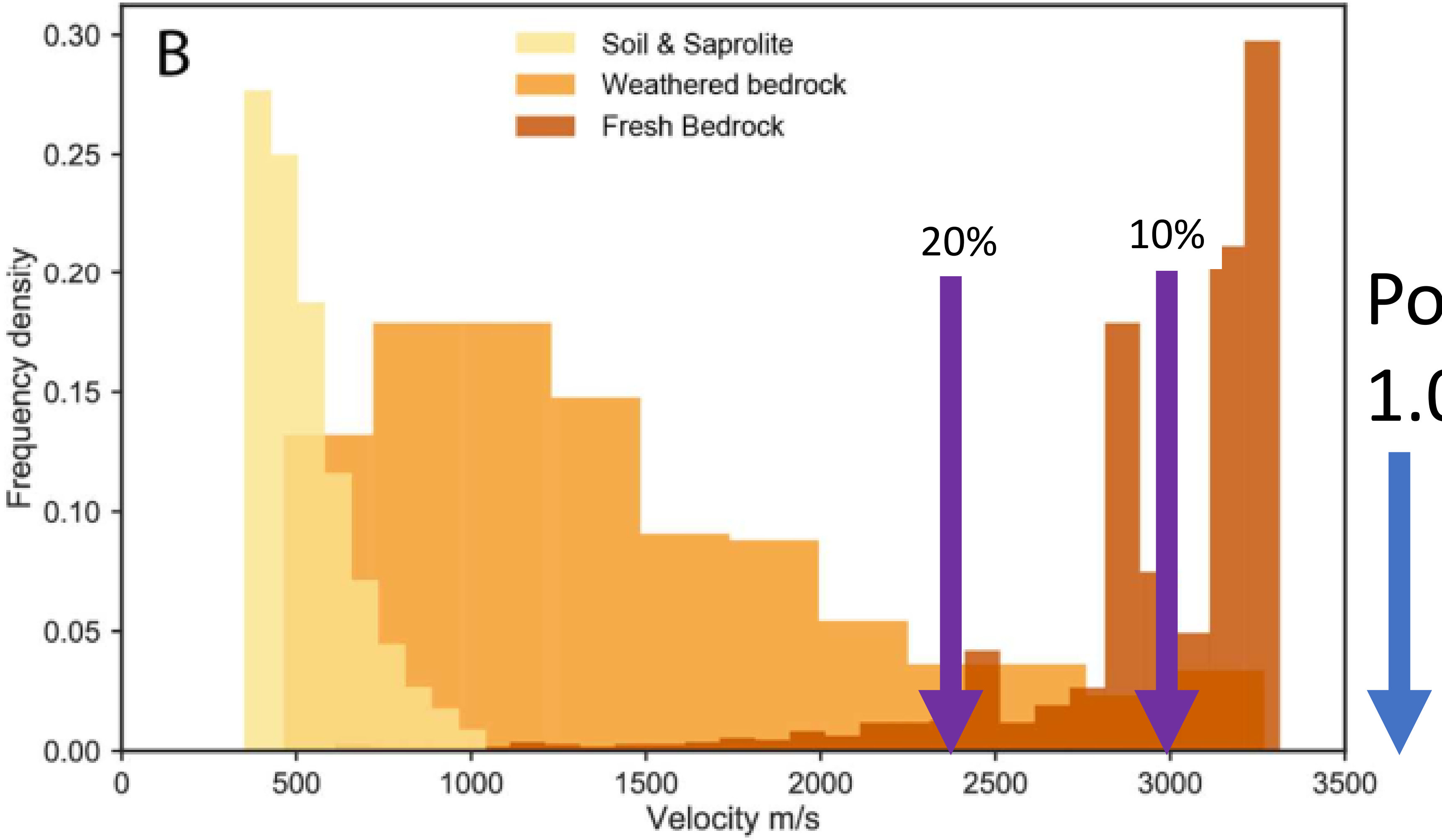
Results



P wave velocity as a function of porosity
with several pore types
P wave Velocity (m/s)
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Porosity (%)
MHS-Upper
Voigt bound
Reuss bound
VRH bound
Initial model
Randomly assigned pore space

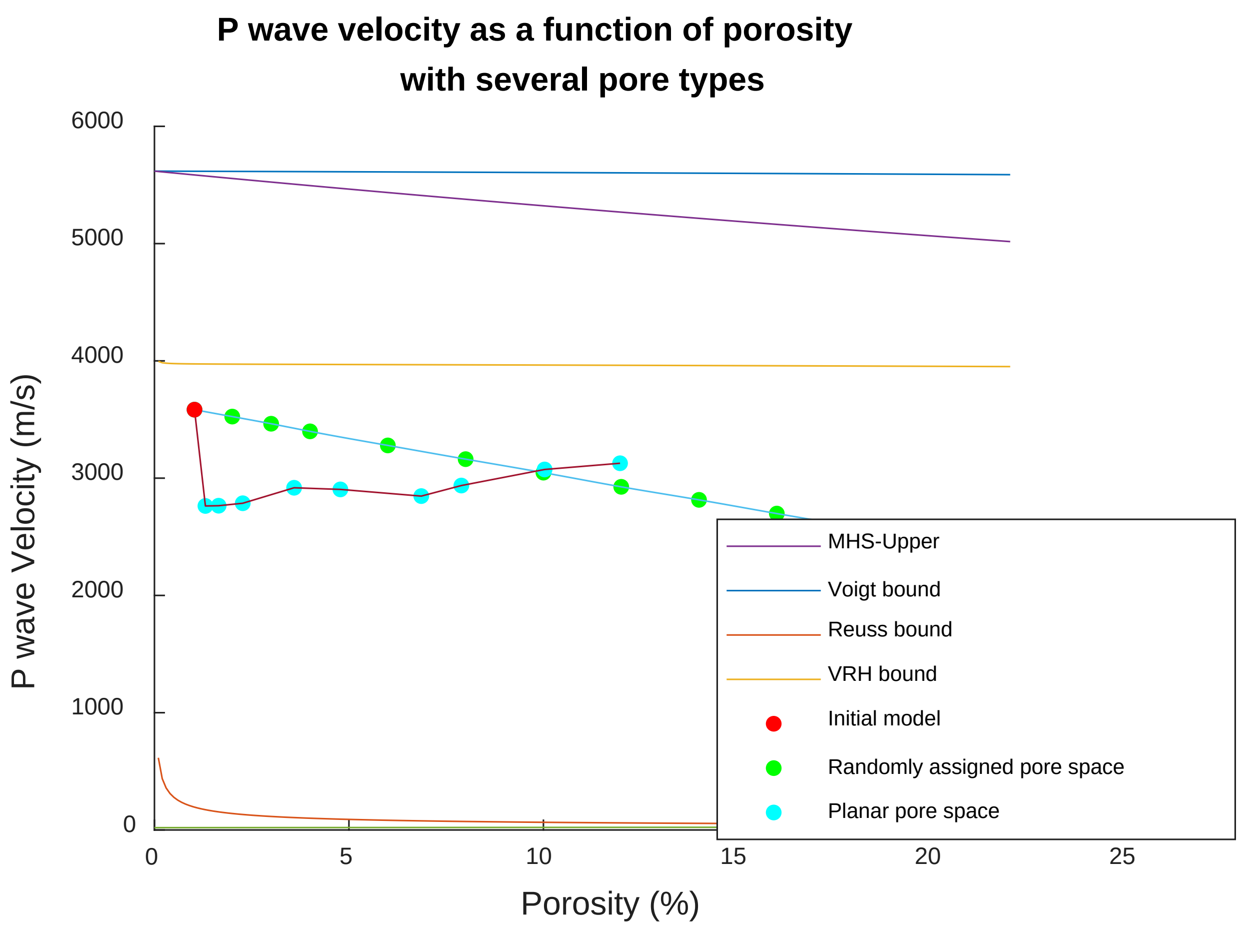
Results

randomly assigned



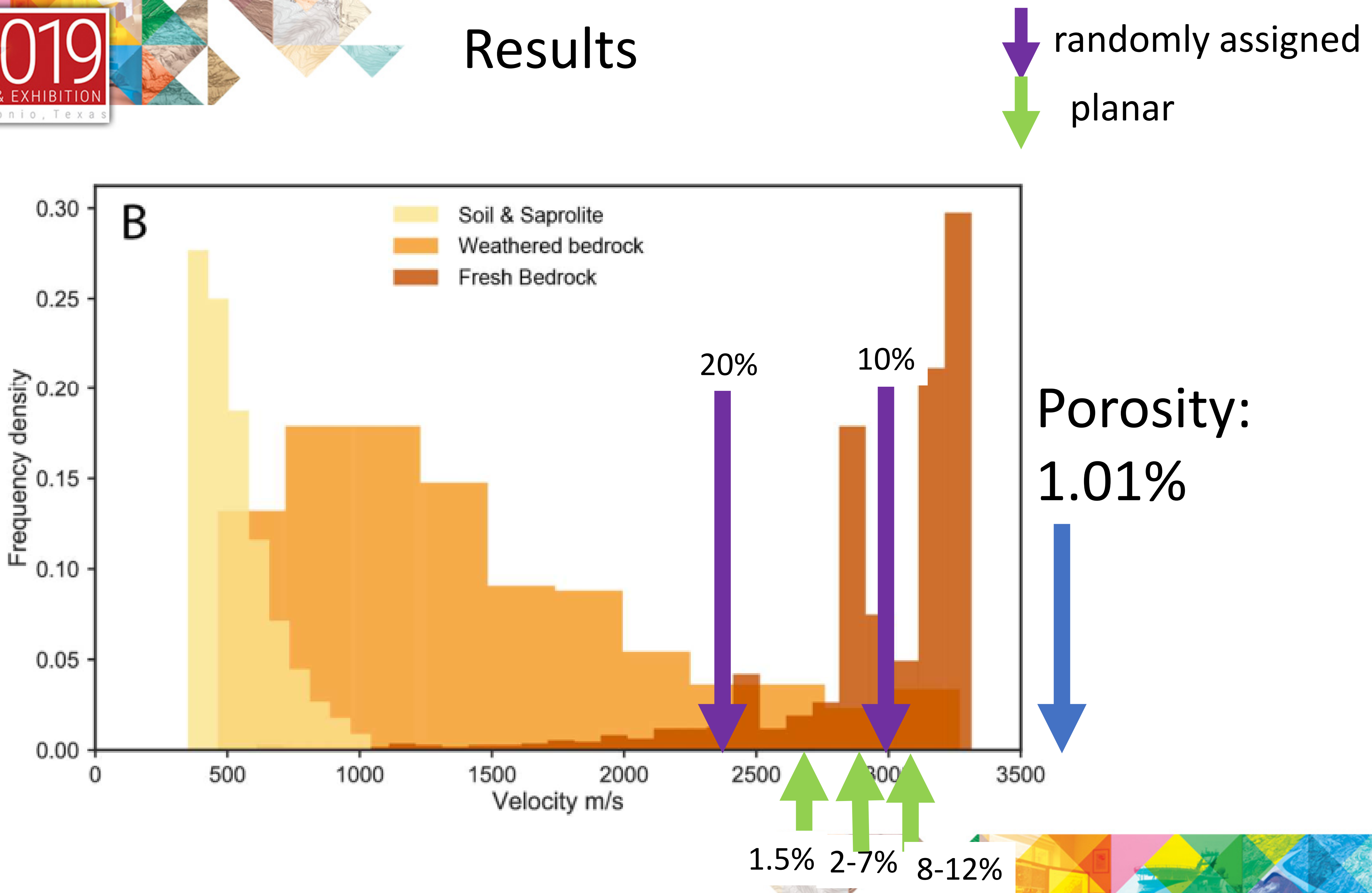
Porosity:
1.01%

Results

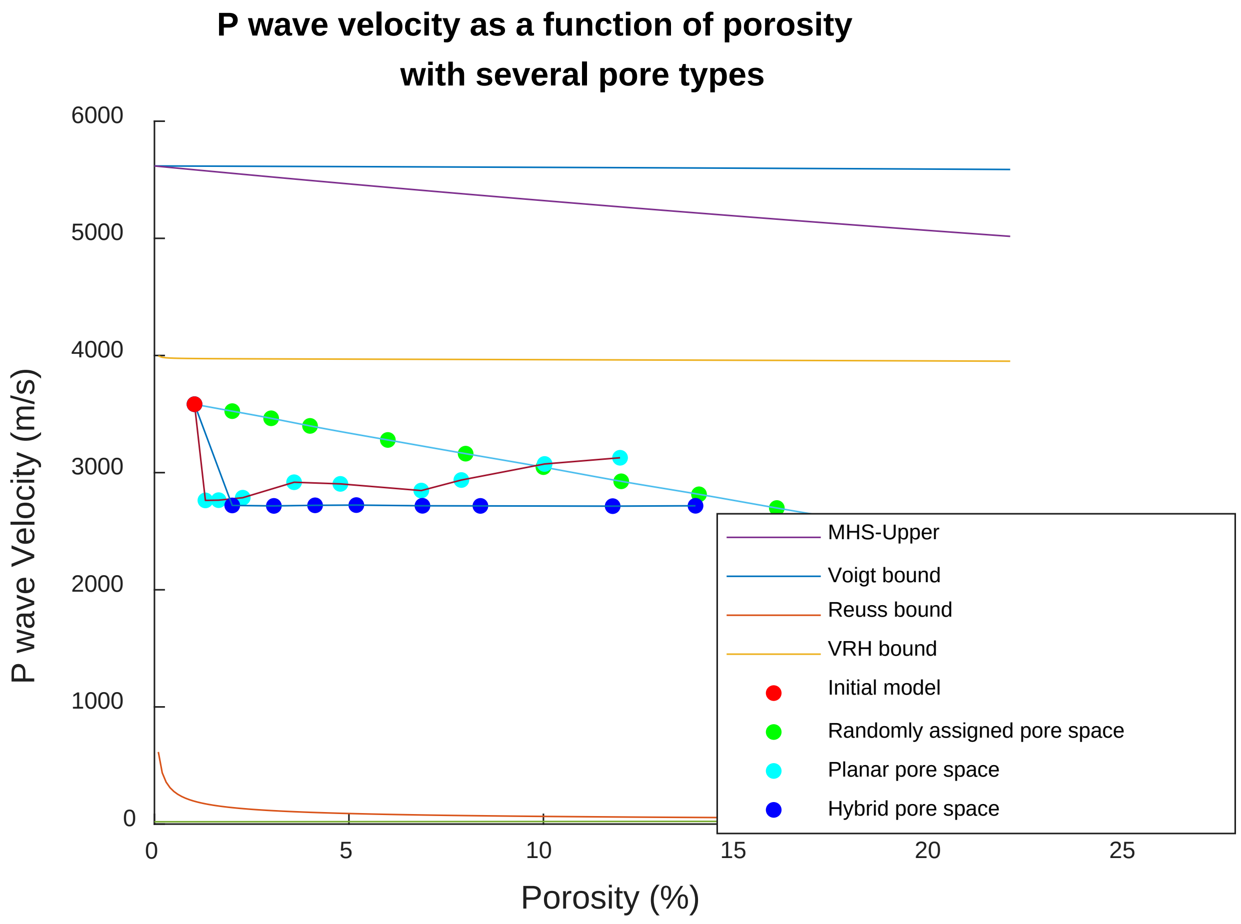


P wave velocity as a function of porosity
with several pore types
P wave Velocity (m/s)
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Porosity (%)
MHS-Upper
Voigt bound
Reuss bound
VRH bound
Initial model
Randomly assigned pore space
Planar pore space

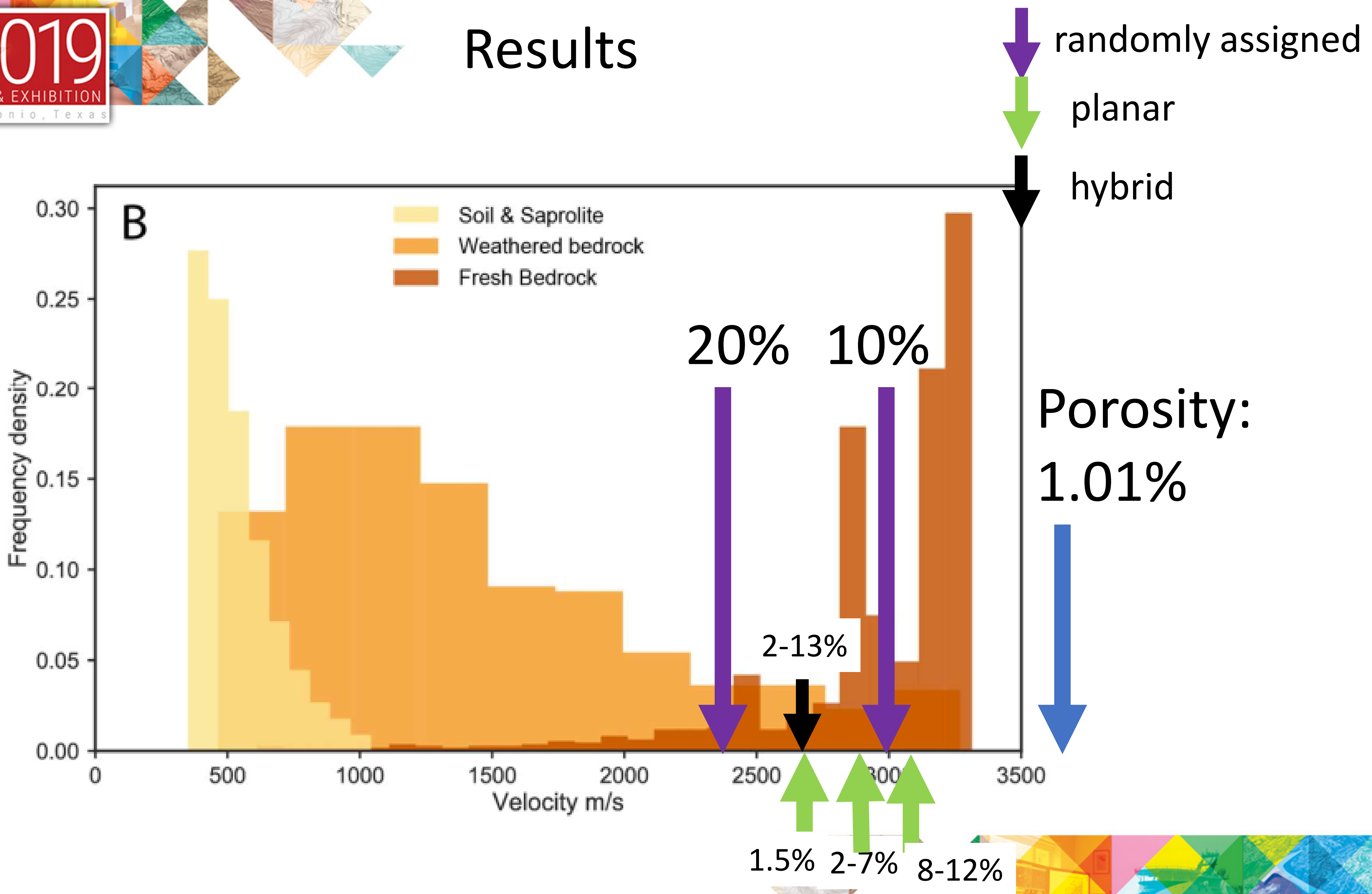
Results


randomly assigned
planar
B
Soil & Saprolite
Weathered bedrock
Fresh Bedrock
Frequency density
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
500
1000
1500
2000
2500
3500
Velocity m/s
20%
10%
Porosity:
1.01%
1.5%
2-7%
8-12%

Results


P wave velocity as a function of porosity
with several pore types
P wave Velocity (m/s)
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Porosity (%)
MHS-Upper
Voigt bound
Reuss bound
VRH bound
Initial model
Randomly assigned pore space
Planar pore space
Hybrid pore space

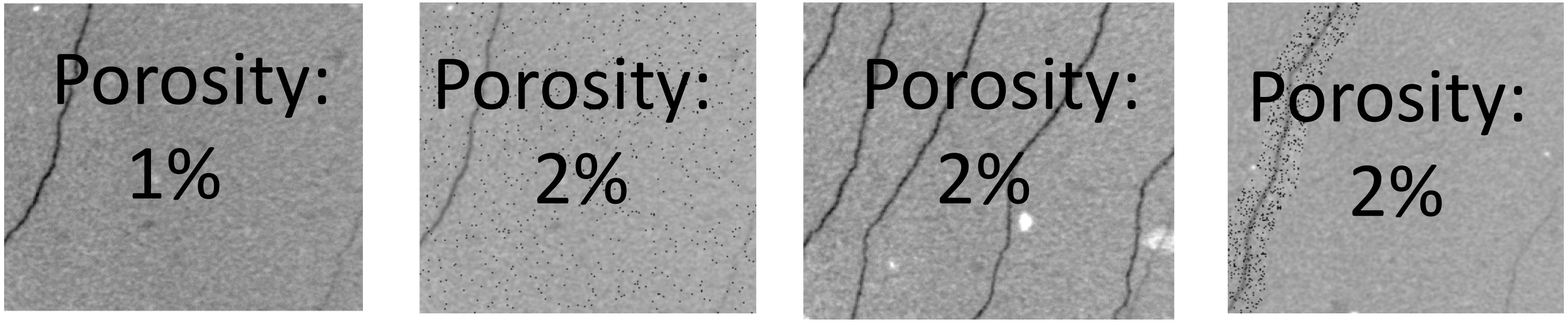
Results


randomly assigned
planar
hybrid
B
Soil & Saprolite
Weathered bedrock
Fresh Bedrock
Frequency density
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
500
1000
1500
2000
2500
3500
Velocity m/s
20%
10%
2-13%
Porosity:
1.01%
1.5%
2-7%
8-12%

(A)

Discussion:

- Better understanding of pore types



original | added as specks | added as fractures | added as hybrid

X-ray CT Gun

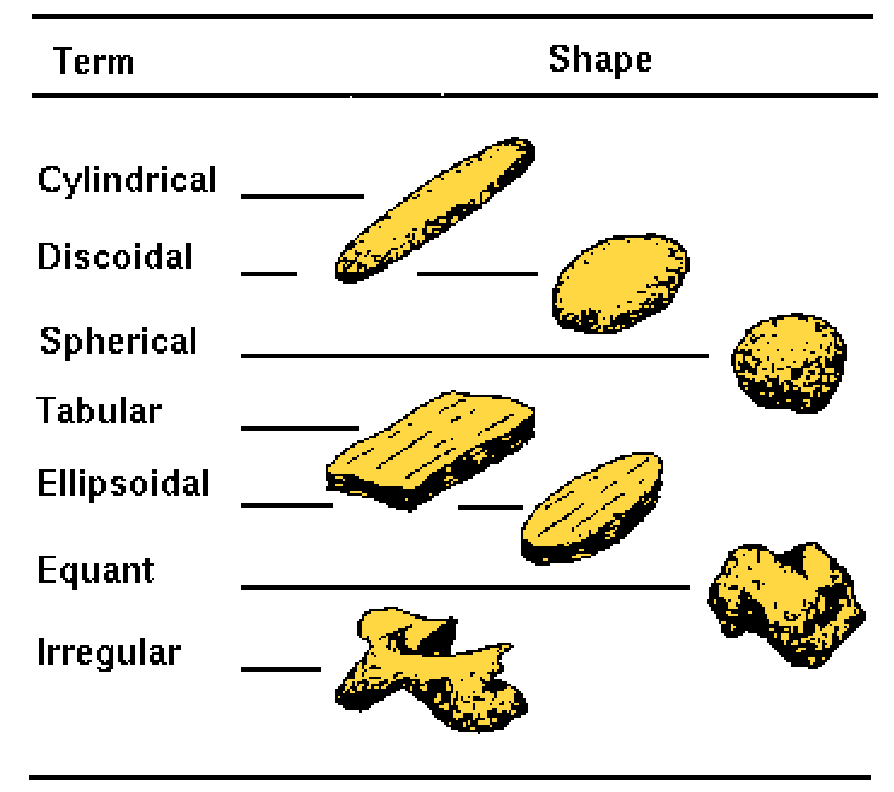
5 mm

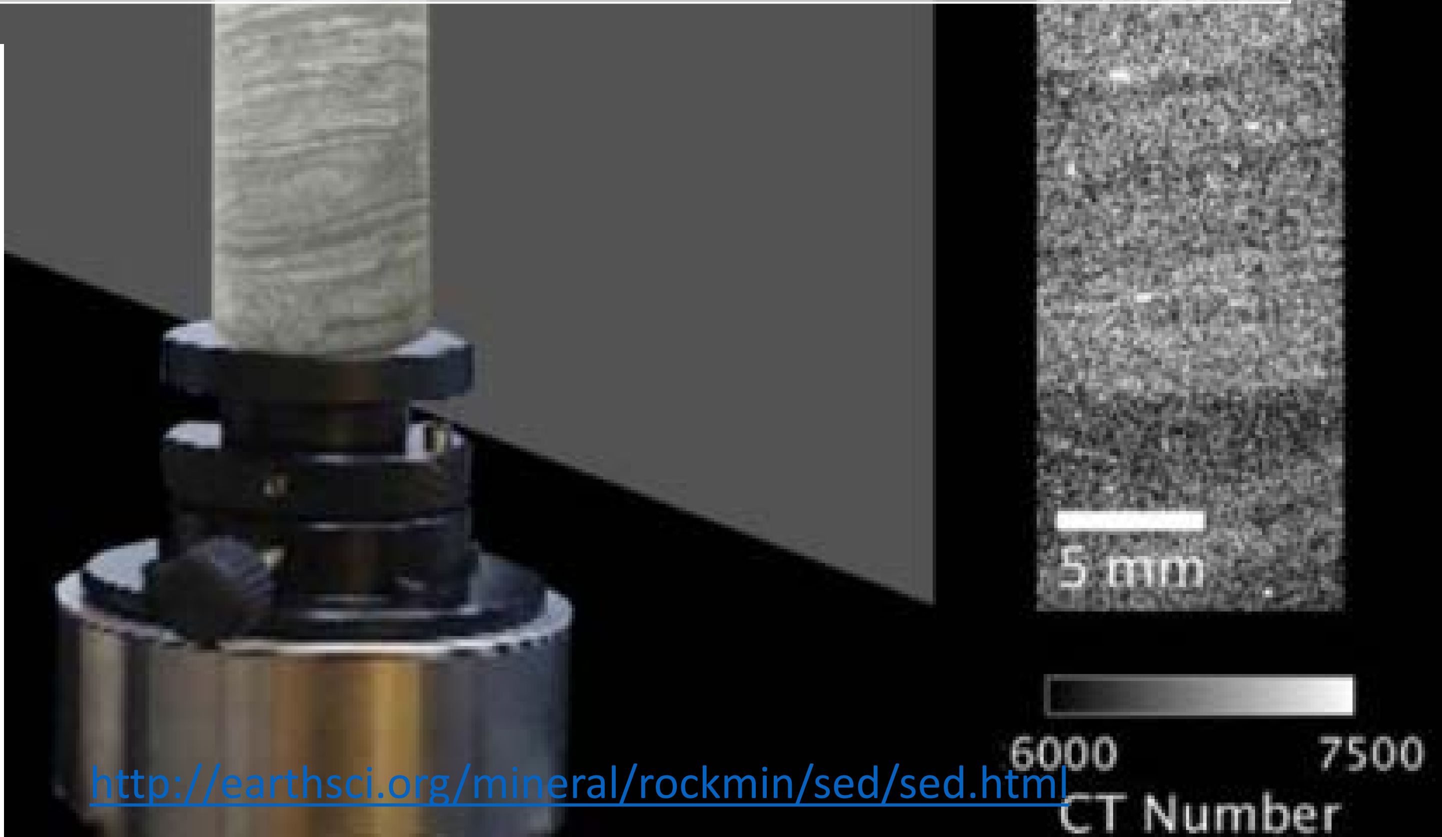
6000 7500

CT Number

Discussion:

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





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

Lee, Shawn S. *Master's Dissertation*. 2018.

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

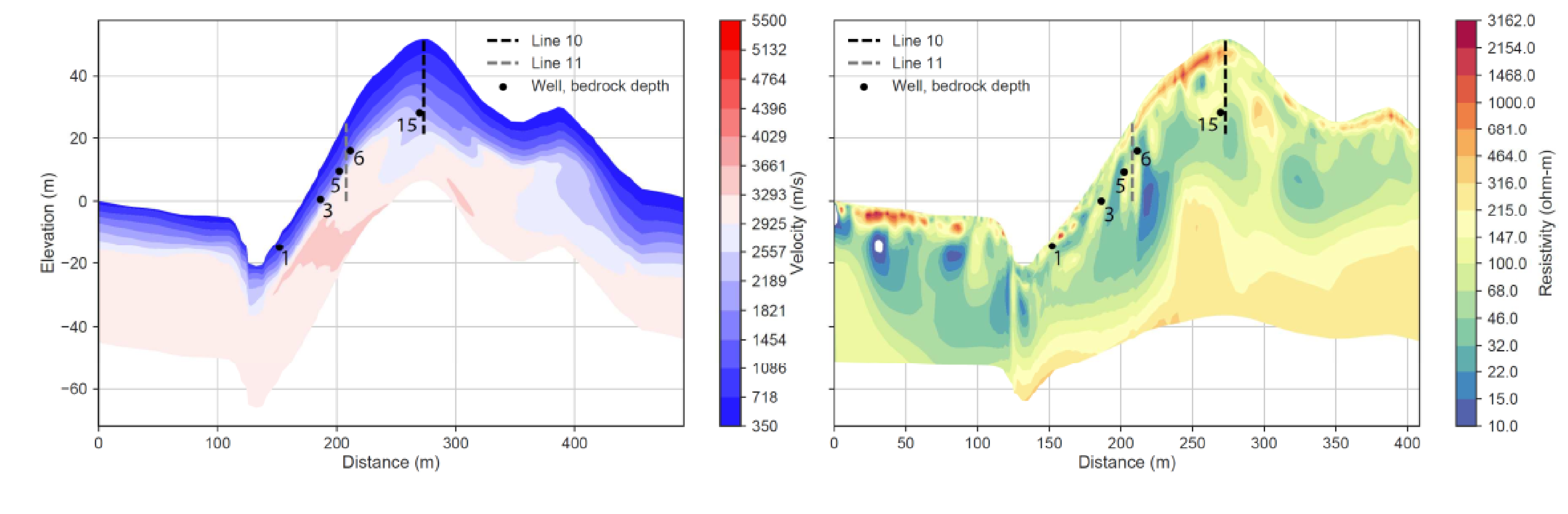
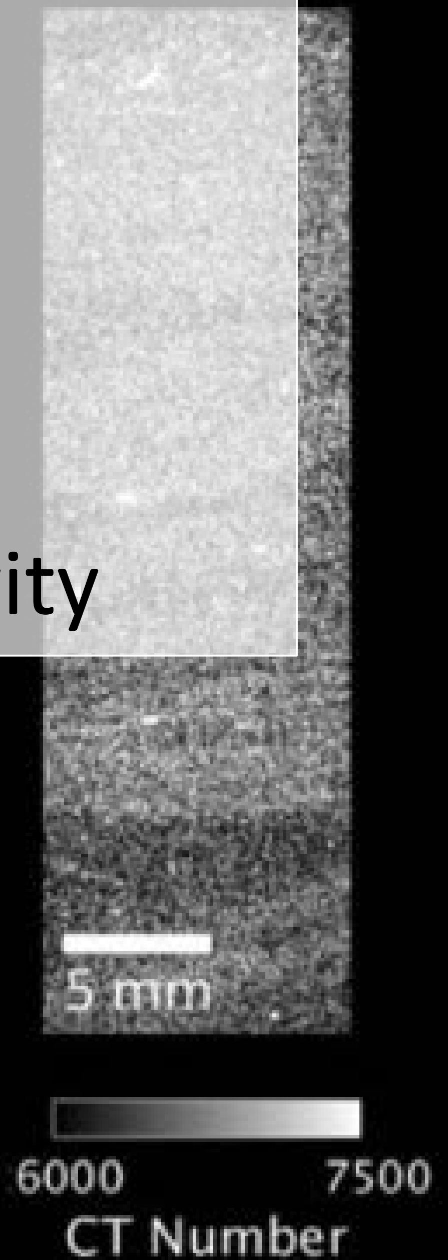
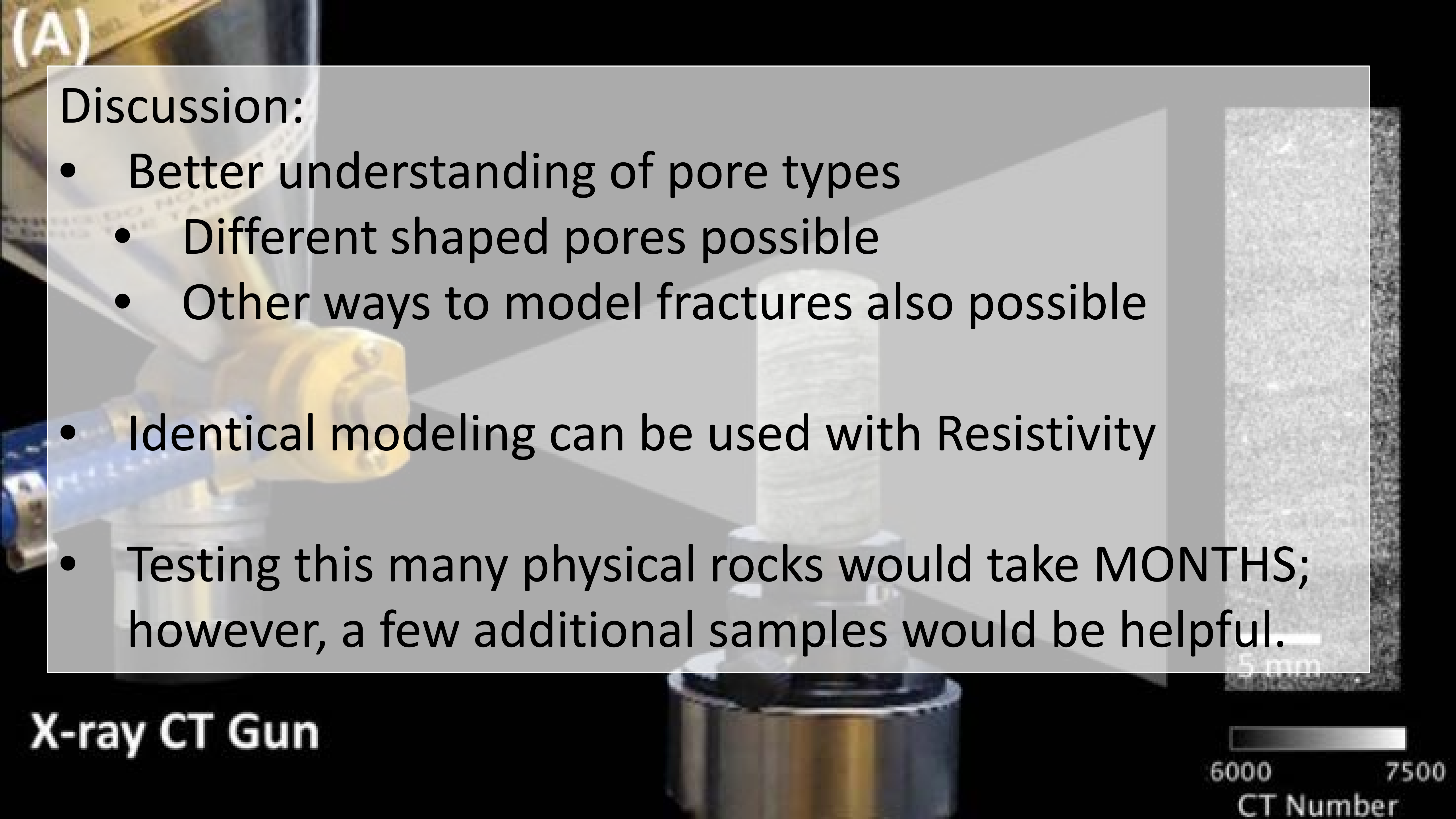


Figure 12. Line 2 surveys at Rivendell hillslope with Lines 10 and 11 intersecting. Seismic





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.

https://wateruseitwisely.com/