Visualization Sciences Group

Poromechanics Investigation at Pore-scale Using Digital Rock Physics Laboratory

COMSOL CONFERENCE
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Session: Multiphysics
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Agenda

- Introduction
  - Motivation
  - Goal of study
- Theory
- Approach – digital rock physics lab
  - 3D Imaging
  - Avizo digital rock analysis
  - Comsol simulation
- Results

Between Rock and A Hard Place

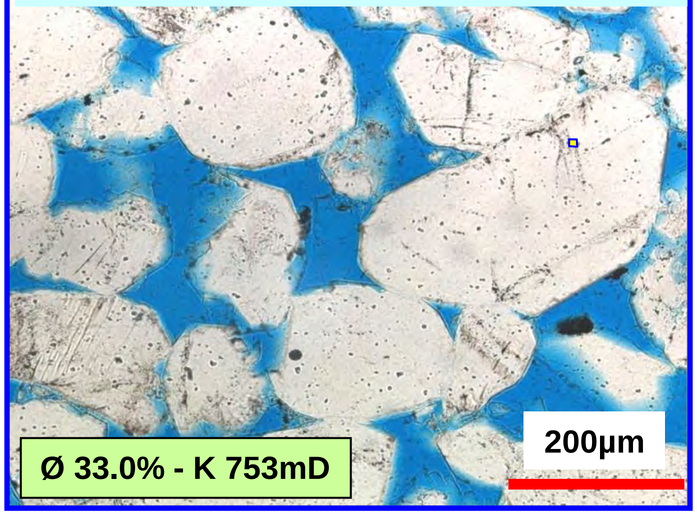
- Is rock that hard?

Quartzite
Sandstone
Metamorphism
About.com

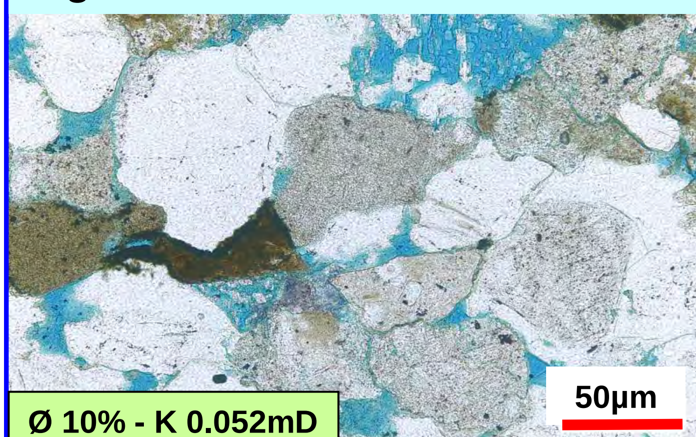
Motivation: porous rock network

Visualization Sciences Group

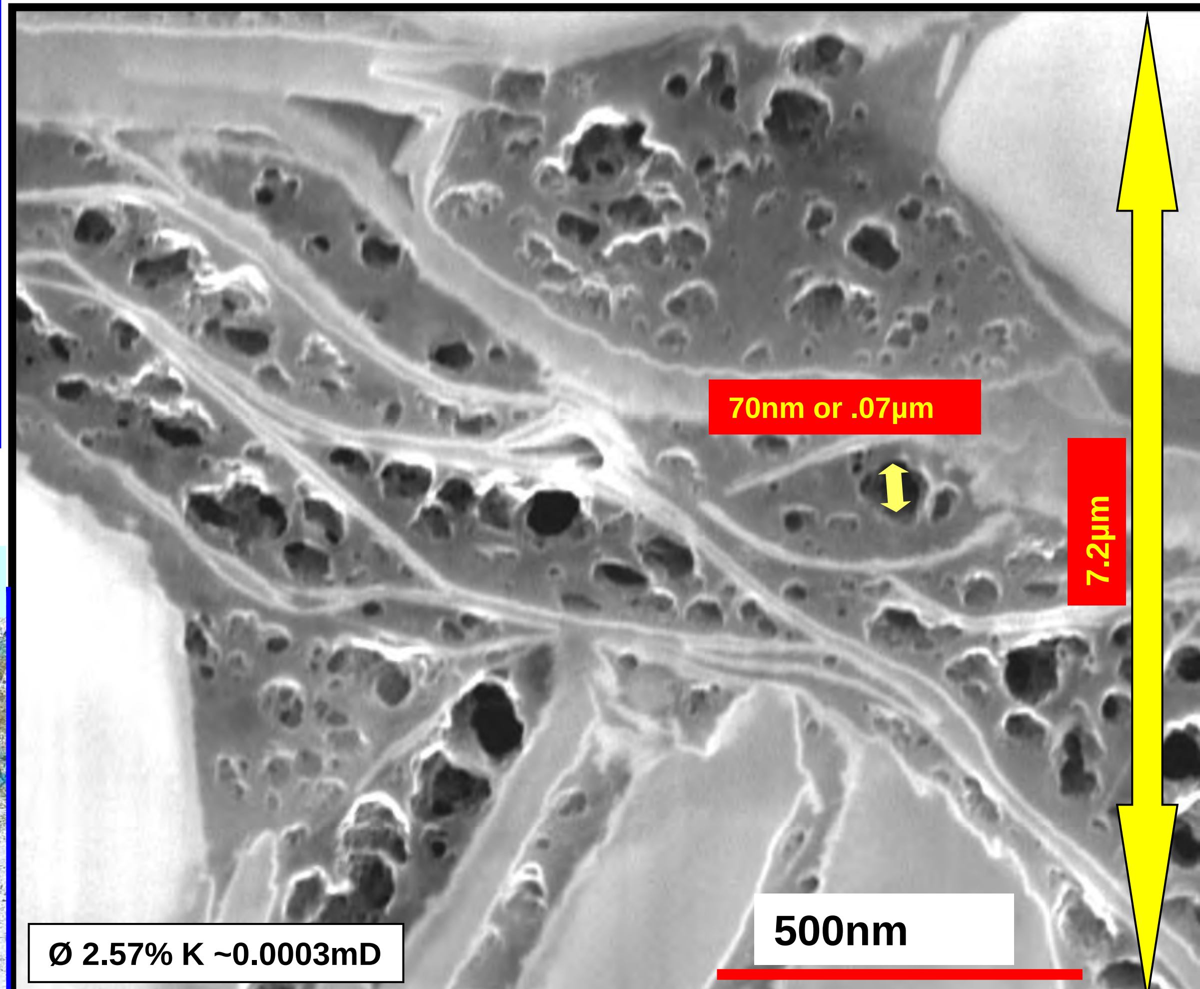
Convention Sandstone Reservoir



Tight-Gas Sandstone Reservoir

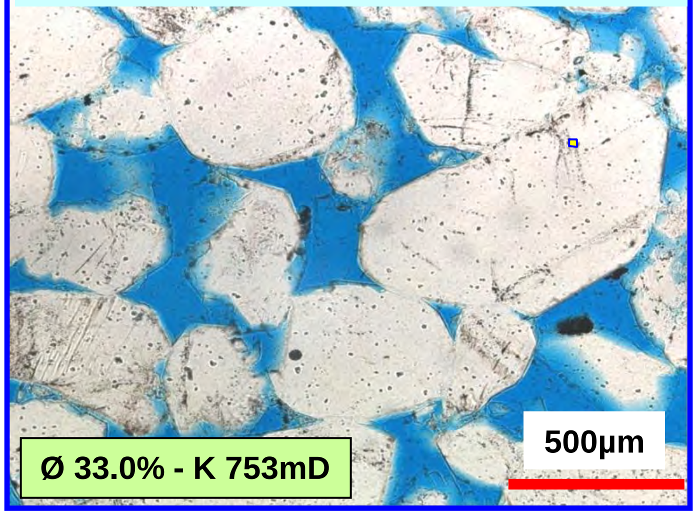


Shale Gas Reservoir, 70,000x Magnification

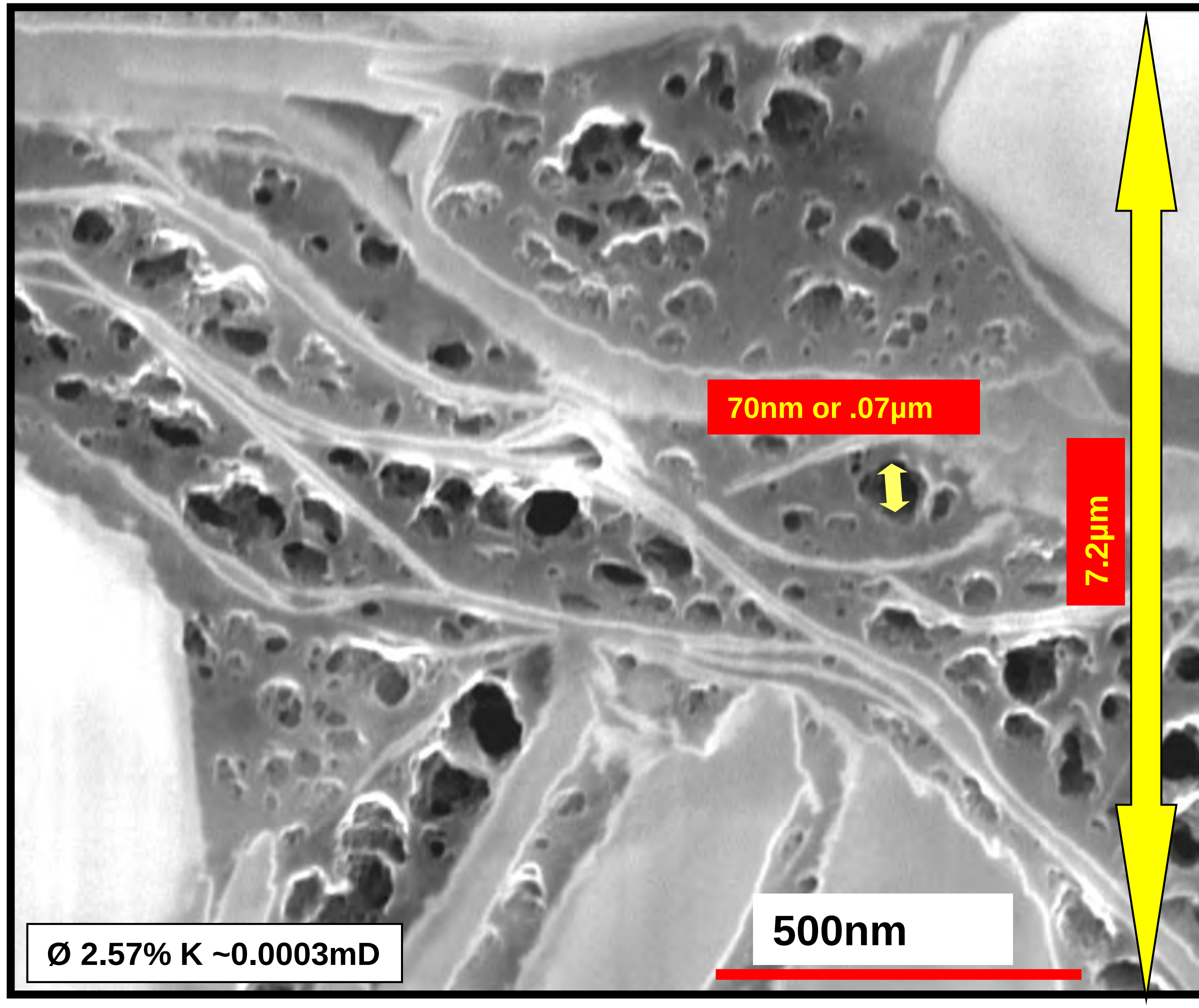


Motivation: porous rock network

Convention Sandstone Reservoir



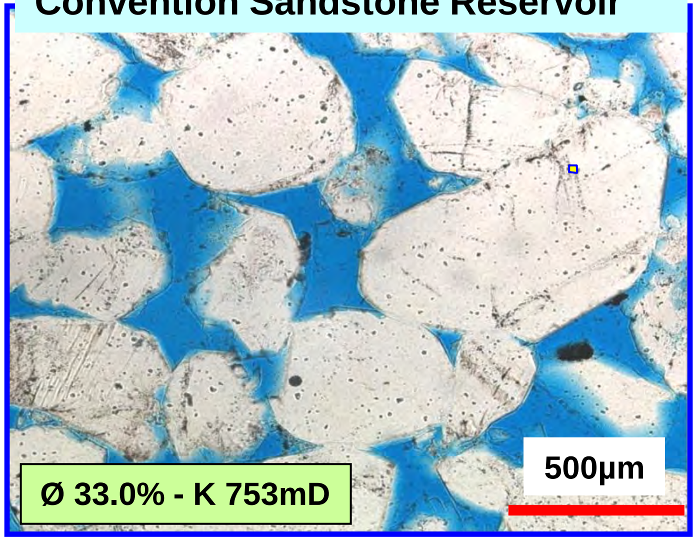
Shale Gas Reservoir, 70,000x Magnification



Important
- Oil and Gas
- Geology
- Hydrology

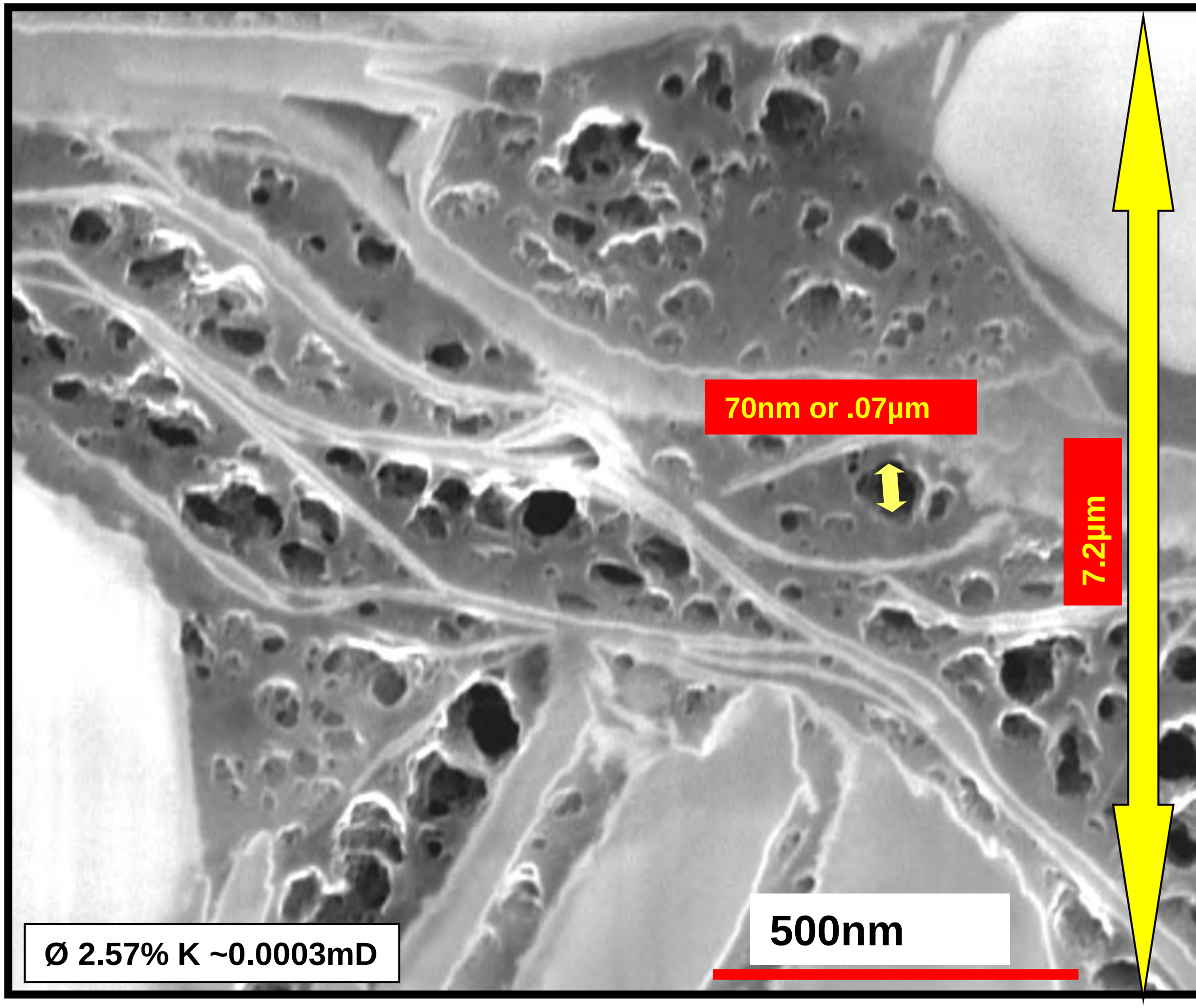
Motivation: porous rock network

Convention Sandstone Reservoir



Complex
- Multiscale
- Multiphase
- Multiphysics

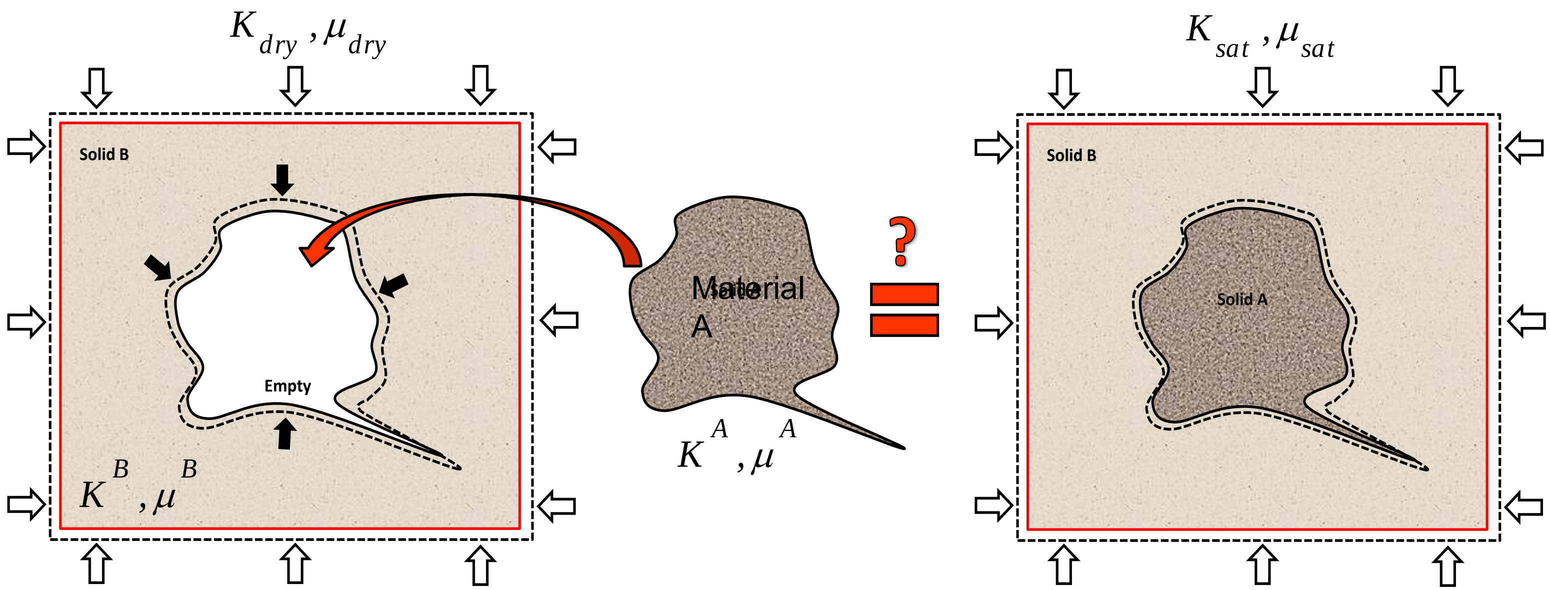
Shale Gas Reservoir, 70,000x Magnification



Goal: Validate Pore Filling Theory

- This Presentation,
  - Validates the use of solid material filling to replace more commonly used fluid filling theory;
  - Designs the validation framework using digital rock physics.
- Work in progress,
  - Derives generic pore filling theory;
  - Validates new theory in a similar framework with more complex physics.

Pore filling Theories: Substitution Equation



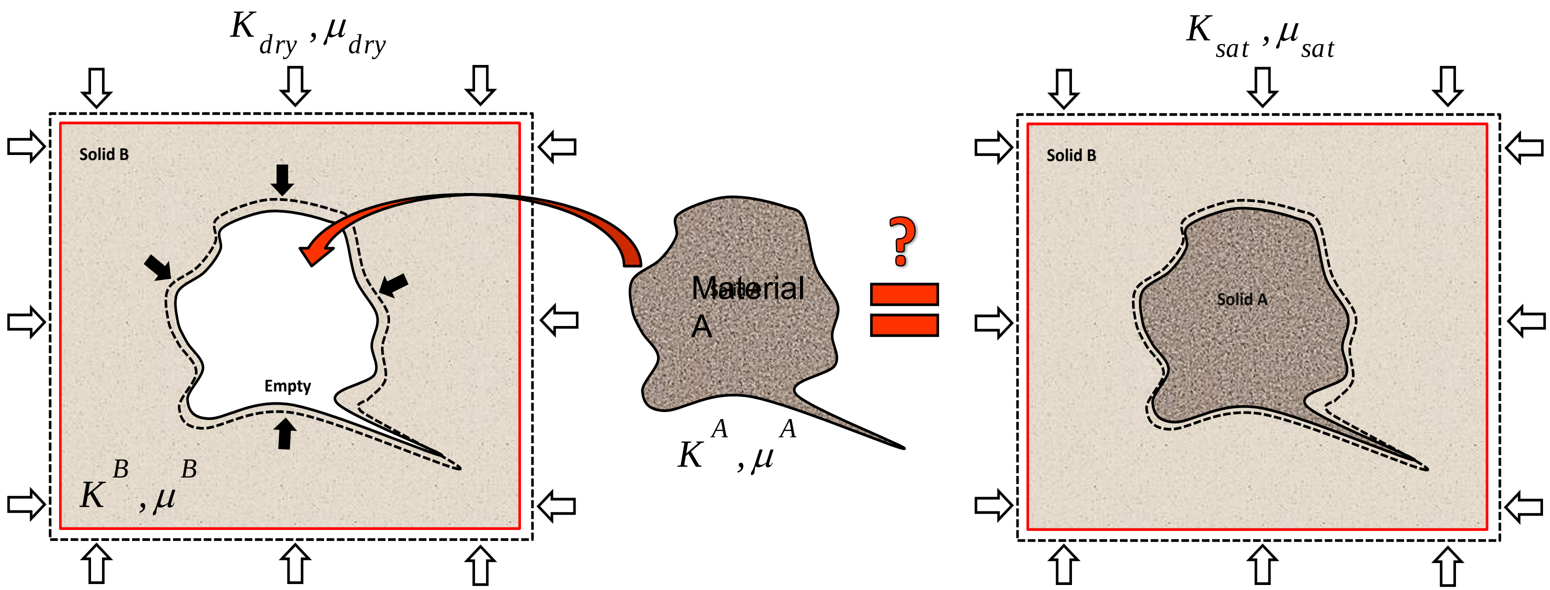
Fluid Substitution:

- Brine Sand, Oil Sand, Gas Sand

Solid Substitution:

- Heavy oil, Bitumen filled

Pore filling Theories: Substitution Equation



Fluid Substitution:
- Gassmann, 1951

$$K_{sat} = K_{frame} + \frac{\left(1 - \frac{K_{frame}}{K_{matrix}}\right)^2}{\frac{\phi}{K_{fl}} + \frac{(1-\phi)}{K_{matrix}} - \frac{K_{frame}}{K_{matrix}^2}}$$

Solid Substitution:
- Ciz & Shapiro, 1997

$$K_{sat} \approx \frac{\eta_0^A\left(\frac{1}{K^B} - \frac{1}{K^A}\right) + \left(\frac{1}{K^B} - \frac{1}{K_{dry}}\right)}{\frac{\eta_0^A}{K_{dry}}\left(\frac{1}{K^B} - \frac{1}{K^A}\right) + \frac{1}{K^B}\left(\frac{1}{K^B} - \frac{1}{K_{dry}}\right)}$$

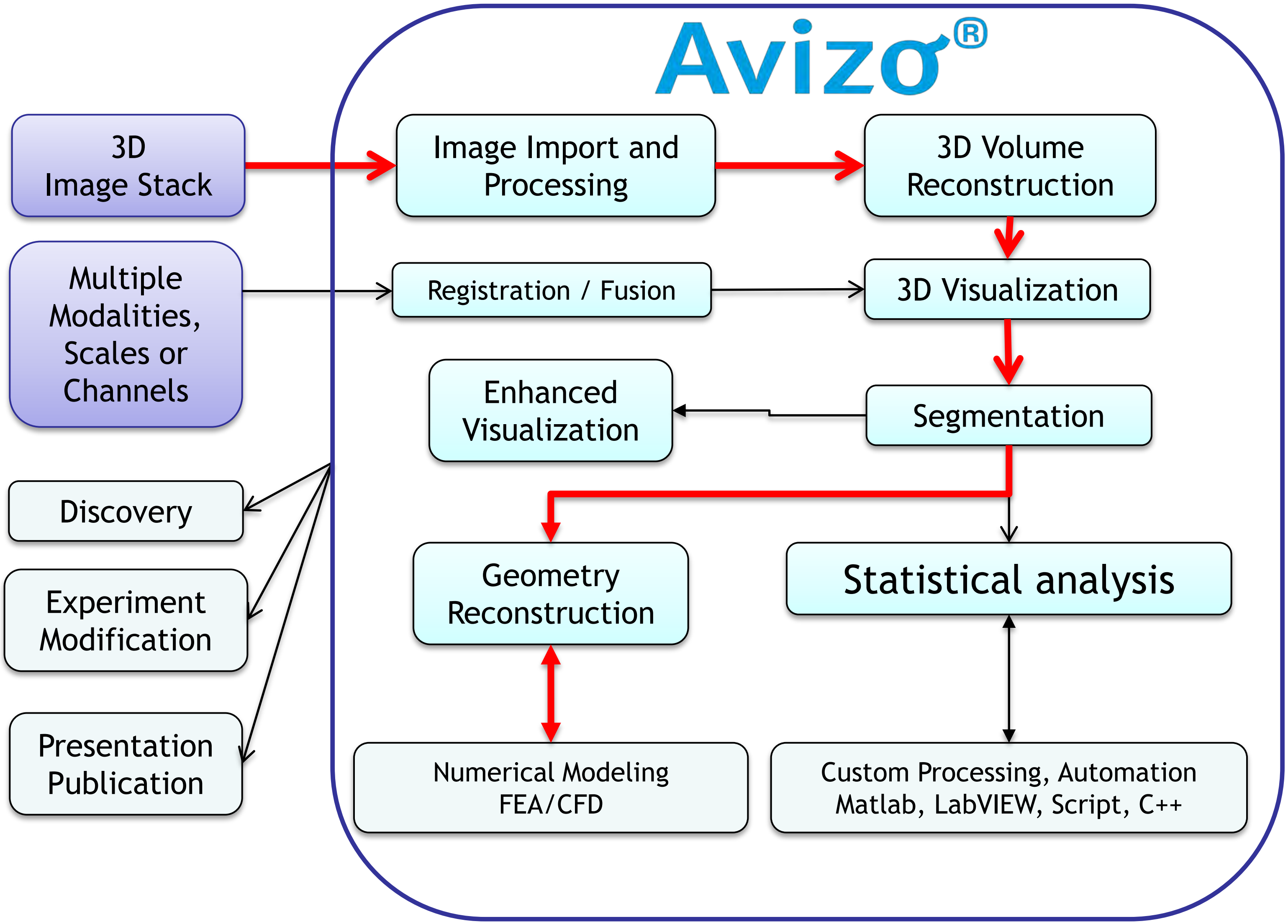
Solid Substitution equation

$$K_{sat} \approx \frac{\eta_0^A\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}{\frac{\eta_0^A}{K_{dry}}\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\frac{1}{K^B}\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}$$

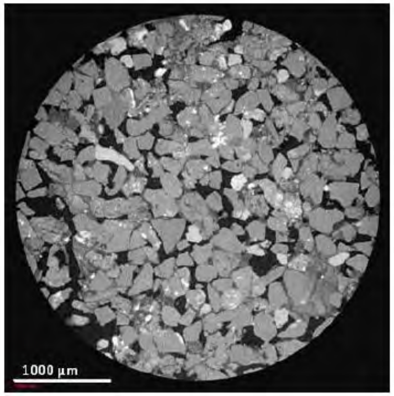
where

K_{sat}	Effective bulk modulus
η_0	Porosity
K_{dry}	Dry (drained) rock bulk modulus
K^A	Bulk modulus of the pore-filling mineral
K^B	Bulk modulus of the solid matrix

Avizo workflow



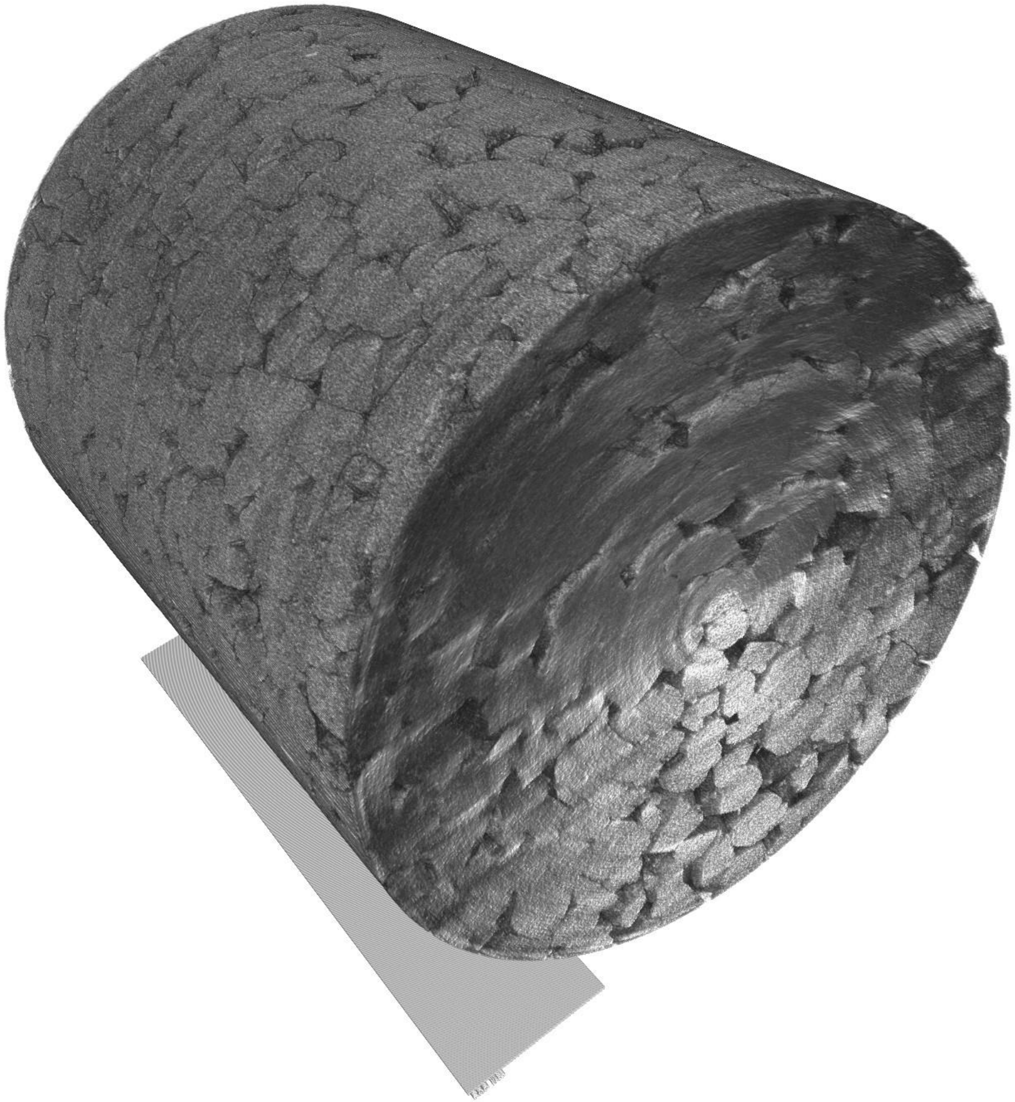
3D Imaging



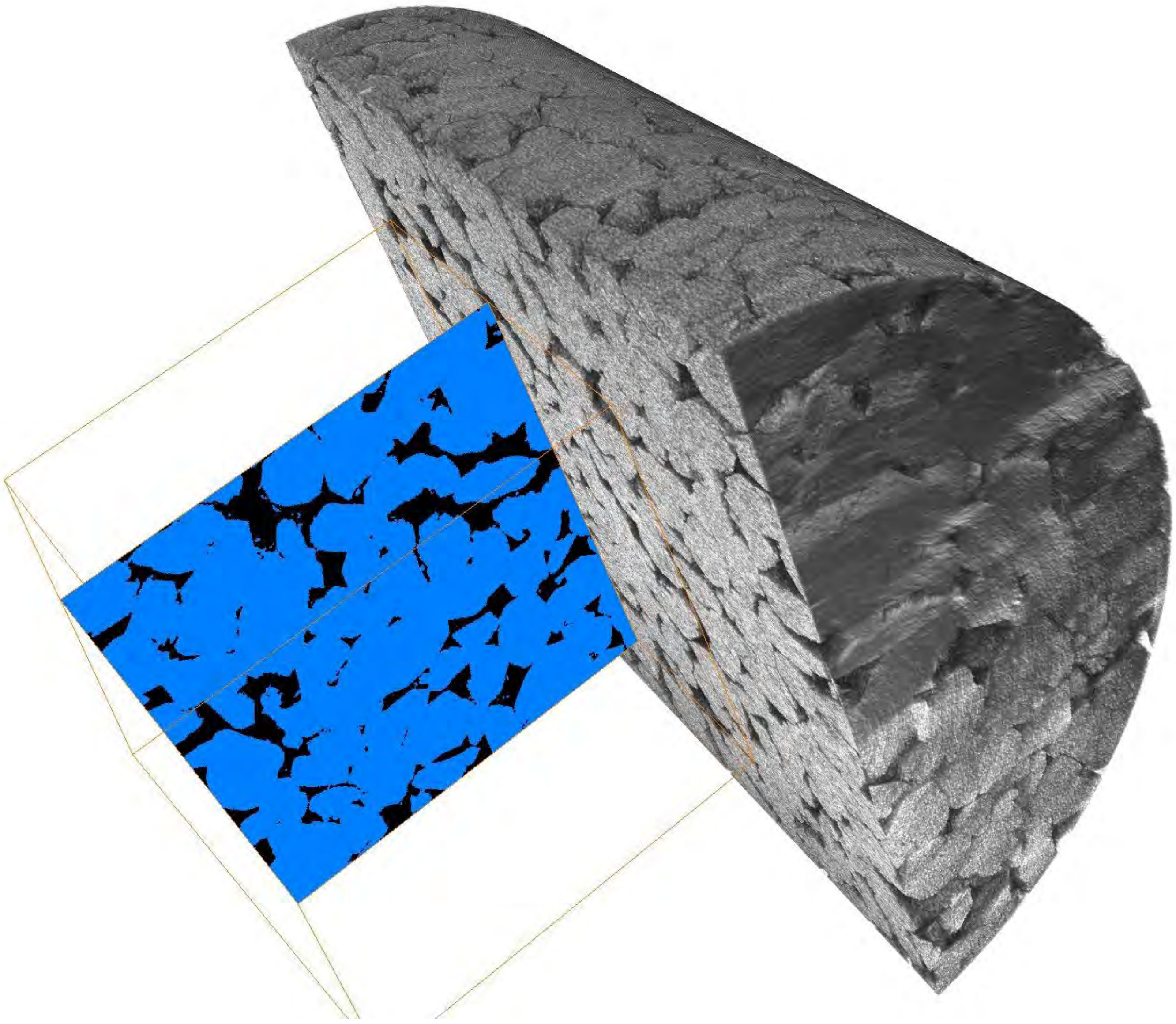
Imaging Data

- Electron microscopy
    - S/TEM tomography
    - TEM serial sectioning
    - FIB-SEM Nanotomography
- Light microscopy
    - Confocal
    - Polish and view 3D (e.g. Robo-MET)
- X-ray tomography
    - Industrial
    - Material sciences (micro and nano)
- MRI
- Ultrasound
- GPR
- LIDAR
- Remote Sensing Satellite Imagery

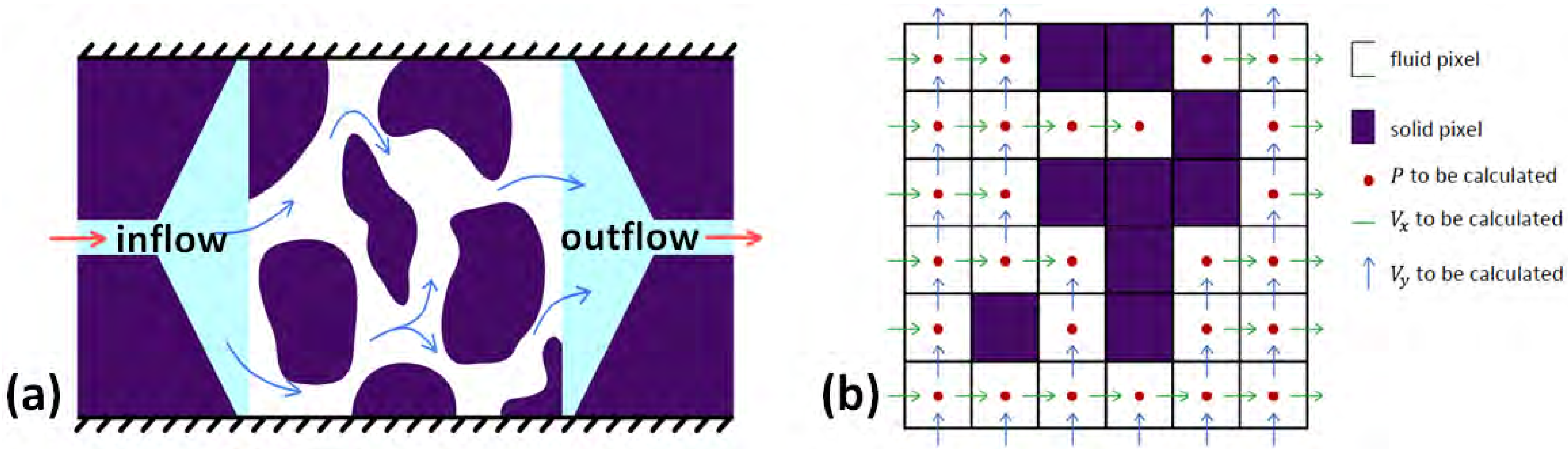
Reconstruction



Segmentation



Petrophysical parameters derived from image based simulation

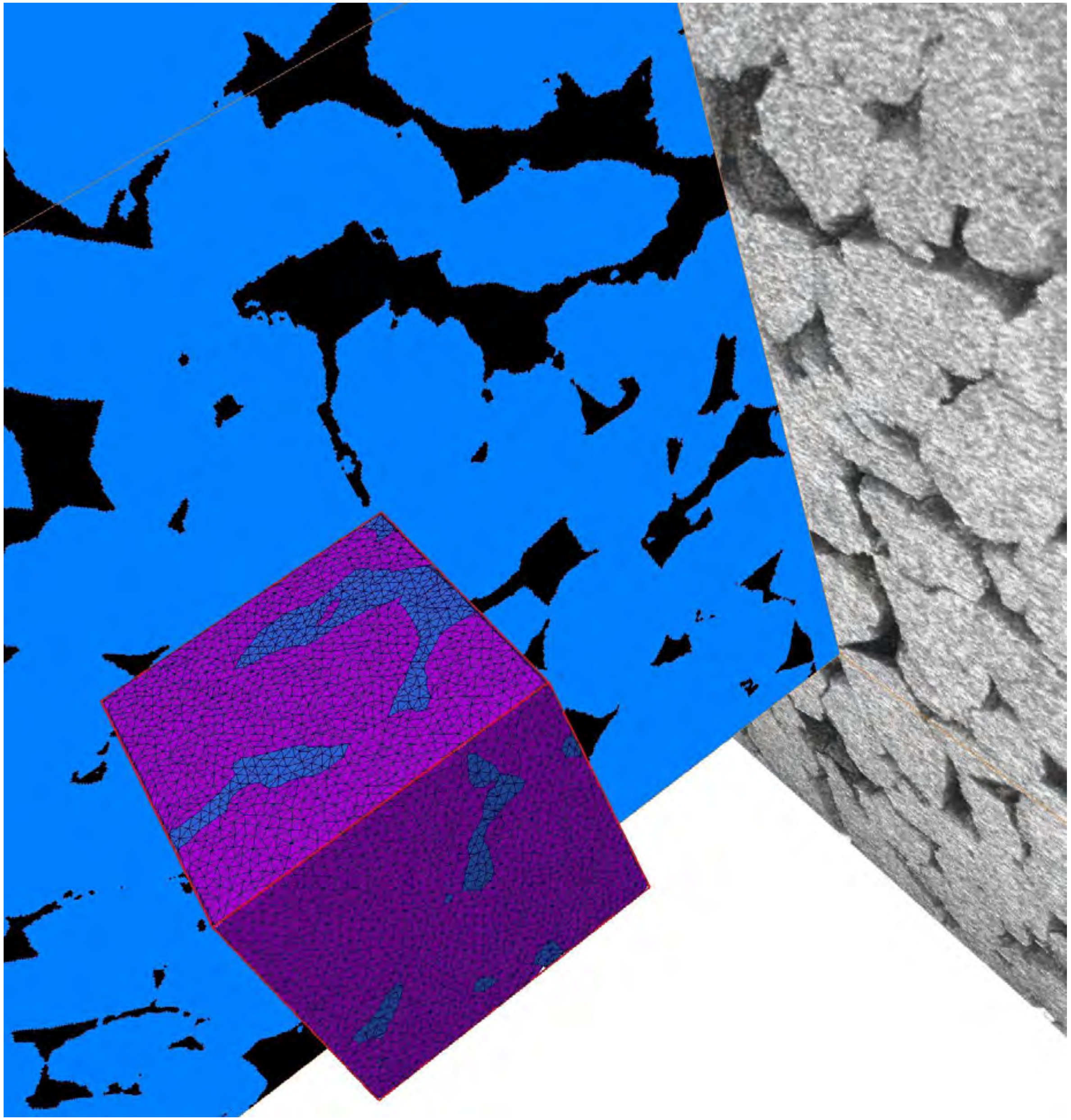


Porosity	0.168
Permeability X	$1x10^{-3}$ Darcy
Permeability Y	$0.89x10^{-3}$ Darcy
Permeability Z	$0.57x10^{-3}$ Darcy

Mesh reconstruction & Comsol BC

Boundary conditions,

- Normal displacement at external surface with strain 10^-3.
- Continuity of displacement and traction at pore/rock interface.
- Quasi-static simulation (inertial effects are negligible).

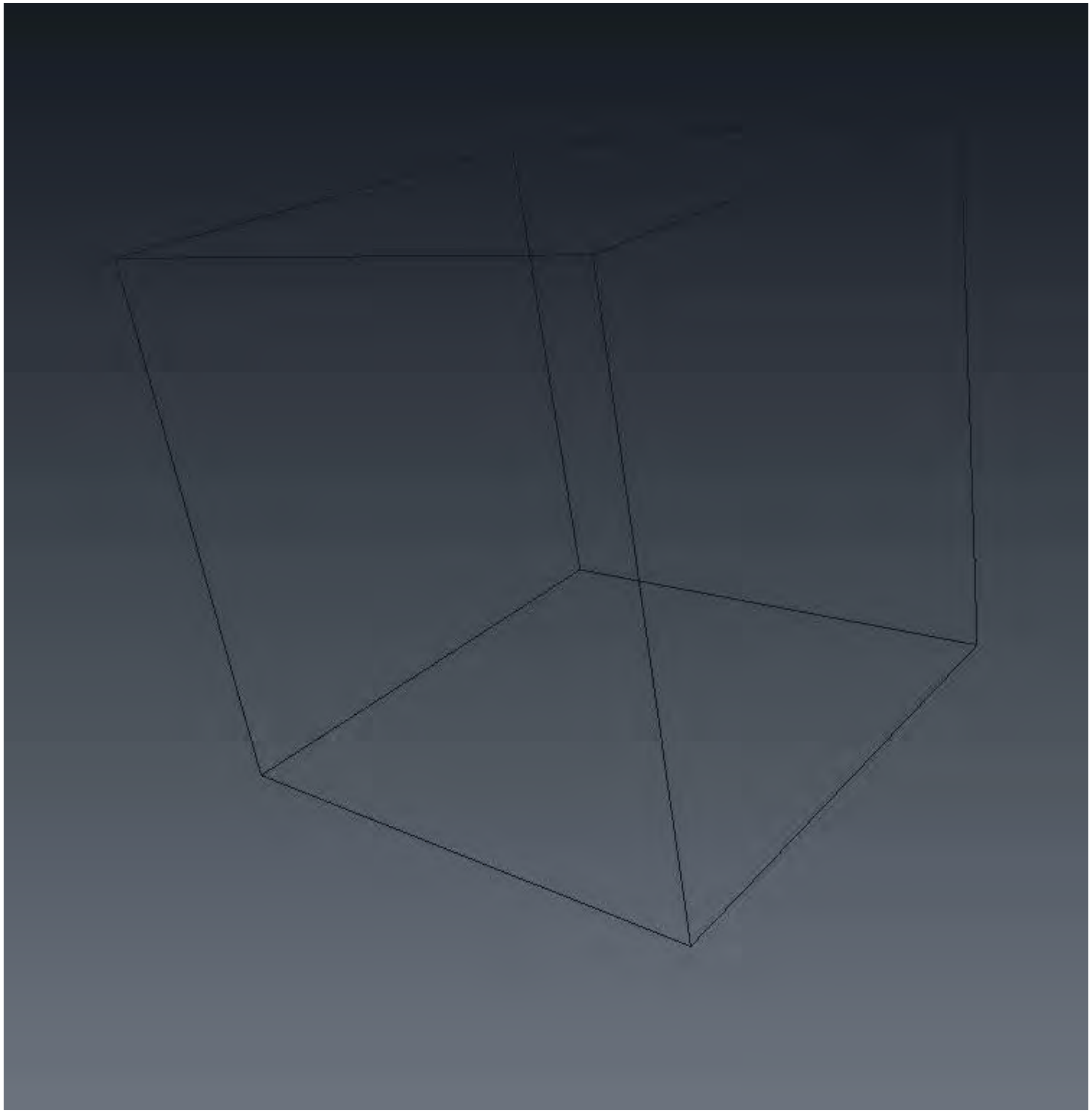


Different Pore-filling Material: Pressure

$$K_{sat} \approx \frac{\eta_0^A\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}{\frac{\eta_0^A}{K_{dry}}\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\frac{1}{K^B}\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}$$

Different K^A (Pa)

0	0.01×10^{10}
1	0.41×10^{10}
2	0.81×10^{10}
3	1.21×10^{10}
4	1.61×10^{10}
5	2.01×10^{10}
6	2.41×10^{10}
7	2.81×10^{10}
8	3.21×10^{10}



Different Pore-filling Material: Strain

$$K_{sat} \approx \frac{\eta_0^A\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}{\frac{\eta_0^A}{K_{dry}}\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\frac{1}{K^B}\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}$$

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7	2.81×10^{10}
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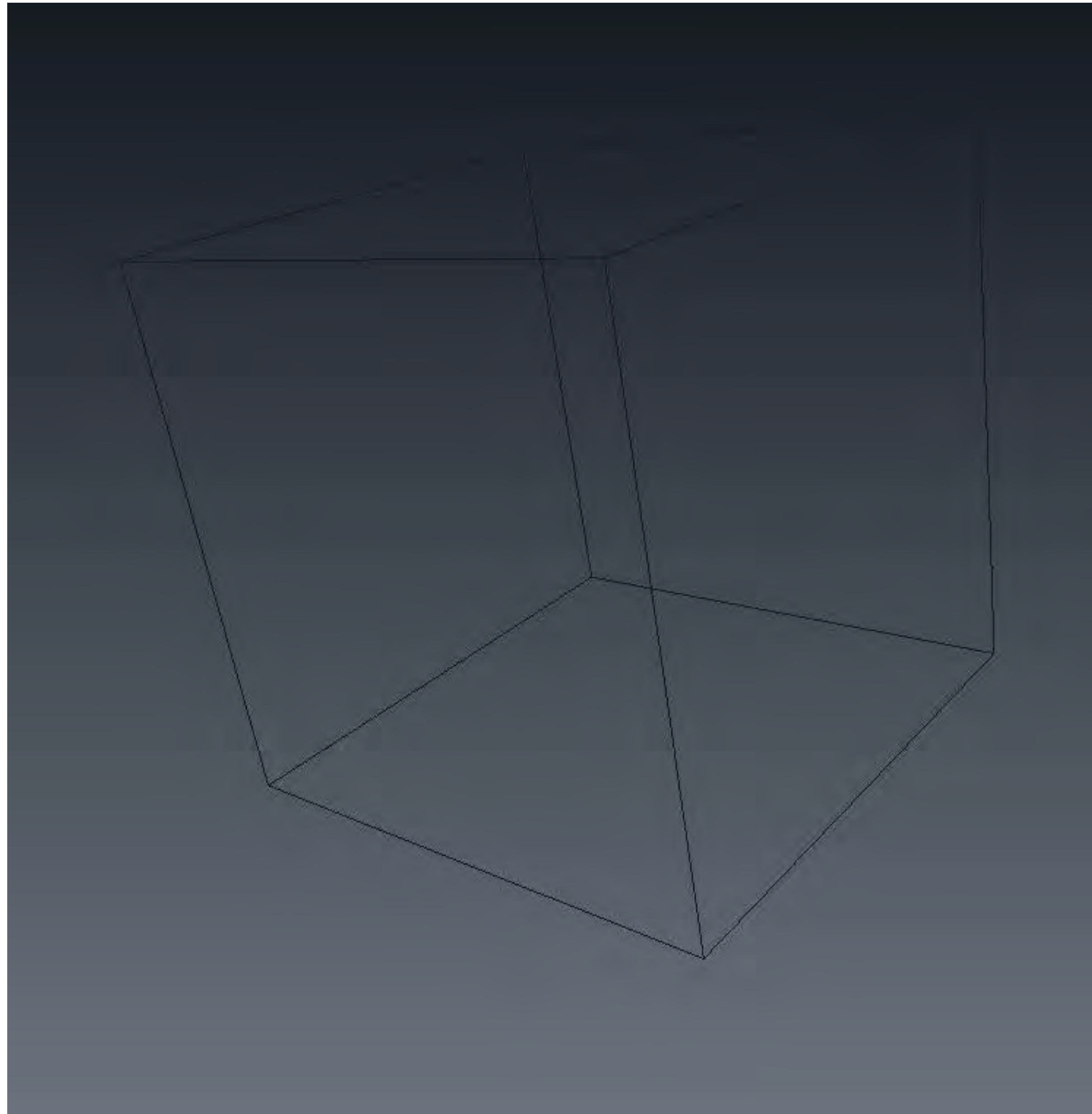

Different Pore-filling Material: Validation

$$K_{sat} \approx \frac{\eta_0^A\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}{\frac{\eta_0^A}{K_{dry}}\left(\frac{1}{K^B}-\frac{1}{K^A}\right)+\frac{1}{K^B}\left(\frac{1}{K^B}-\frac{1}{K_{dry}}\right)}$$

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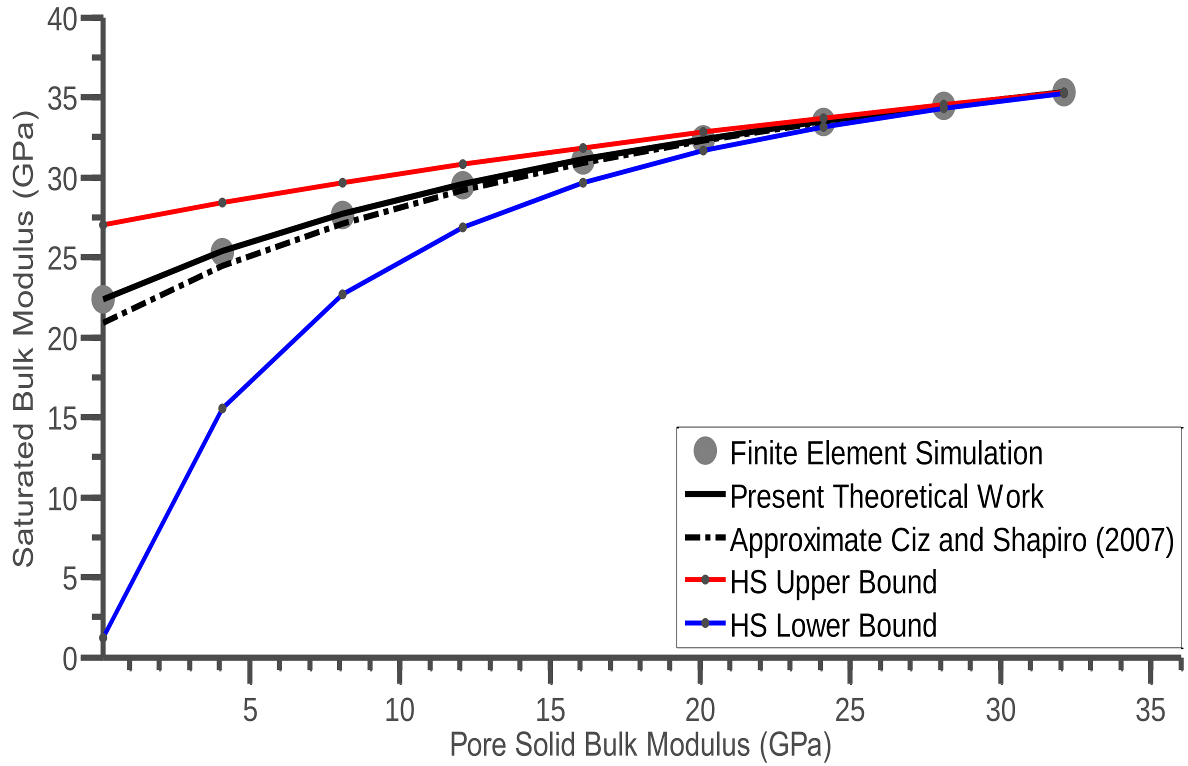

Concluding remarks

- A theoretical rock pore material substitution model is validated with a digital rock physics framework.
- We are working on,
  - Derives generic pore filling theory;
  - Validate it in a similar framework but with more complex physics, e.g., shear traction, fluid structure interaction, etc.

K_{dry} $K_{pseudo-dry}$

Solid B

Applied Stress
Deformed body
Reference body
Internal traction
Stress to maintain
$\overline{P}^A = P^0$

Empty