Natural Fracture Behavior Under Increasing Confining Pressure, Applying Helical CT Scanning Technology*

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Conclusion

- Kinematic aperture is not sufficient data.
- Core must be pressurized for accurate porosity calculations.
- With advances in CT scanning and software we can:
  - Visualize 3D volumes of materials within fractures,
  - Quantify fracture porosity,
  - Bring core closer to reservoir conditions by pressurizing samples,
  - Find the porosity volume preserved in a partially cemented fracture,
  - Distinguish between kinematic and effective aperture in the subsurface.
- Are all fractures closed under stress? -Not really.

Reference

Nelson, R.A., 2001, Geologic Analysis of Fractured Reservoirs: Second Edition, 352 p.

AAPG GTW Baltimore, July 2013

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Natural Fracture Behavior Under Increasing Confining Pressure

Applying Helical CT Scanning Technology

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40 LABORATORY LOCATIONS IN 22 COUNTRIES

NORTH AMERICA
Canada
United States

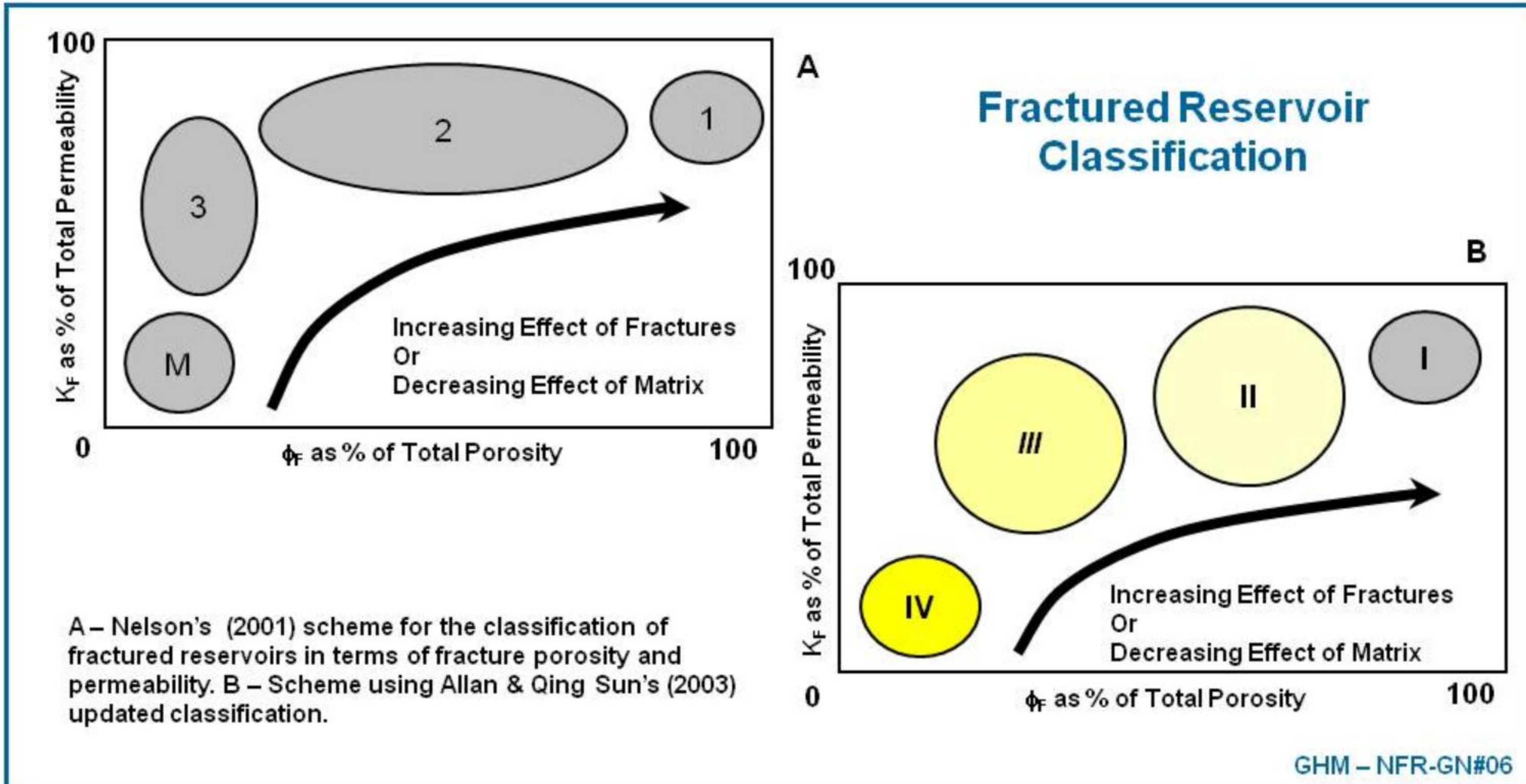
EUROPE
Norway
United Kingdom
Kazakhstan

LATIN AMERICA
Brazil
Mexico
Trinidad
Venezuela
Argentina

MIDDLE EAST / NORTH AFRICA
Kuwait
Libya
Oman
Saudi Arabia
United Arab Emirates
Iraq

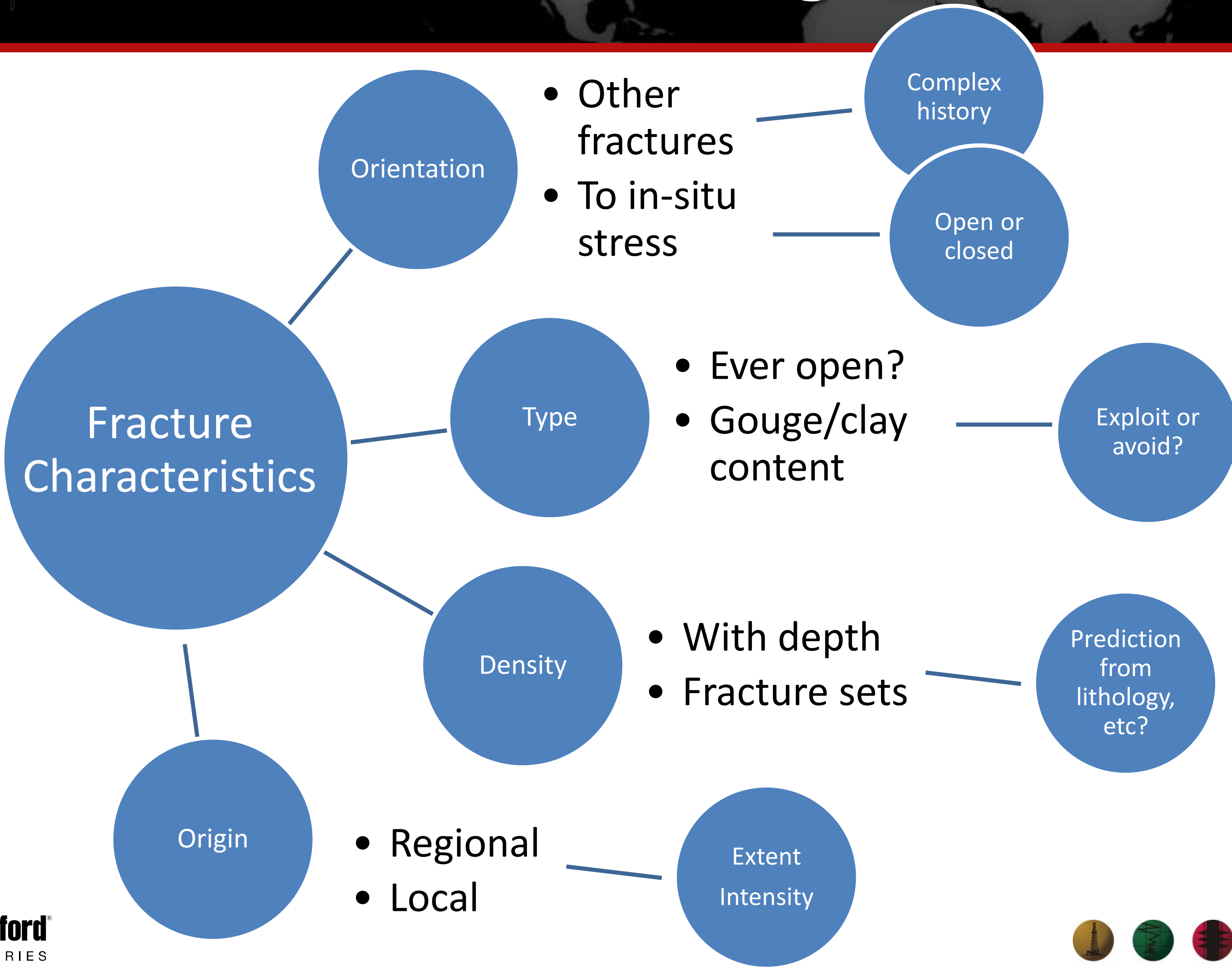
ASIA PACIFIC
Australia
India
Malaysia
Thailand
New Zealand
Indonesia

Fractured Reservoir Classification



A) Nelson (2001); B) Allan and Qing Sun (2003)

Natural Fracture Analysis in Core



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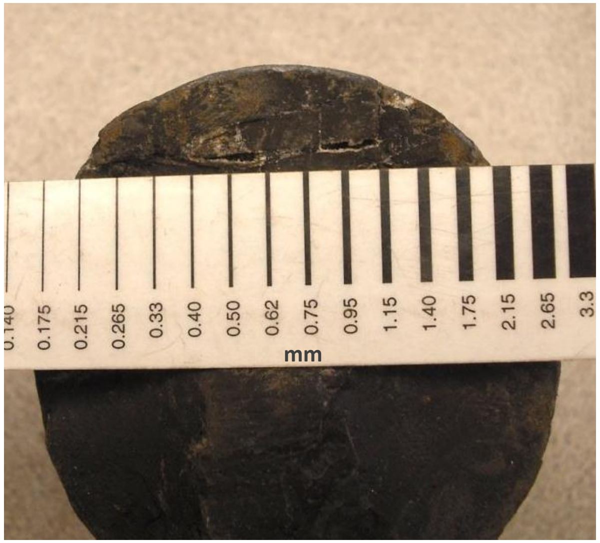
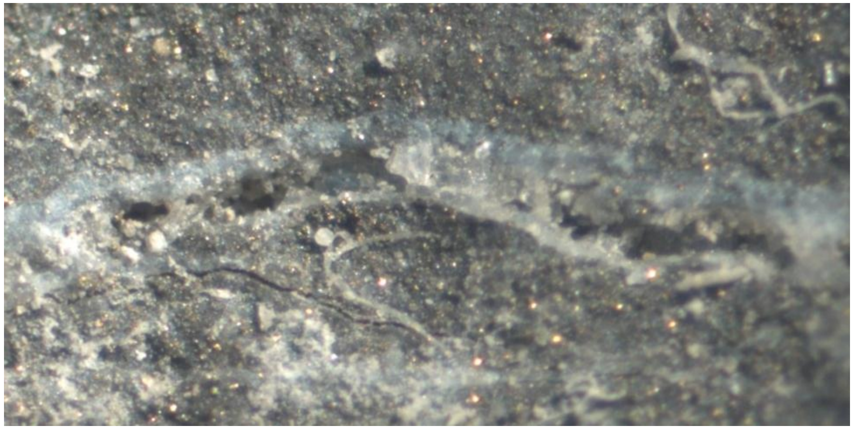
Natural Fracture Permeability

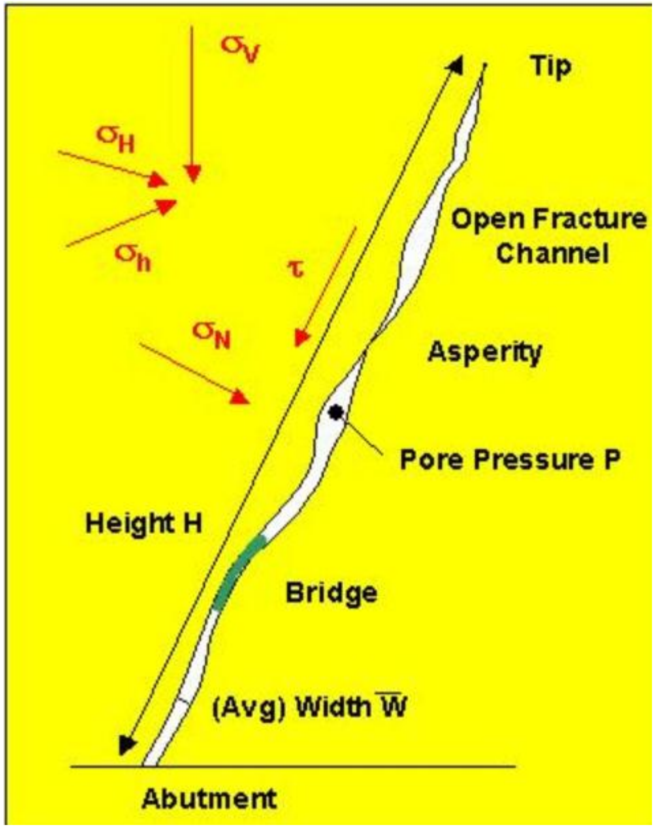
- Dependent on:
  - Orientation of fracture plane
  - *In situ* stress
    - S_{Hmin} normal to plane
    - S_{Hmax} oblique to plane
  - Pore fluid pressure within fracture
    - Overpressured is best
    - Hydrostatic pressure is neutral
    - Underpressured is bad
  - Fracture roughness

How do we determine fracture ϕ and k for fracture sets?

Fracture Morphology







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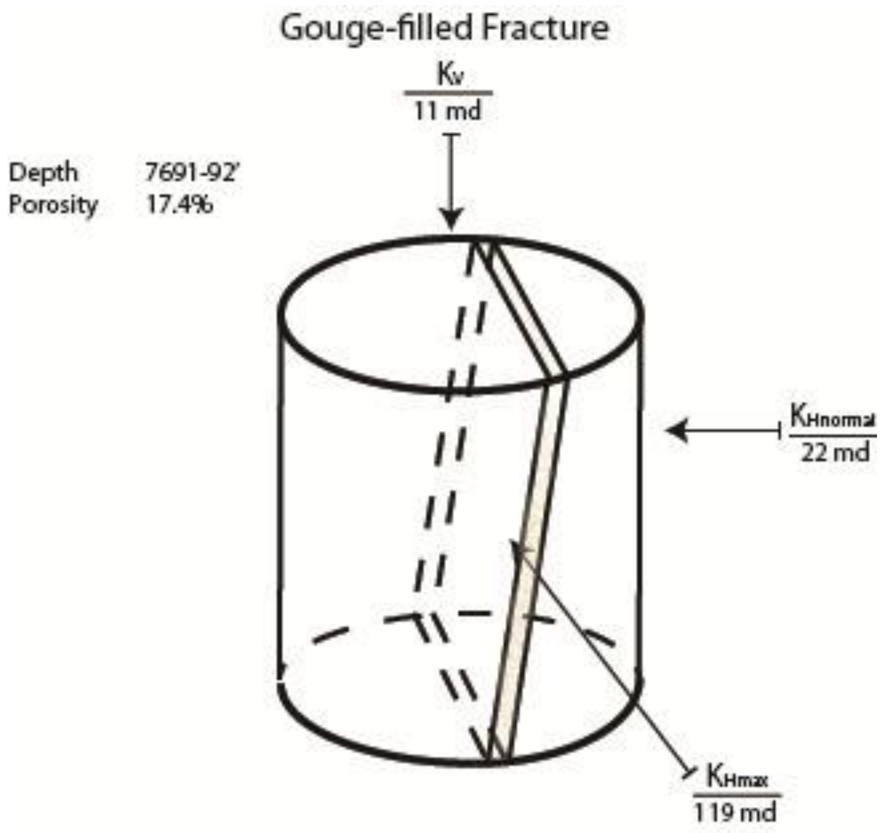
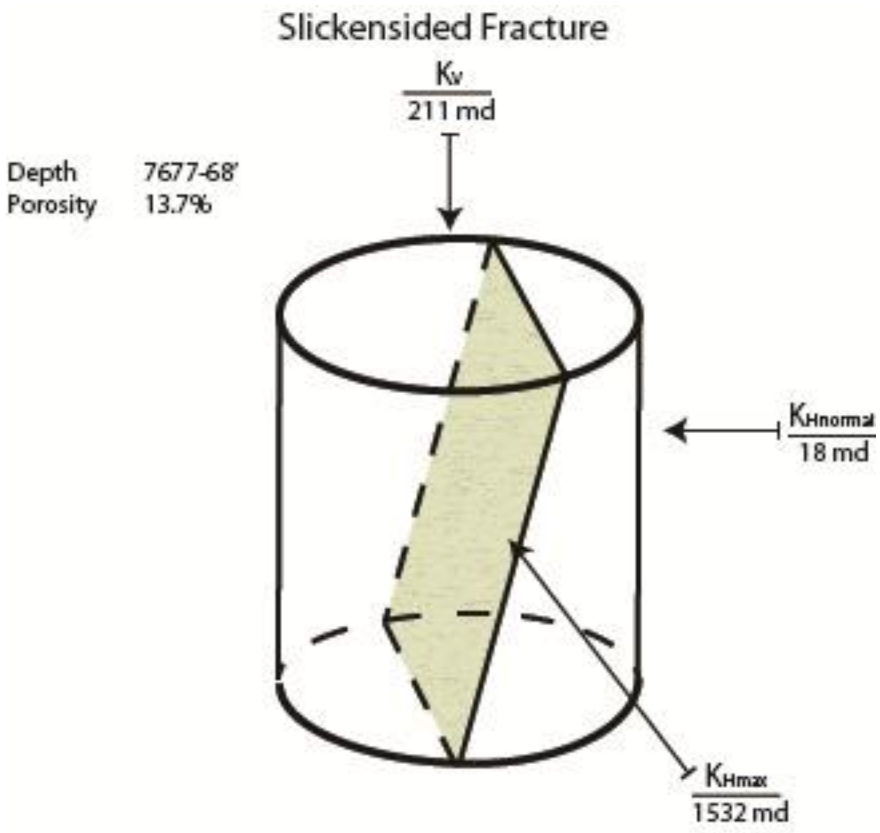
Fracture / Matrix Permeability

Fault Permeability Effect





After Nelson, 2001

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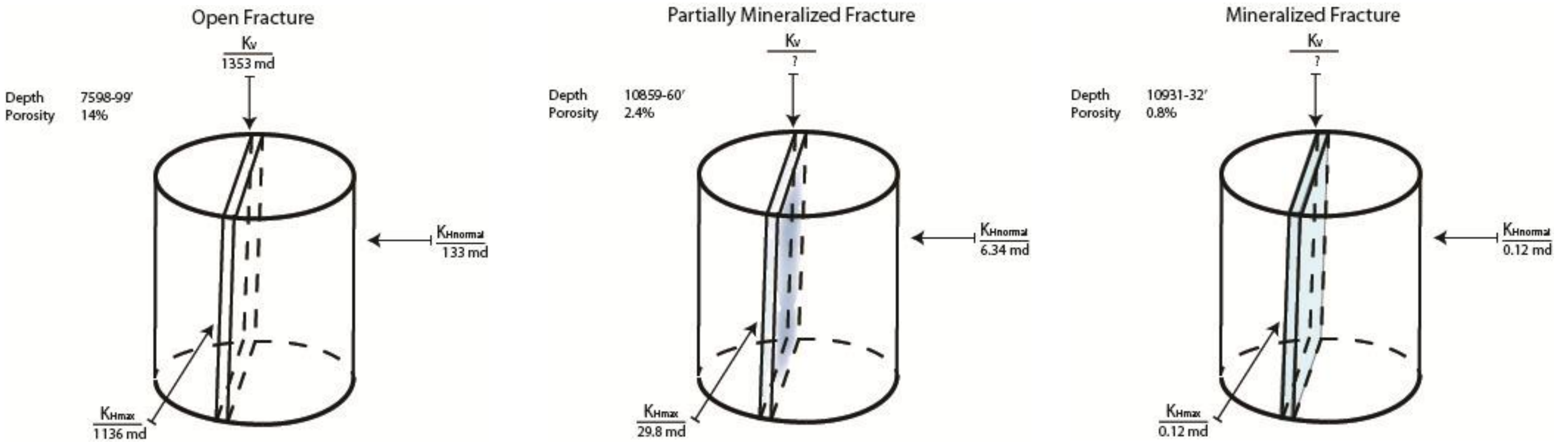
Joint Permeability Effect

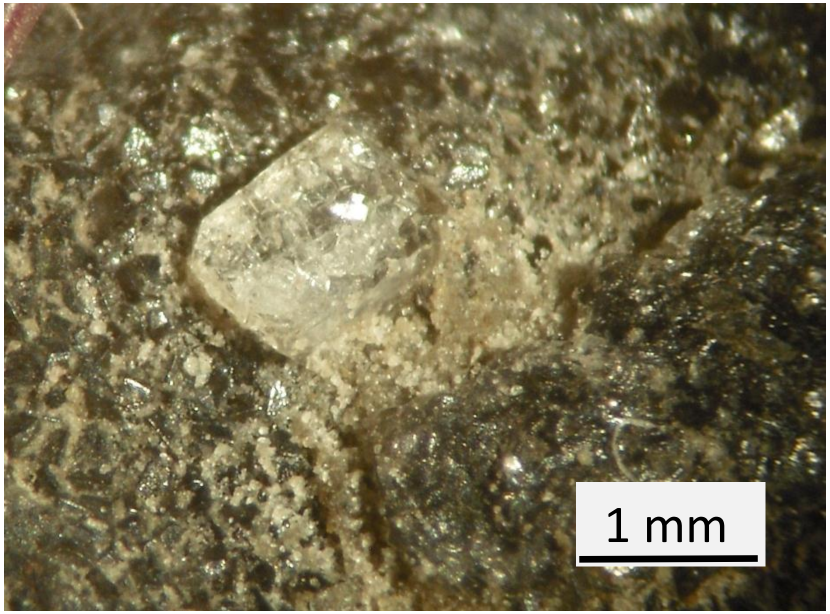


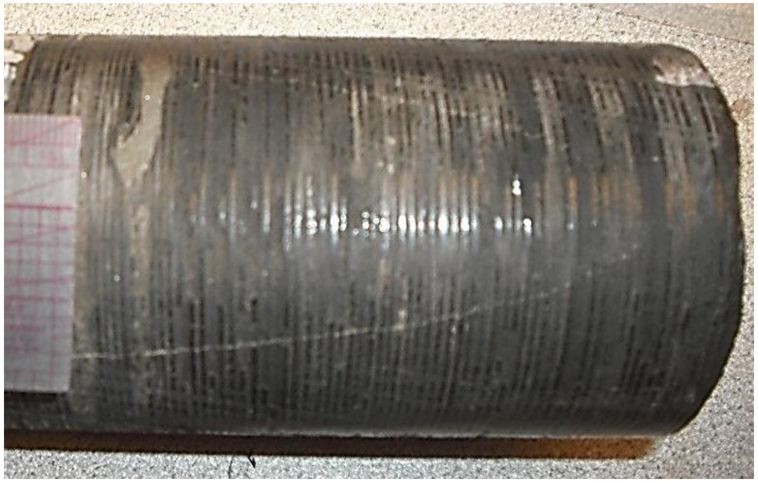
After Nelson, 2001

Large uncertainty in determining the permeability of partially and fully mineralized joints!

Aperture

- Partially or fully mineralized
- Often irregular (asperities, bridges, etc.)
- Measured in core or thin section
- Calculated in image logs
- Kinematic aperture versus effective aperture
- Related to porosity and permeability
- Changes with stress-state
  - Dependent on cement strength



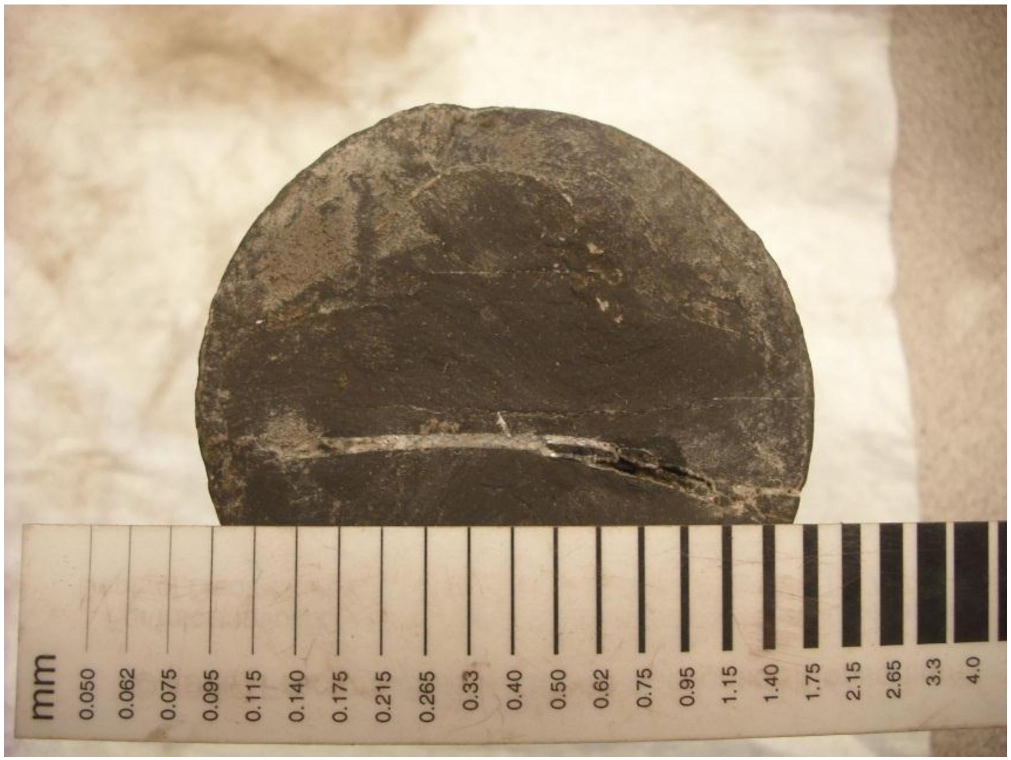


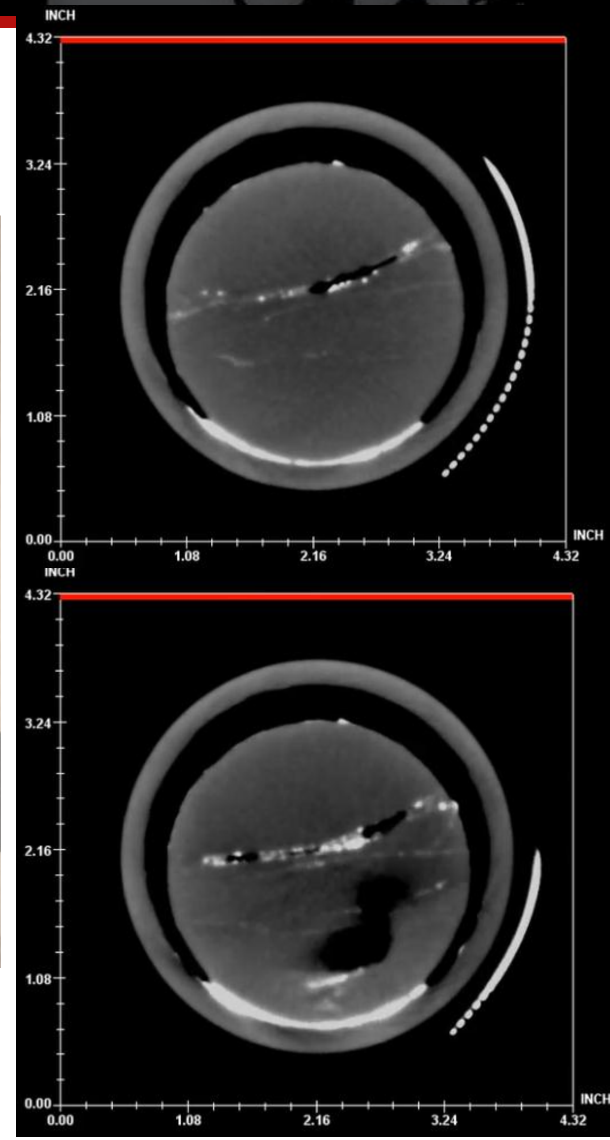
Effective Aperture

- Kinematic aperture
  - Cubic-law could be used if:
    - Ideal open fracture
    - No asperities, cement bridges, etc.
    - Laminar flow of a Newtonian fluid
- Fracture roughness
  - Joint Roughness Coefficient
- Percent Contact Area
- Percent mineralization
  - Mineralization threshold values

Large uncertainties

Helical CT Scanning





Fracture Volume Modeling

- Volume modeling can help to determine:
  - Volume of pore space
  - Volume of mineralization
  - Connectivity of porosity

Detailed Fracture Analysis
- Determine dominant fracture set(s)

→

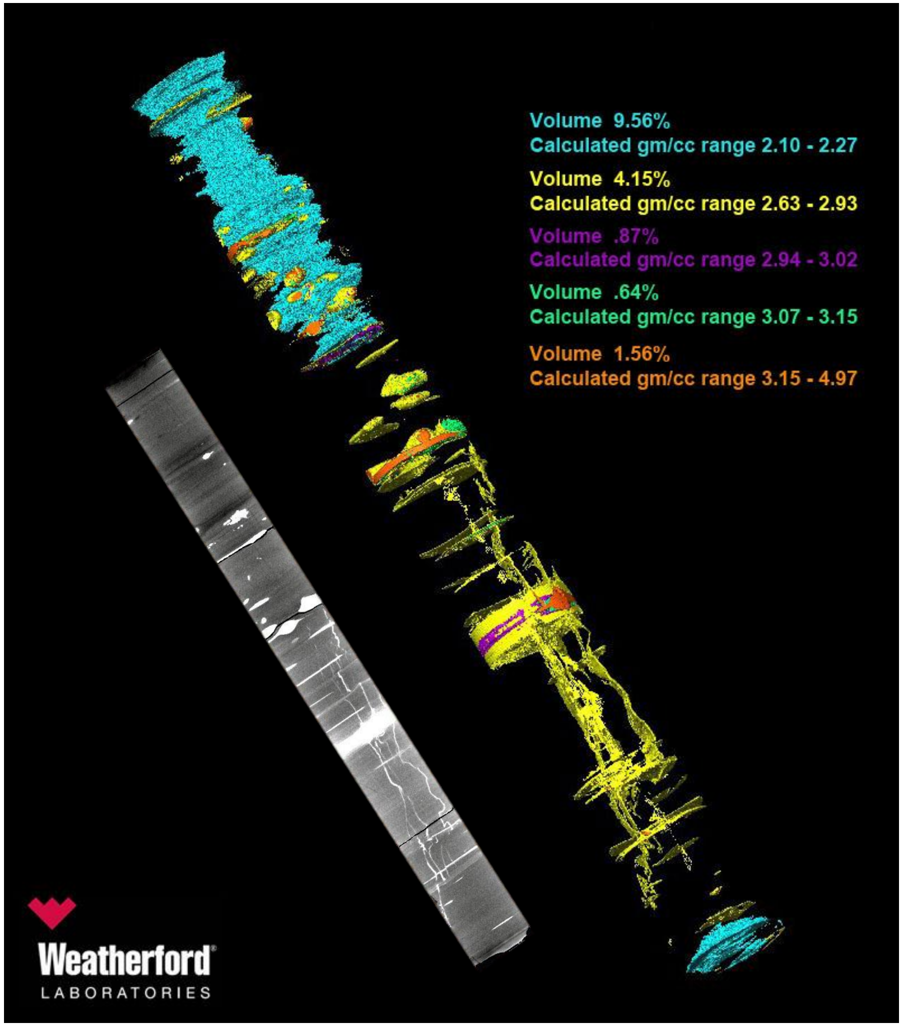
Select Representative Zone
- Representative fracture
- Representative zone within fracture

→

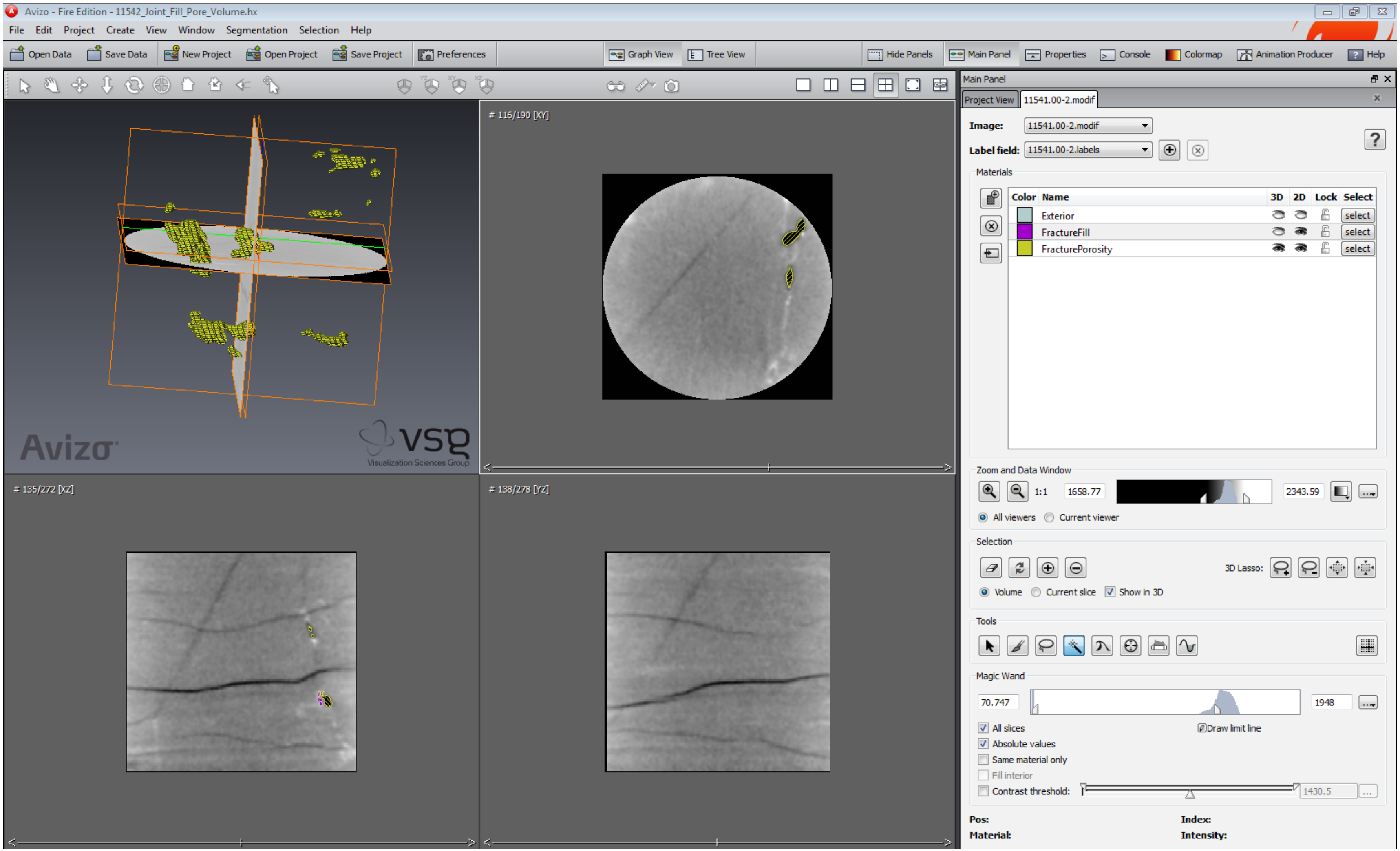
Volume Modeling and Statistical Analysis
- Segmentation of fracture
- Material within fracture

64 Slice Helical CT Scanner

- Converted medical scanner
- 0.3 mm voxel resolution
- Approx. 3200 data points per 3ft.
- CT Number and Calculated Density
- Avizo Fire ® Software for volume modeling



Avizo® Fire Volume Modeling



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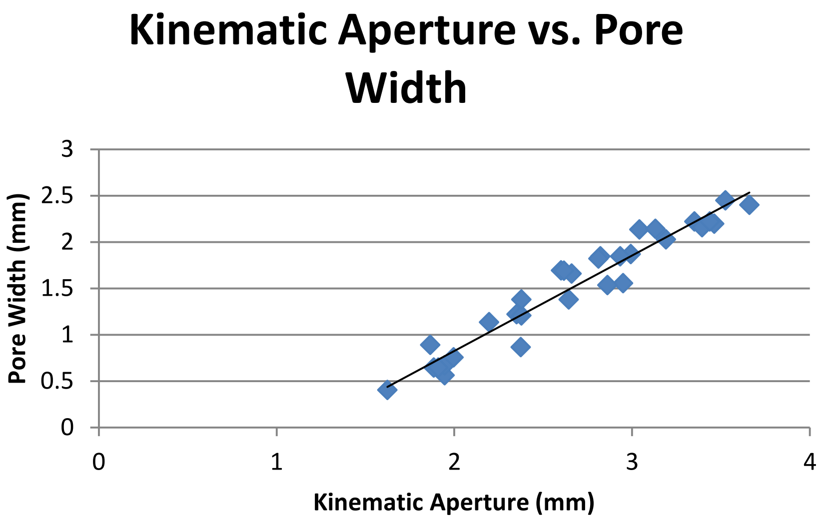
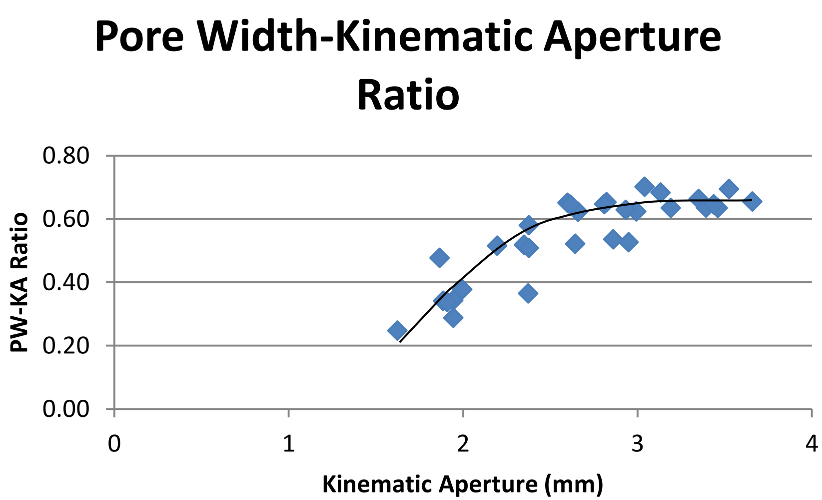
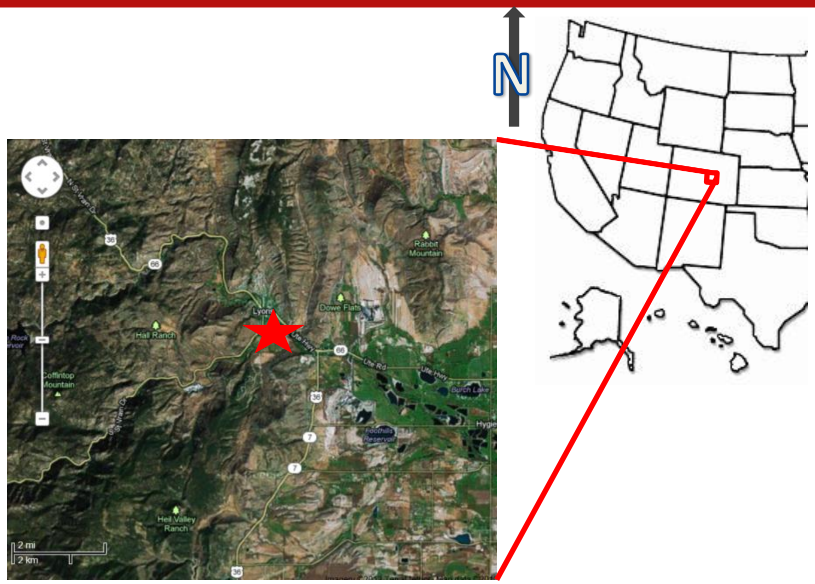
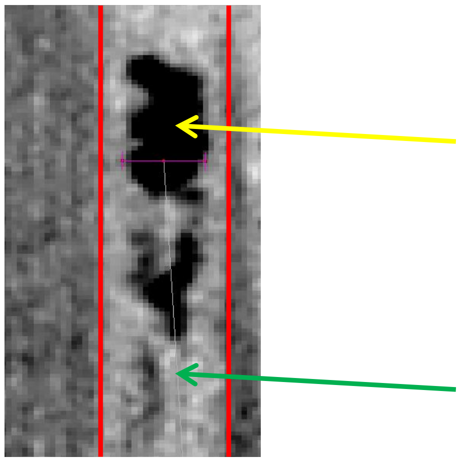
Width Measurements









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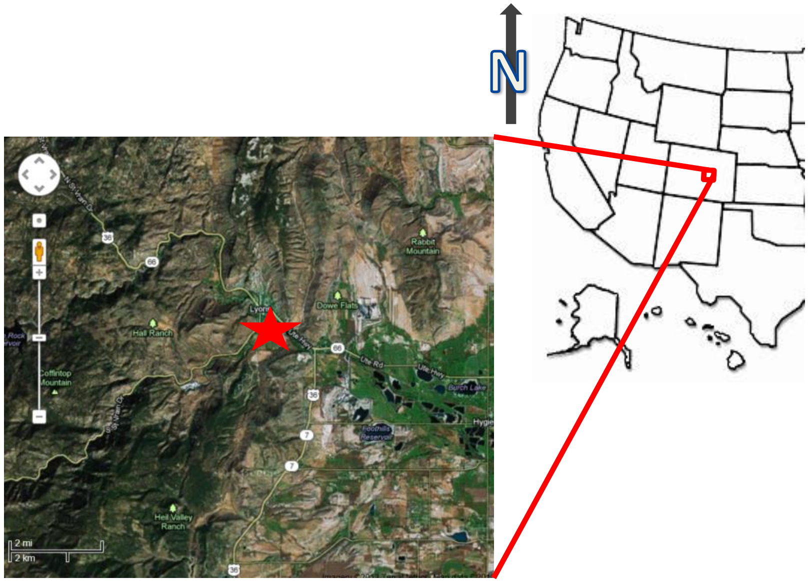
CEMEX Quarry

- Cretaceous Niobrara Formation
- CEMEX Quarry
- Calcite-filled



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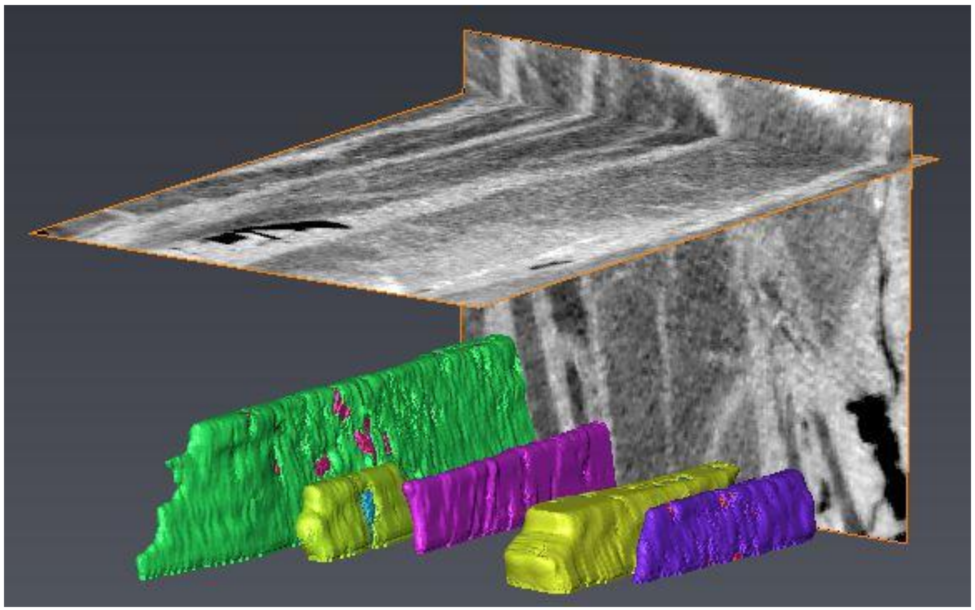
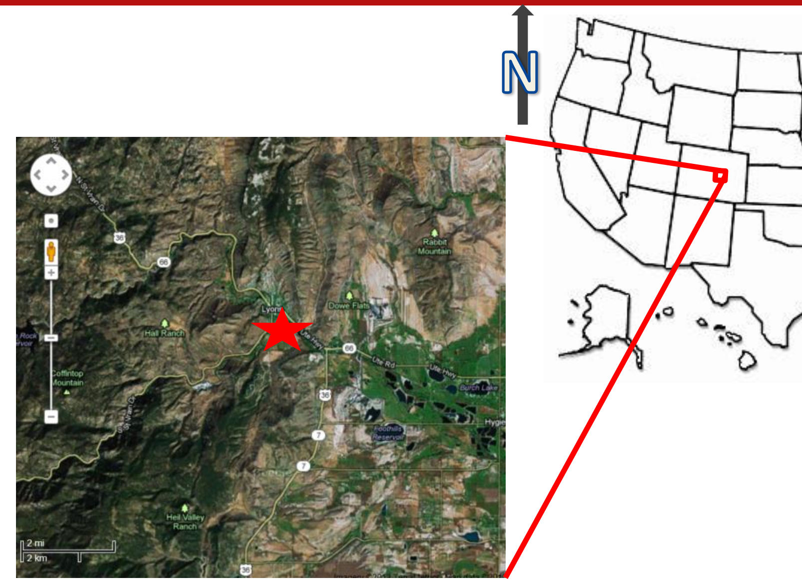
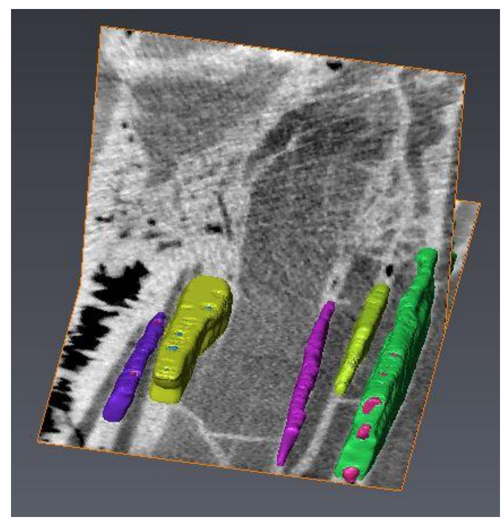
CEMEX Quarry

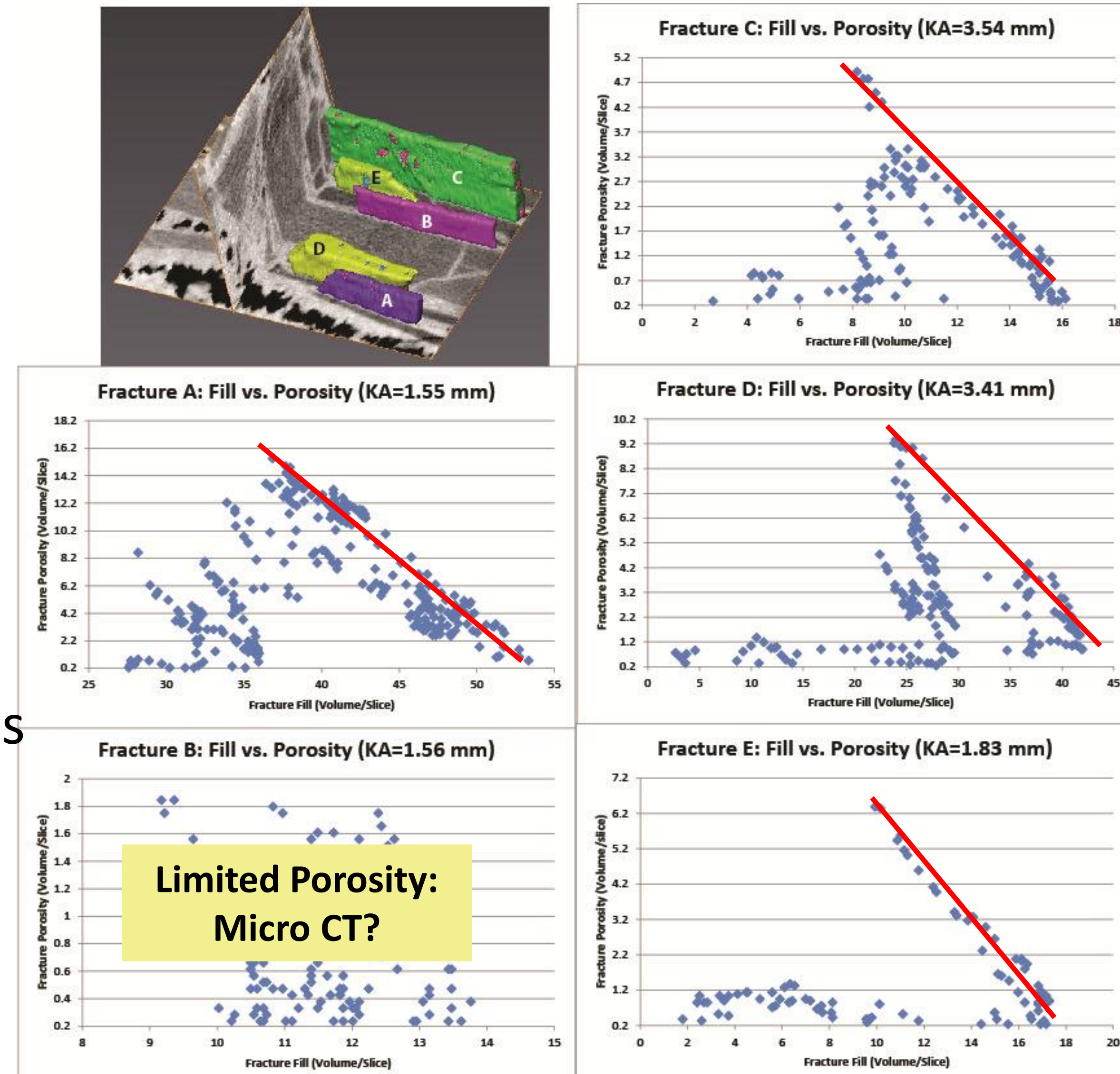






Volume Modeling

- Multiple threshold peaks where porosity is preserved
- Peak in porosity in variable aperture fractures (A, C, and D)
- Final decline in porosity where cement bridges exist holding the fractures open (red lines)



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Confining Pressure Test

- Core is not at reservoir conditions
- Porosity and permeability are maximum values
- Get to subsurface conditions for more realistic values

Plug Fractured Zone

- 1 ½” plug of fracture
- Partially calcite mineralized

→

CT Scan in Carbon Fiber Core Holder

- 500 psi to 5000 psi
- Incrementally Increasing Pressure (250 psi to 1250 psi)

→

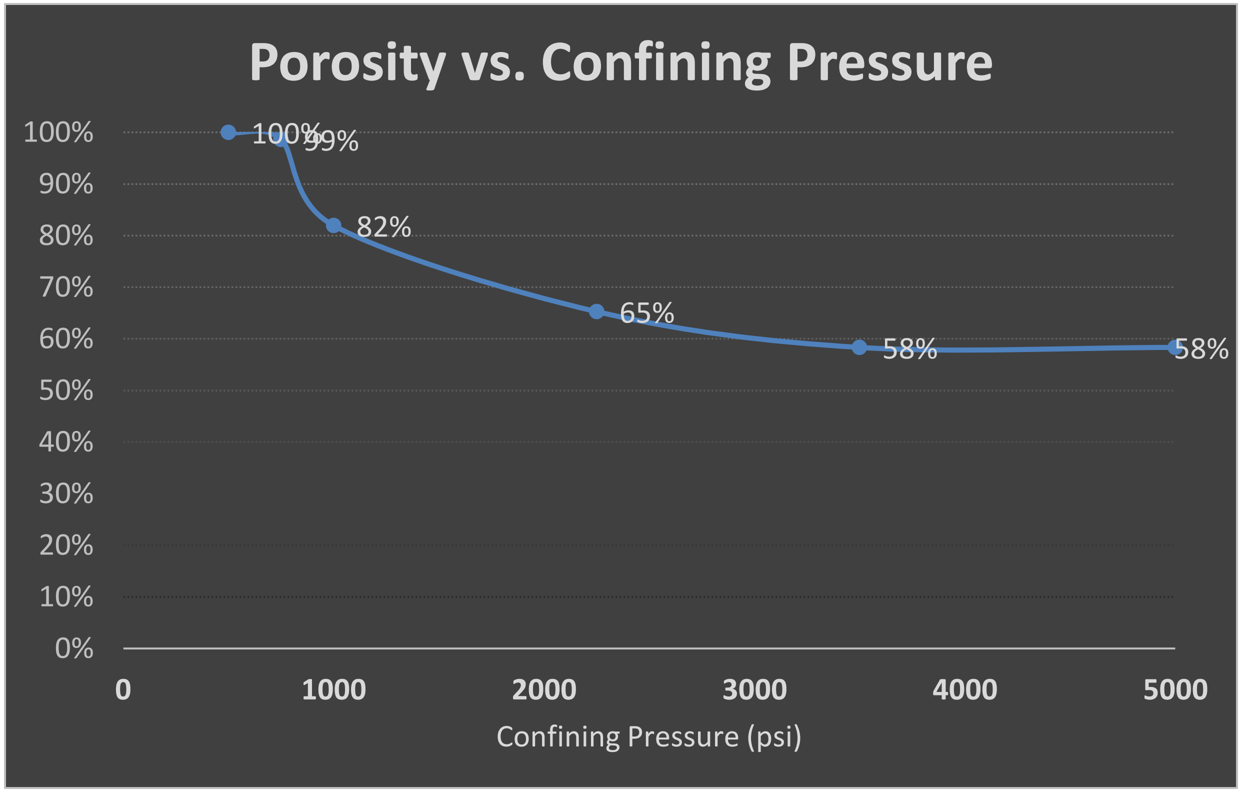
Volume Modeling and Statistical Analysis

- Segmentation of fracture
- Porosity within fracture
- Set CT Number (Hu) Range

Fracture Volume Modeling (BEG)

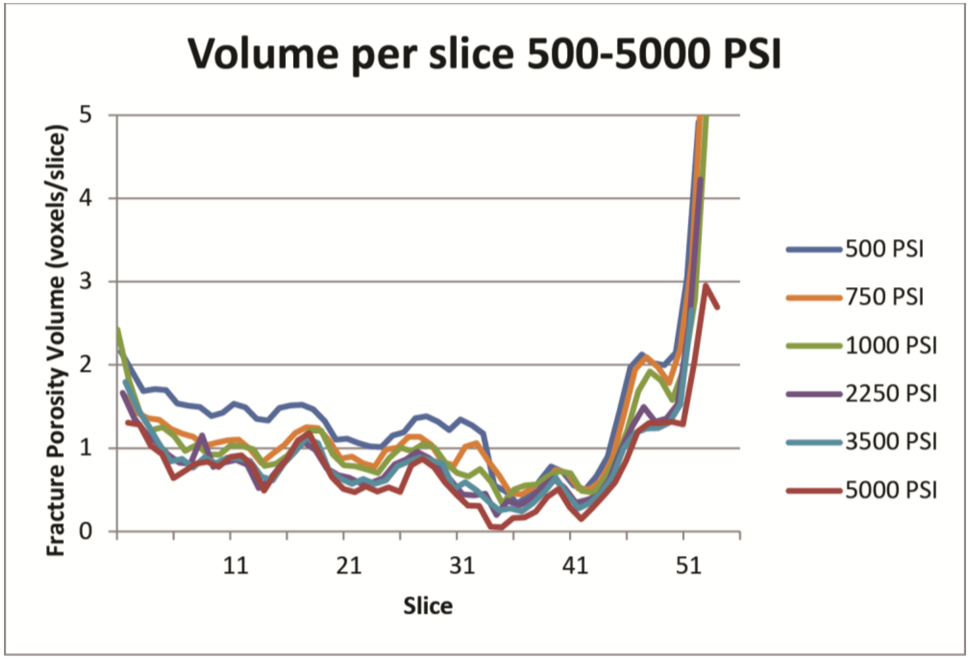
Confining Pressure Intervals

- Rapid drop in porosity at ~800 psi
- Little change in porosity after ~2500 psi
- Fracture "closes" after confining pressure is applied, but 58% of porosity remains



Confining Pressure Intervals

- Margins reflect anomalously high porosity from coring
- Rapid decrease in porosity with at ~800 psi
- Appears relatively steady from 2250 psi to 5000 psi
- Variable across the fracture



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  - Visualize 3D volumes of materials within fractures
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- Are all fractures closed under stress??? -Not really

Challenges

- Including pore pressure
- Pore connectivity must be applied
- Resolution does not allow imaging of hairline fractures
  - Common in core

Future Analyses

- Include pore pressure
- Map pore connectivity to fractures “closed” under stress
- Porosity/matrix connectivity
- Anisotropic stress
- Micro-CT for hairline fractures

Thank You

Questions?