Statistical Challenges Facing Pore-Scale X-ray Imaging Results

Current capabilities and future experiments to quantify leakage potential through caprocks

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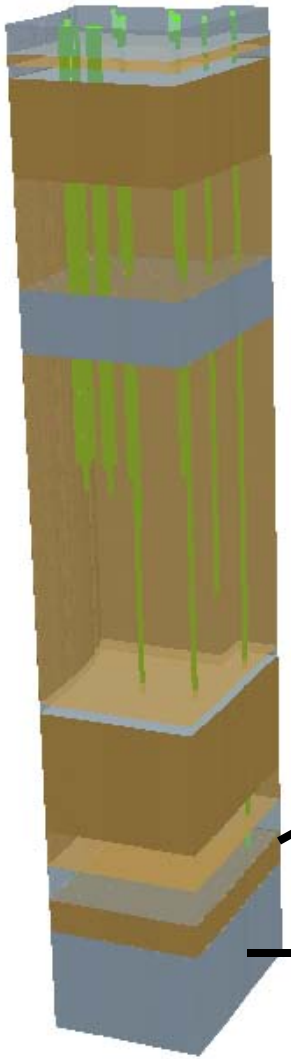
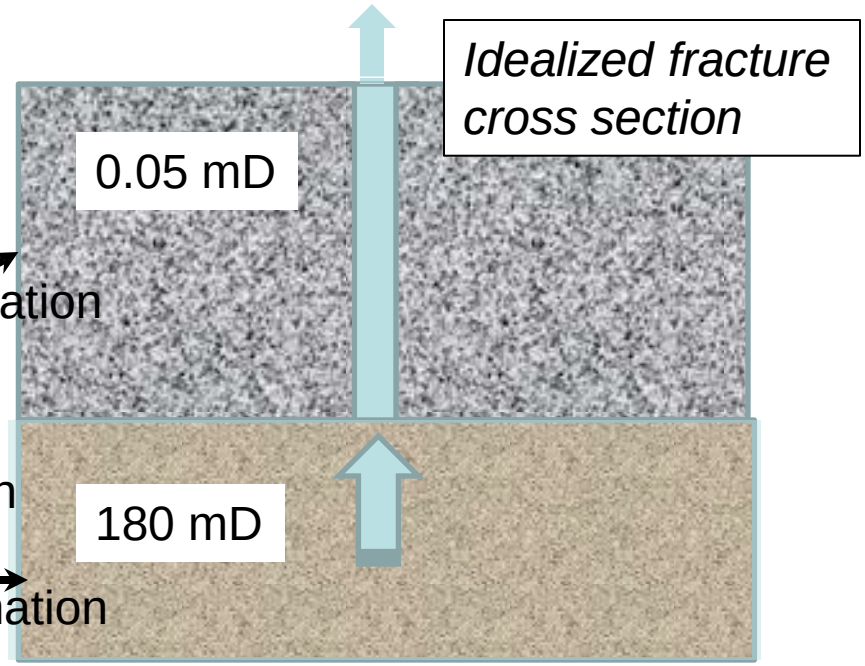
Can we develop rules to evaluate caprock quality?



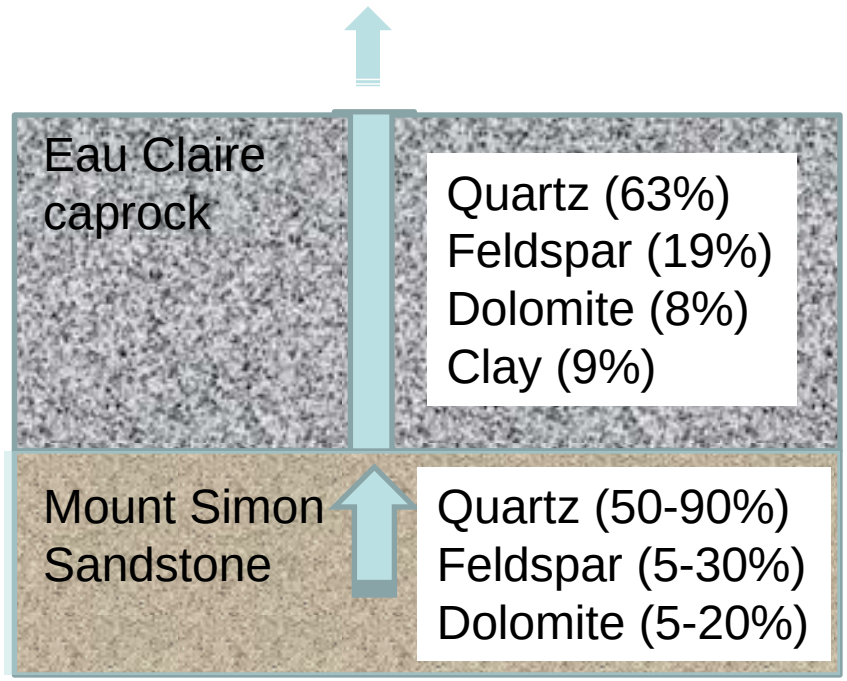
- How much CO2 could leak through the Eau Claire caprock formation?
- *Well perforations (age, cement, plug…)*
- *Permeability thru fracture networks*

existing & induced fractures



Will CO2-acidified brines impact permeability over time?

Model inputs based on what we've got?

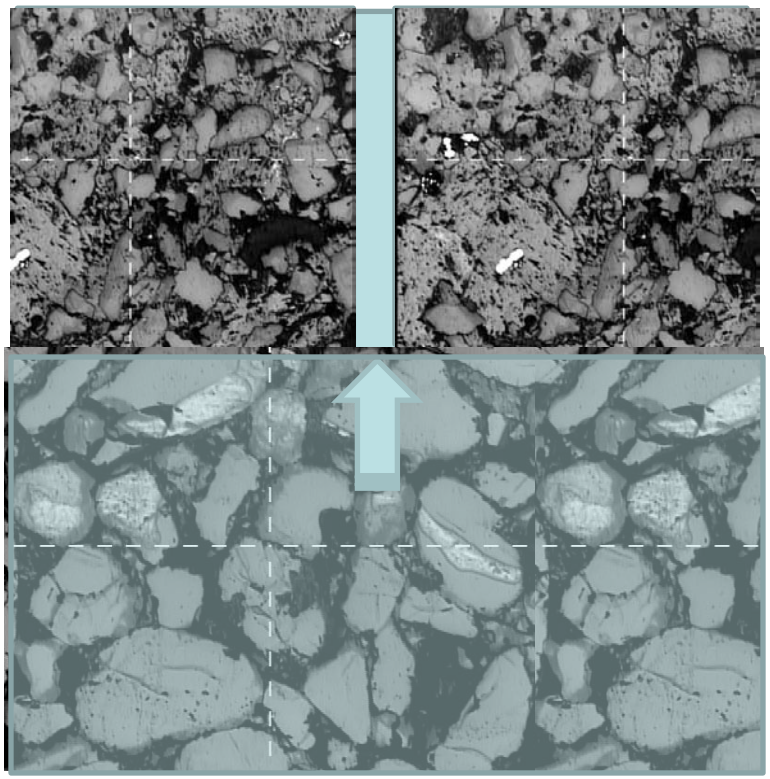


- Formation mineralogy
- *Brine chemistry*
- *Thermodynamic and kinetic terms derived from homogeneous batch studies*

	Na mg/l	Mg mg/l	K mg/l	Ca mg/l	Cl mg/l	pH
min	38000	2719	\	21910	19732	6.16
max	361509	3300	\	27000	120000	6.6
mean	199754.5	3009.5	\	24455	69866	6.38
STD	228755.4	410.829	0	3599.174	70900.18	0.311127
n	2	2	1	2	2	2

The real picture is far more complex

Optical image
of thin sections



- Spatial heterogeneity
- *Unique mineralogy at fracture surface*
- *Potential for preferential flow paths*

How big could we get it wrong?

X-ray microprobe can provide unique spatial information

- Constrain accessible surface area term (high sensitivity)
- Derive empirical relationships between pore-space and geochemical properties
  - *element composition (μXRF)*
  - *mineralogy (μXRD)*
  - *element speciation (μXAS)*
- Define maximum achievable ion concentrations

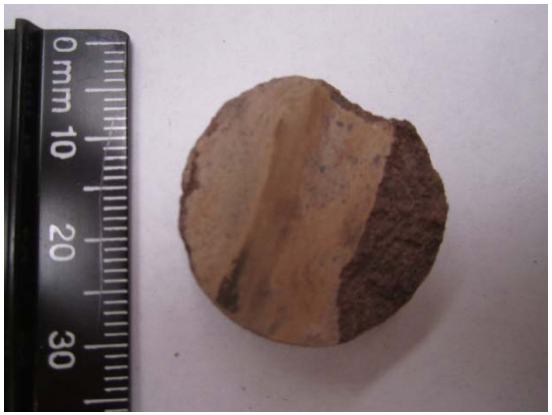
Rock thin section

Spatial resolution often limited by sample thickness

Spatial heterogeneity adds significant complexity

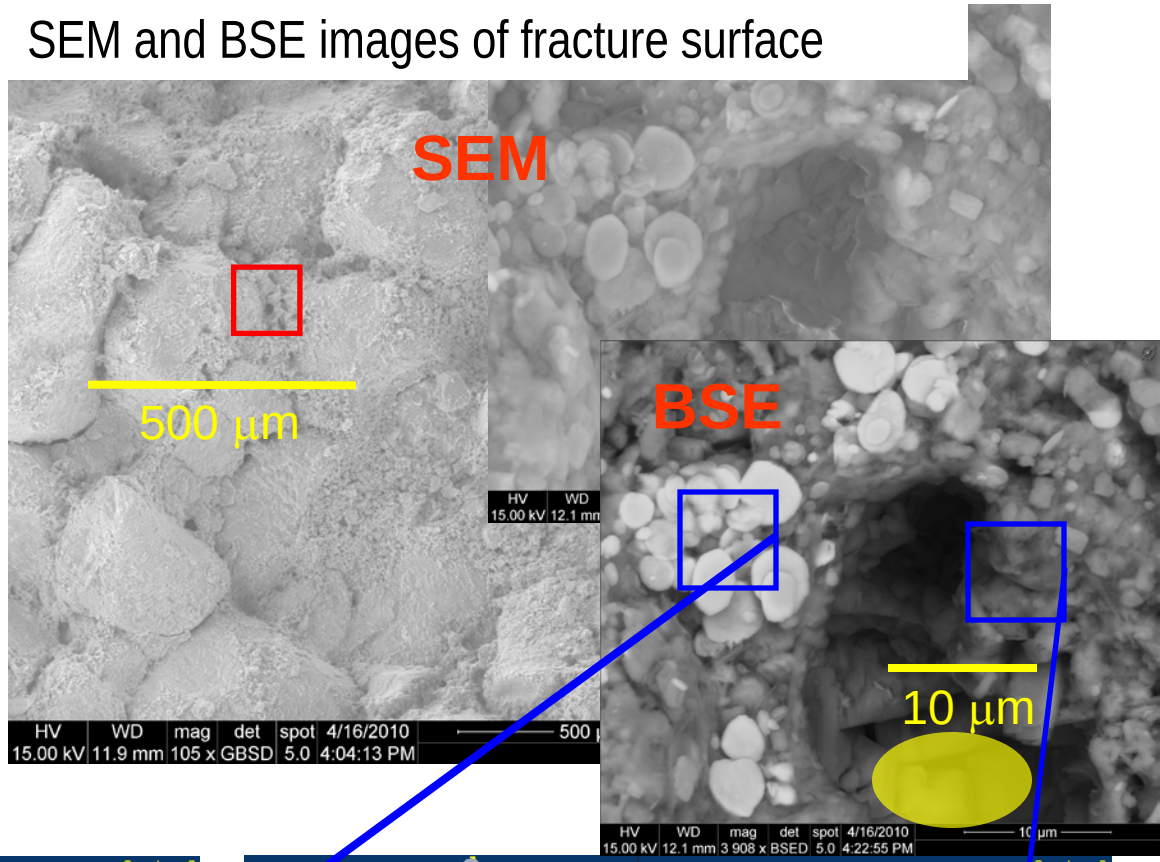
Mt Simon sandstone

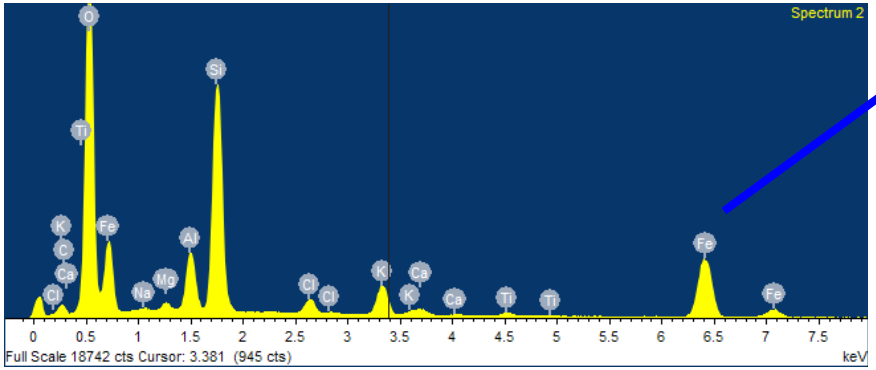
Sub-core from Muskegon Co. Michigan
WMU Core Lab (Dave Barnes)

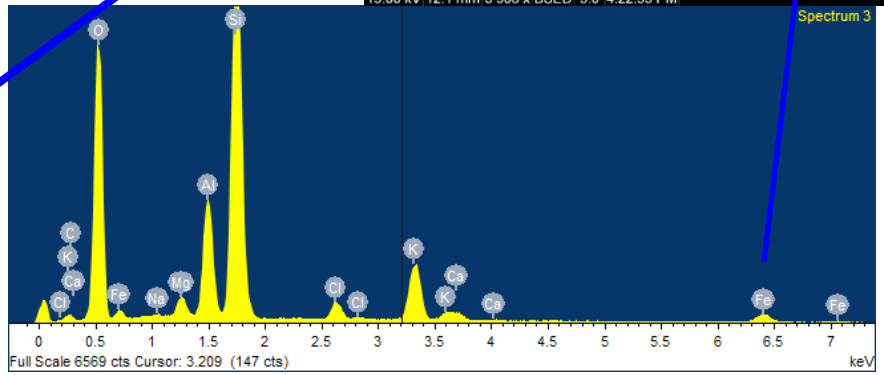


- Pore space scale (see scale bar)
- Mineralogical & Geochemical heterogeneity

SEM and BSE images of fracture surface

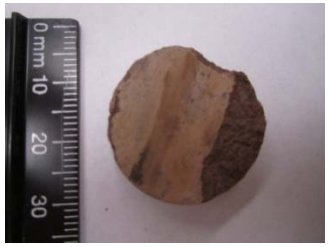




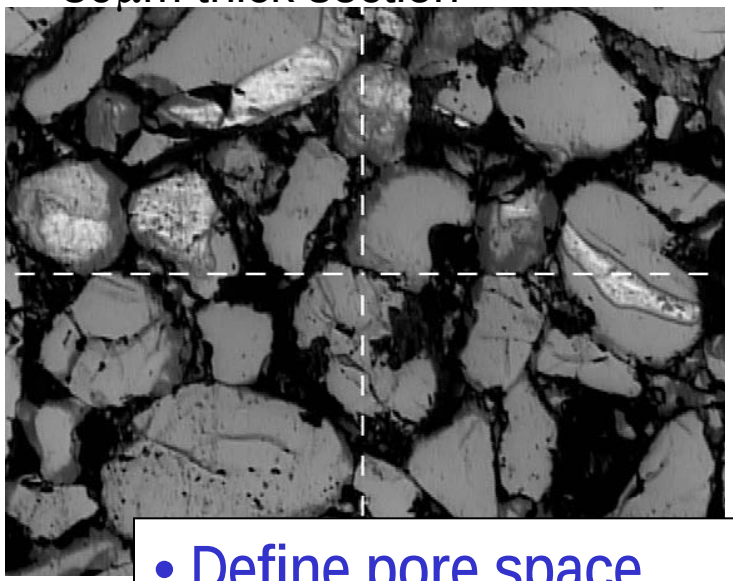


Images by Brian Ellis & Jeff Fitts

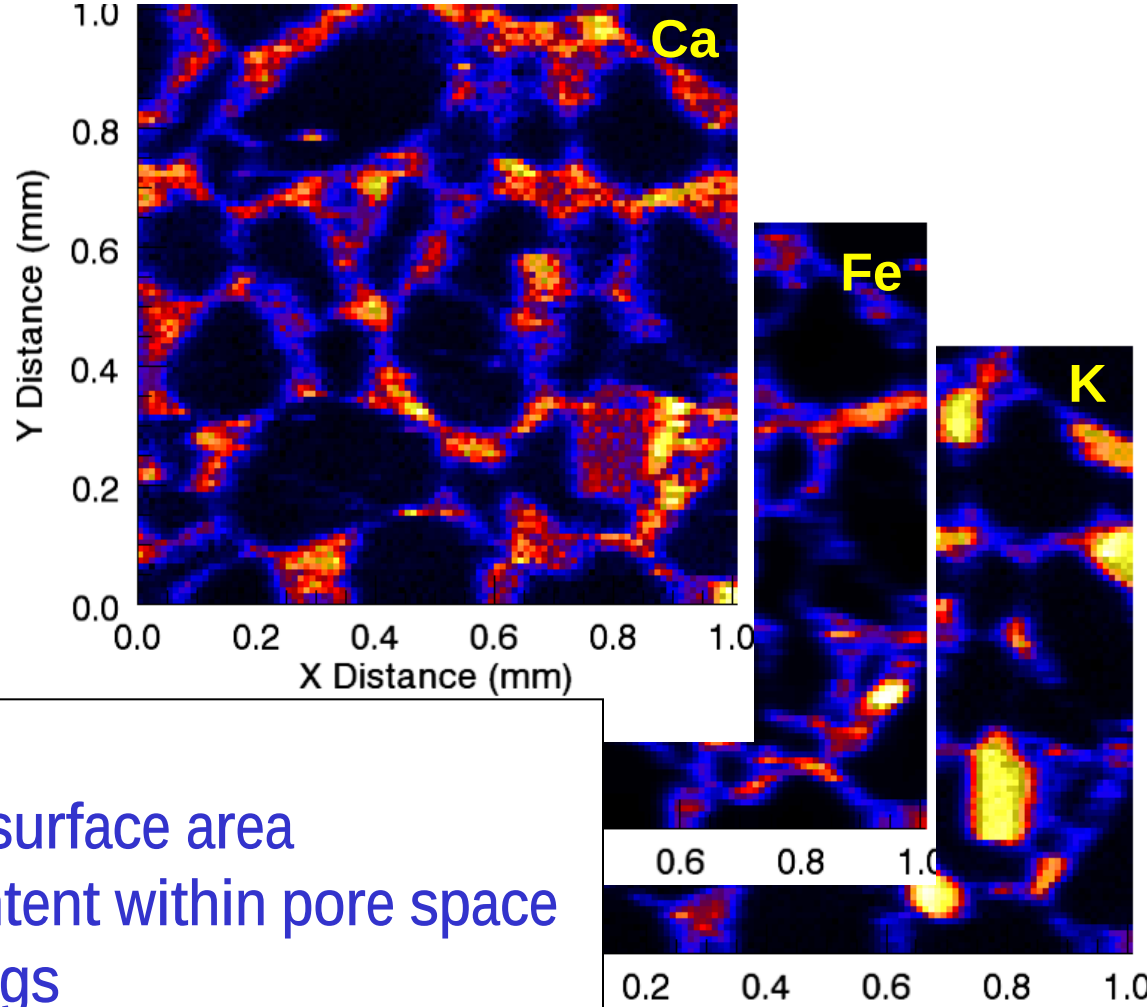
How do we represent so much spatial heterogeneity?



Mt. Simon horizontal orientation
30μm thick section

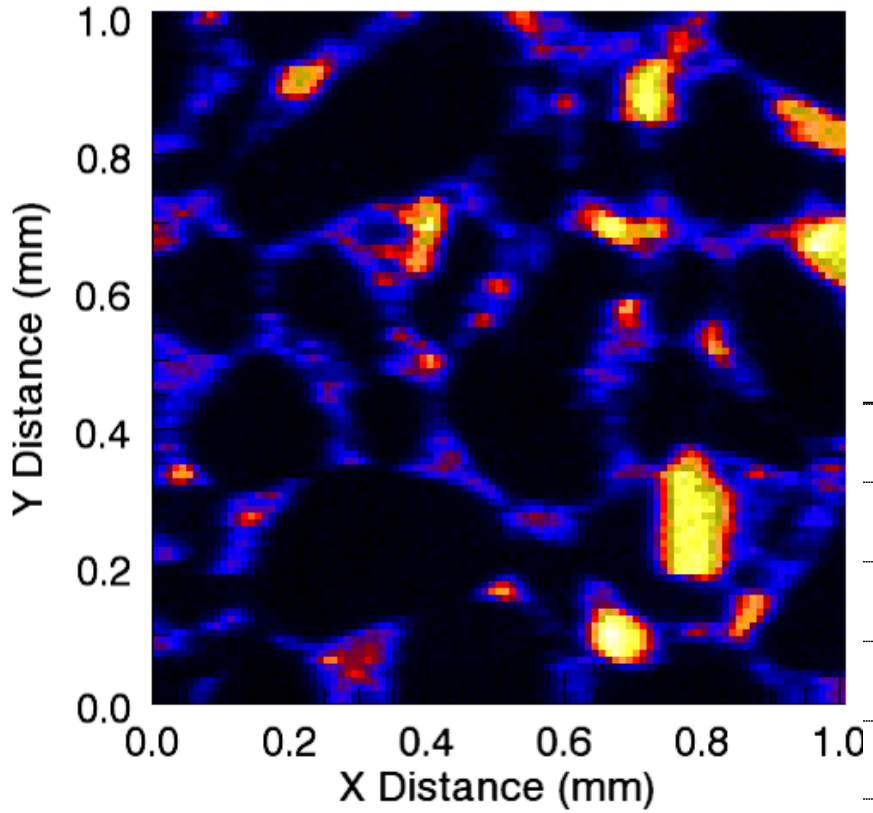


μXRF: Quantify Fe, Ca, K (Ti, Mn) spatial distribution



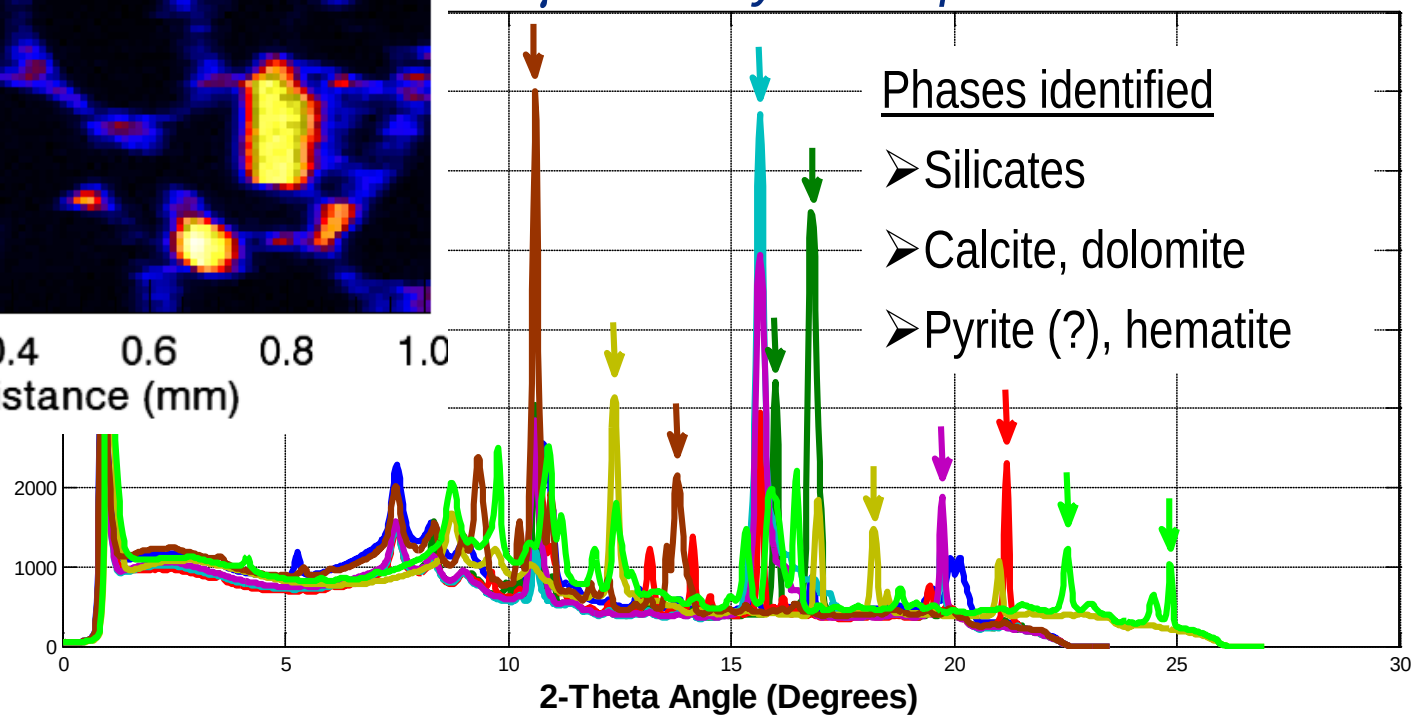
- Define pore space
- Constrain accessible surface area
- Quantify Fe, K, Ca content within pore space and pore surface coatings

Spatial distribution of accessible minerals

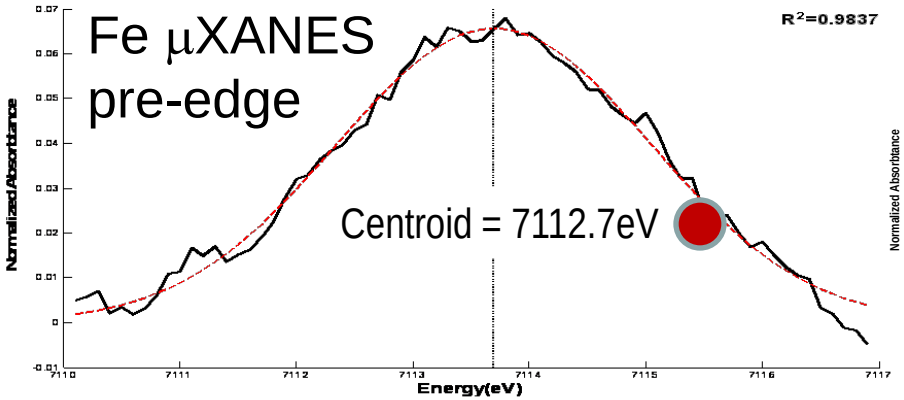


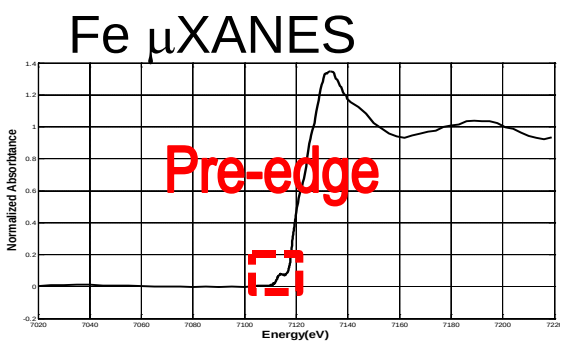
- Define pore space mineralogy
- K, Ca content in primary grains, which is inaccessible

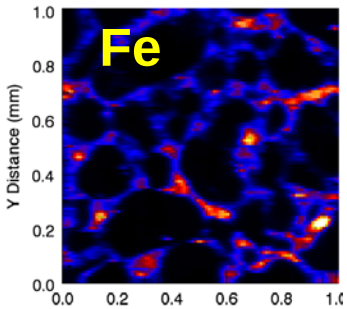
μXRD – crystalline phase identification

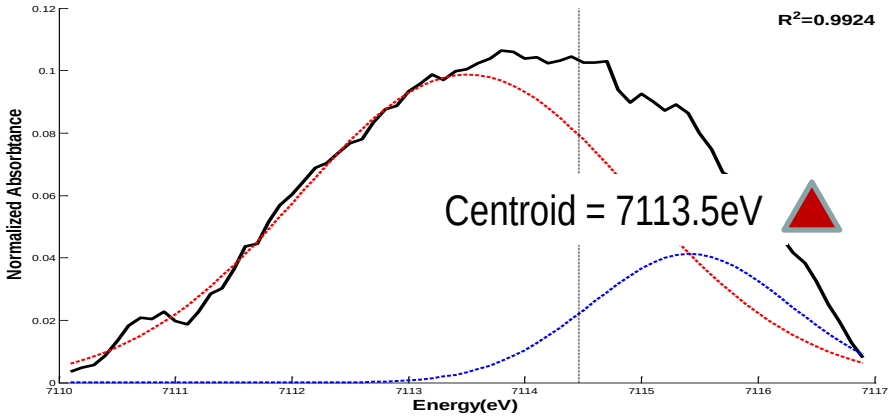


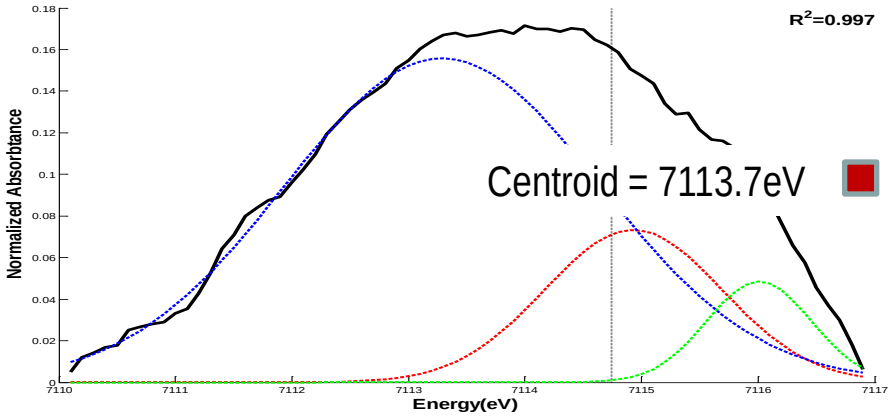
Define spatial distribution of Fe oxidation state & coordination



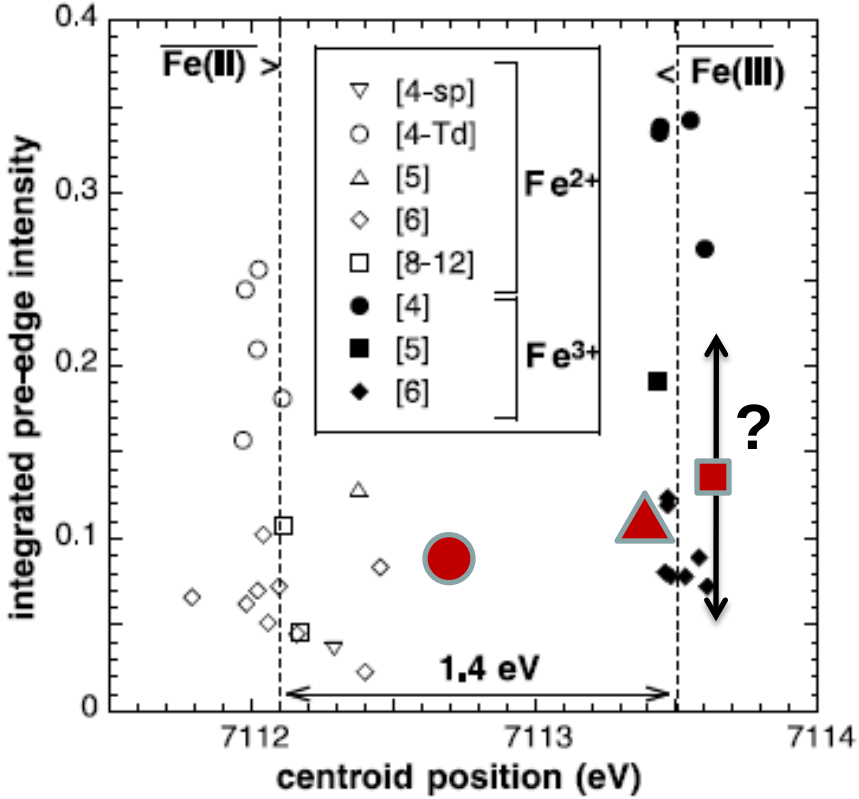








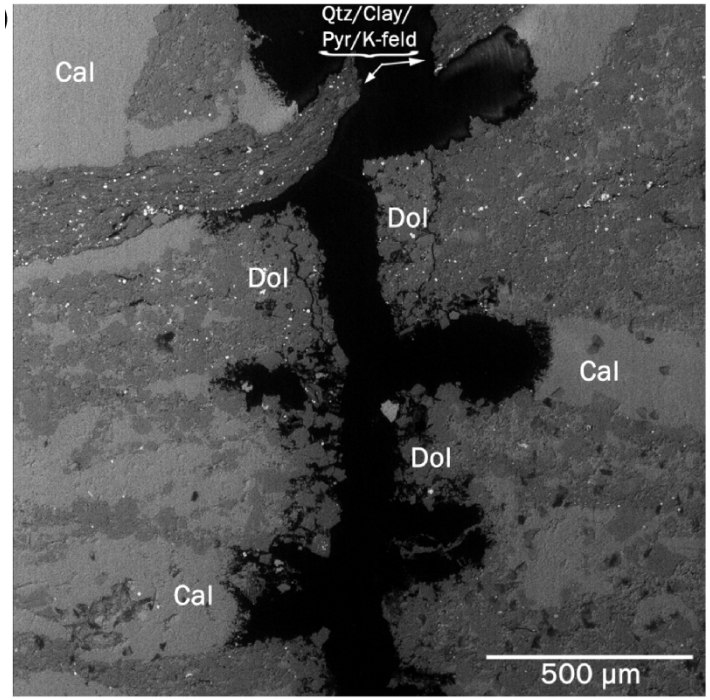
Fe oxidation state & coordination



Wilke et al. American Mineral. 2001

Dream experiment: What are the actual dissolution rates of these calcite & dolomite bands during acidified brine flow?

Amherstburg formation carbonate caprock



We need:

- 3-D Images at multiple time points

  Maintain registry with x-ray beam
- P/T-dependent rates

  Flow-thru sample cells
- Spatially resolved rates

  Good image segmentation
- Precision trace element conc.

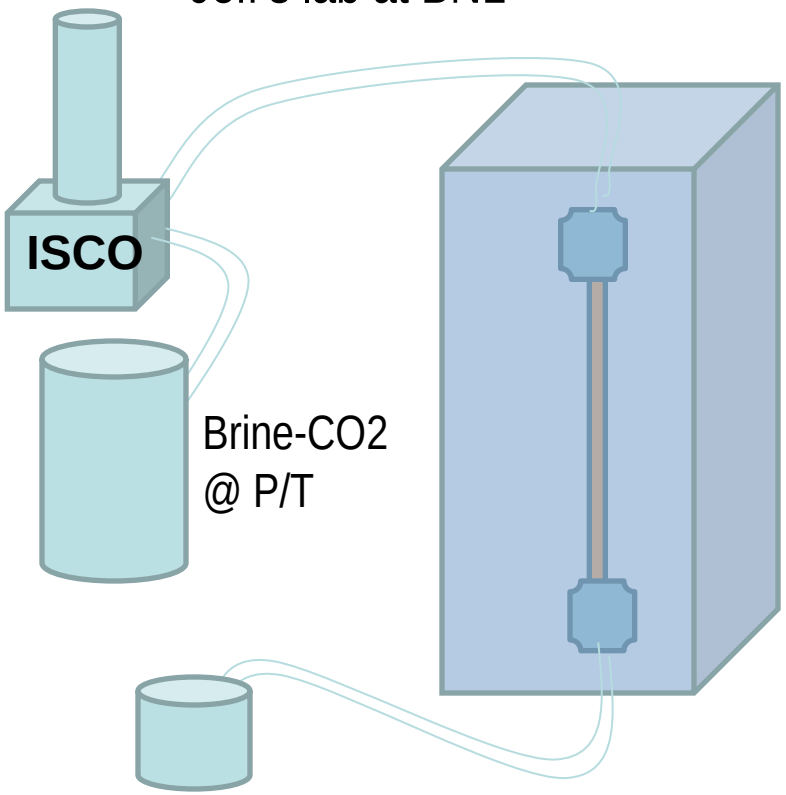
  High XRF sensitivity
- Mineralogy imaging tomography

  Diffraction & diffuse scattering

Online/offline in situ synchrotron-based x-ray tomography

Online mode: flow-thru CO2-brine at P/T

Jeff's lab at BNL

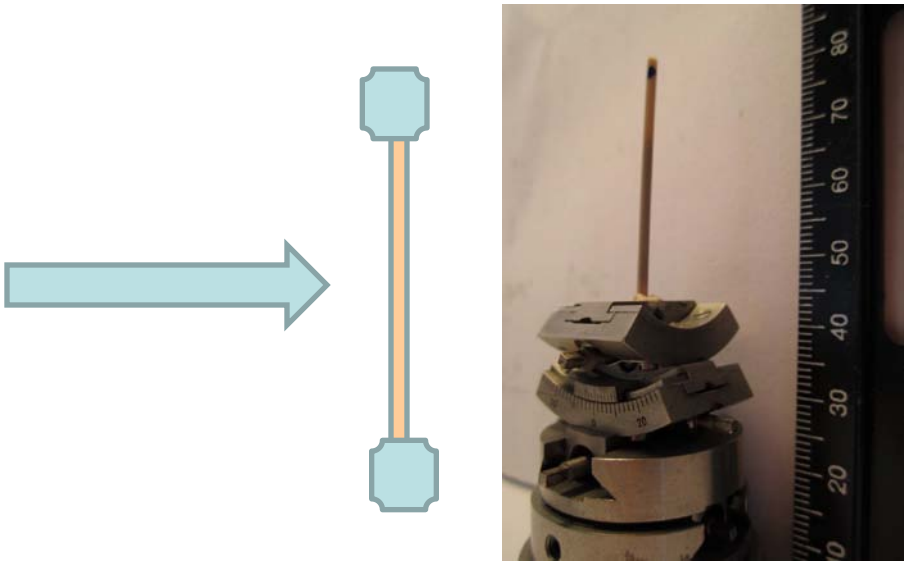


Schoonen Lab (Stony Brook) has working system with PEEK tubing

Note: confining pressure not feasible

Offline mode: mini-core closed off and transferred to beamline at P/T

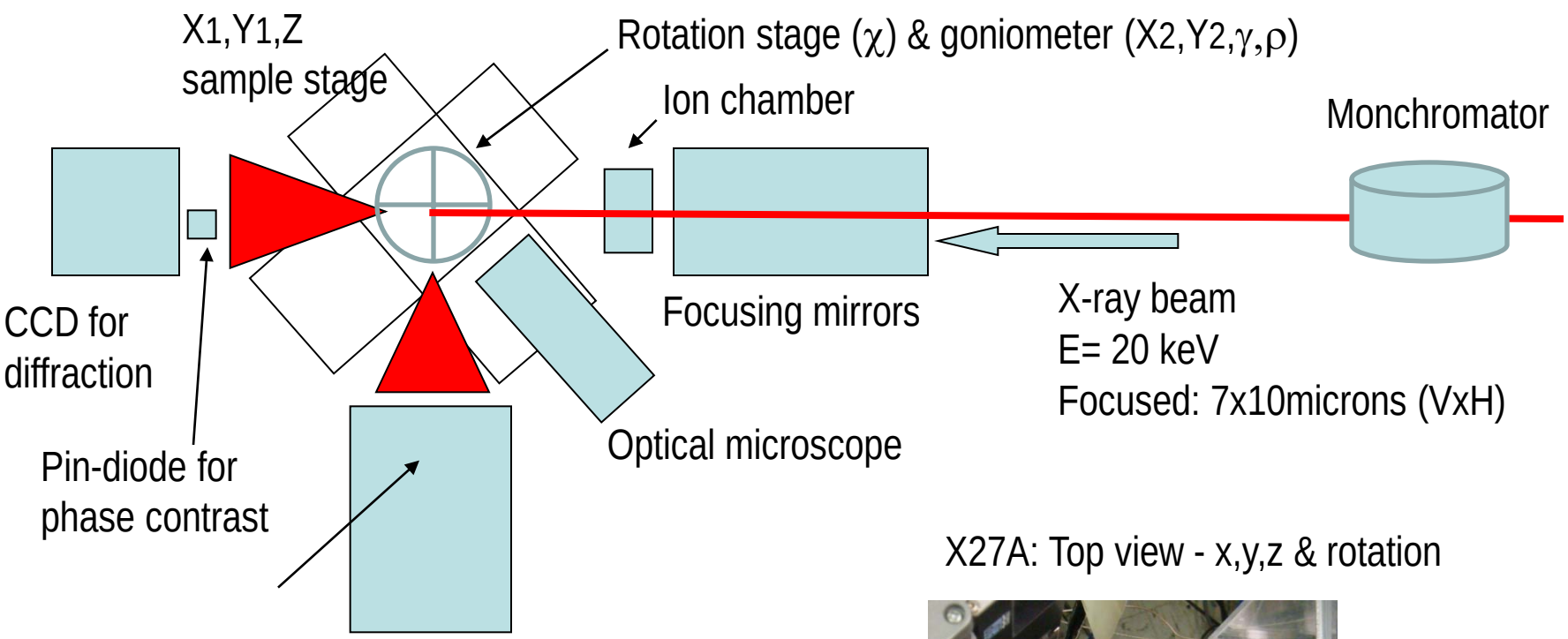
NSLS Beamline X27A & X26A; X2



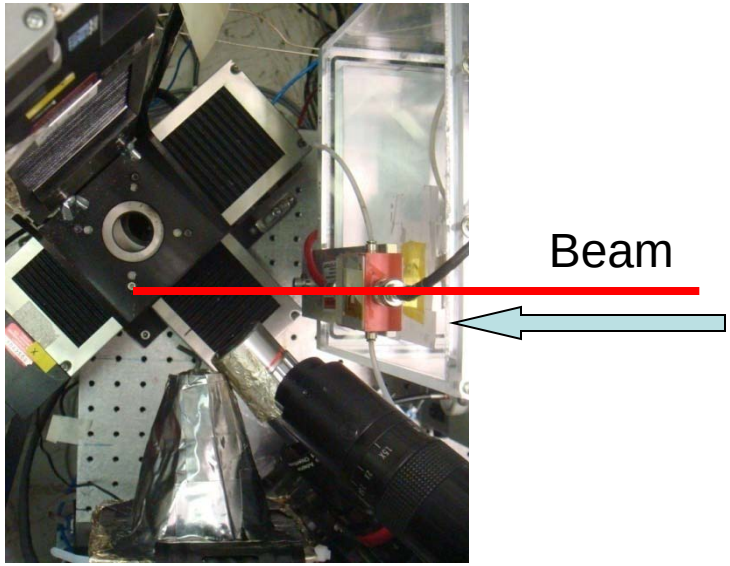
Maintain hydrostatic pressure: stop-cock or BPR

Temperature: radiant or gas blower heating

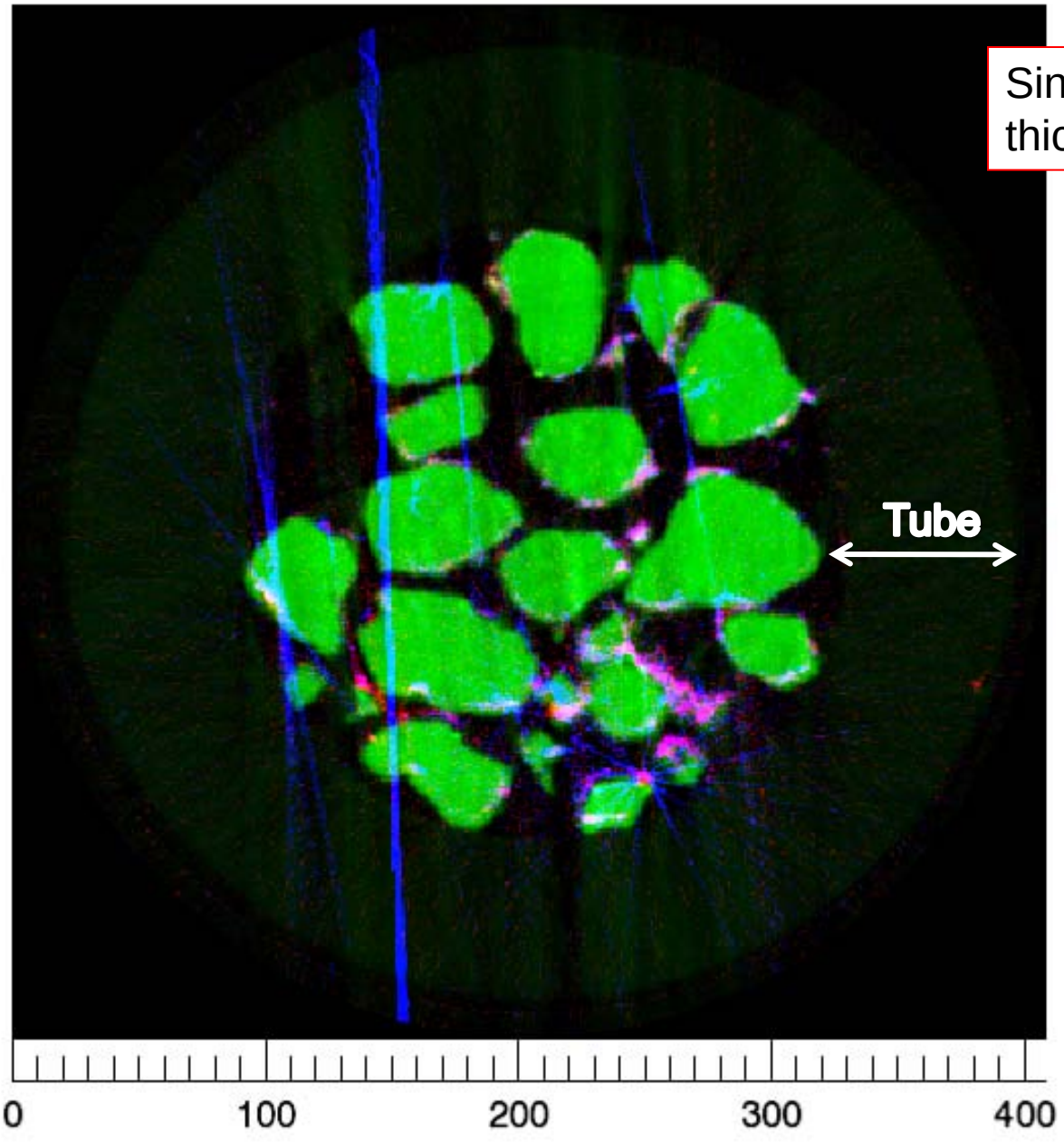
X-ray Microprobe beamline (NSLS beamlines X27A, X26A)



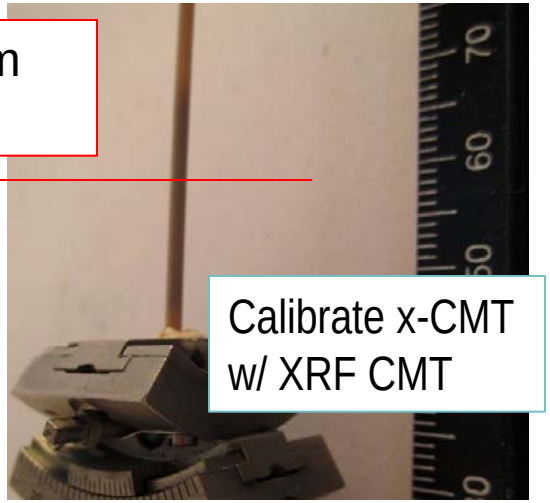
X27A: Top view - x,y,z & rotation



X26A tomo: single slice, phase contrast with pin-diode detector



Single 6µm thick slice

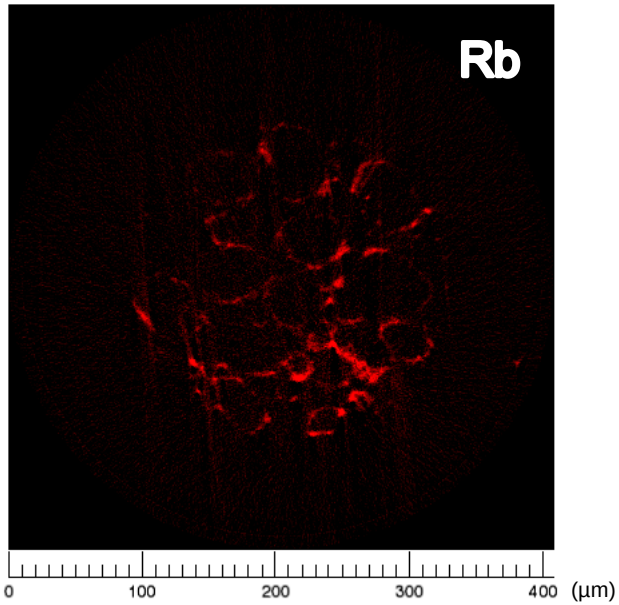


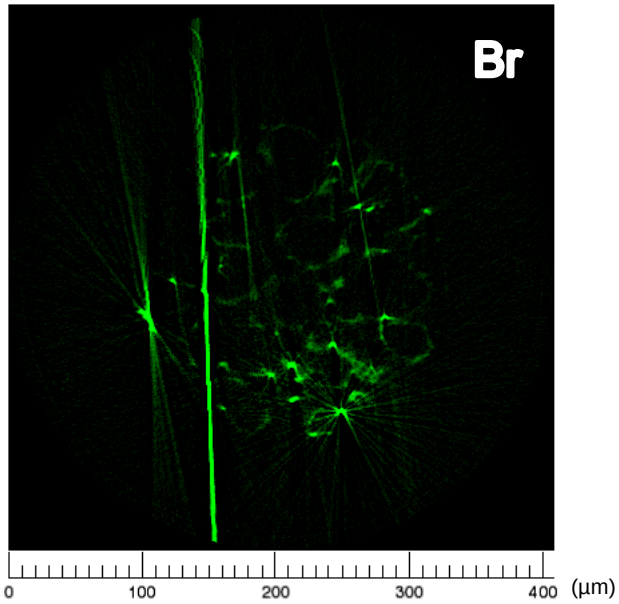
Calibrate x-CMT w/ XRF CMT

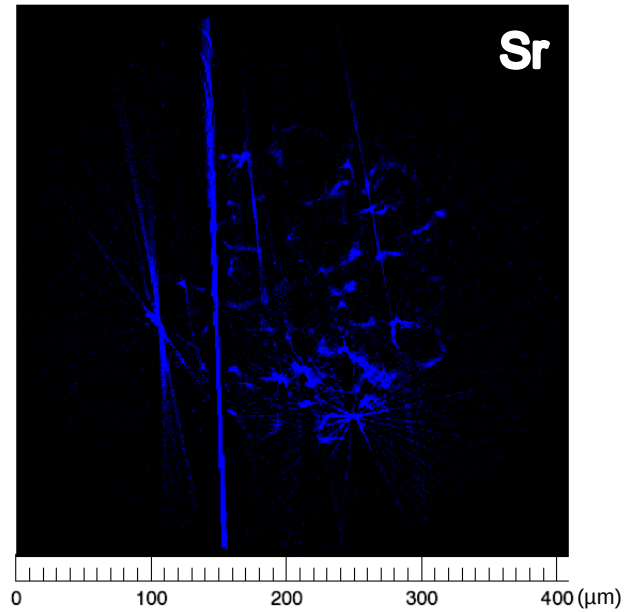
Composite map
Rb (Red) and Sr (Blue) overlay on pin-diode (Green)

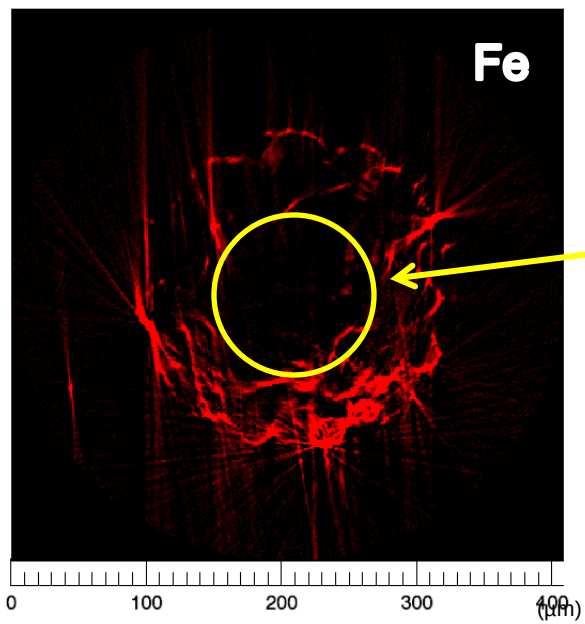
Surface phase coating silica grains?

X26A tomo – Rb, Sr, Fe



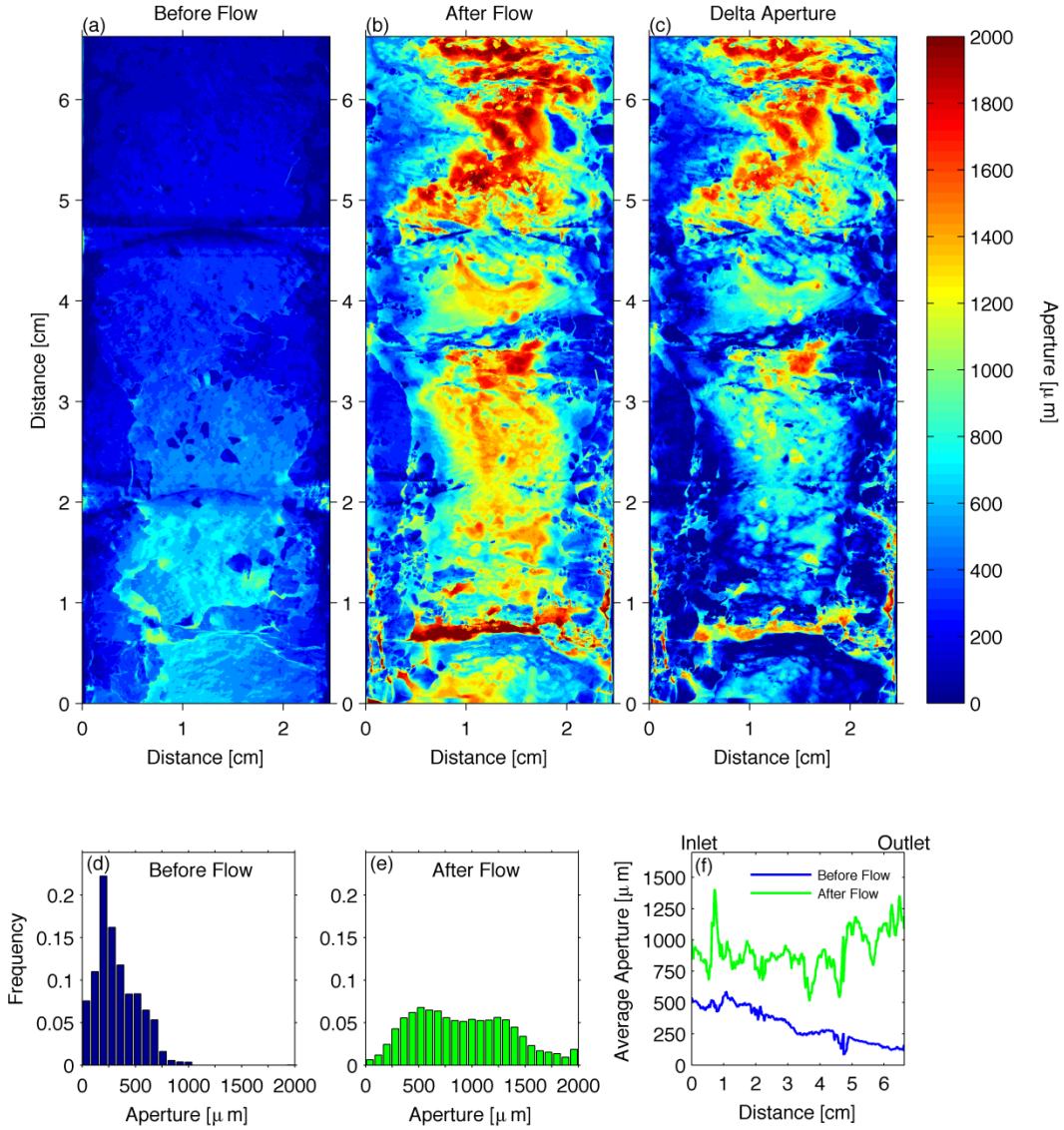






Silica absorbs Fe Kα fluorescence at 7 keV

Need to register with CT imaging

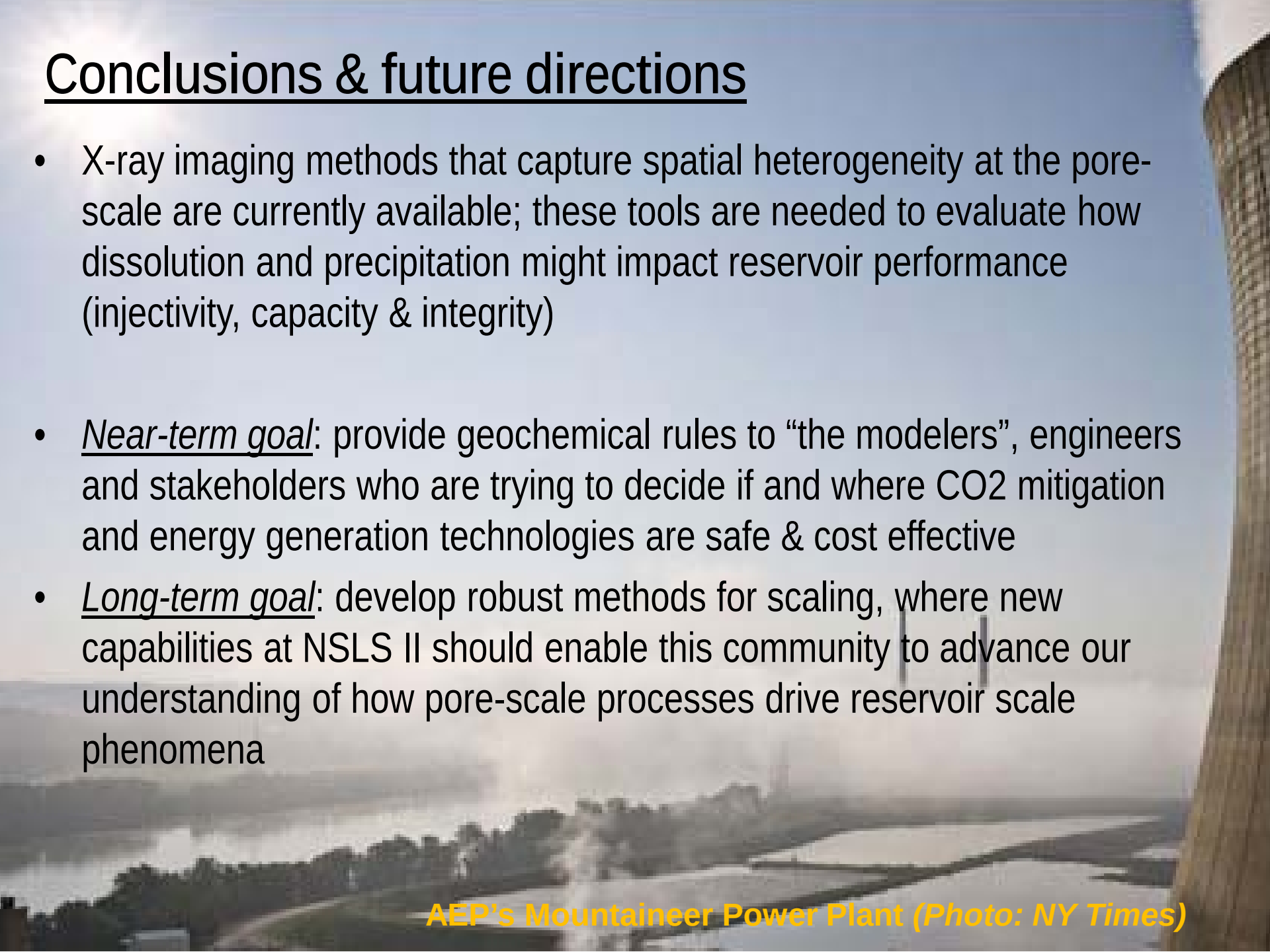


Brian Ellis, Princeton University

Conclusions & future directions

- X-ray imaging methods that capture spatial heterogeneity at the pore-scale are currently available; these tools are needed to evaluate how dissolution and precipitation might impact reservoir performance (injectivity, capacity & integrity)

- *Near-term goal*: provide geochemical rules to “the modelers”, engineers and stakeholders who are trying to decide if and where CO2 mitigation and energy generation technologies are safe & cost effective
- *Long-term goal*: develop robust methods for scaling, where new capabilities at NSLS II should enable this community to advance our understanding of how pore-scale processes drive reservoir scale phenomena



AEP’s Mountaineer Power Plant *(Photo: NY Times)*

Thank you!