August 12th, 2014

Reactive Transport Models with Geomechanics to Mitigate Risks of Carbon Dioxide Utilization and Storage

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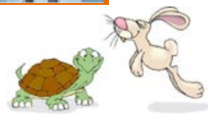
University of Utah



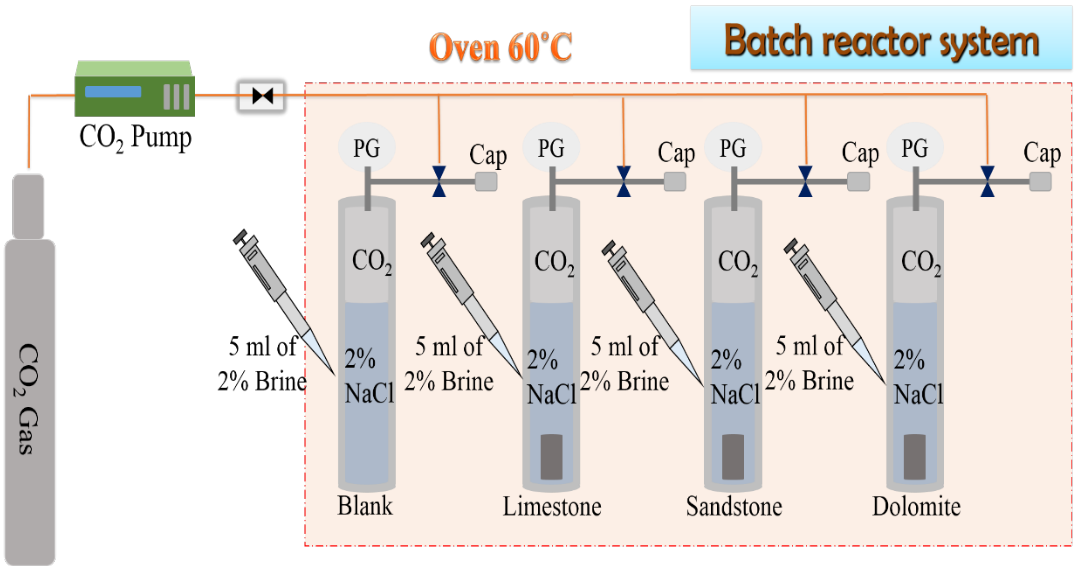
Project Objectives

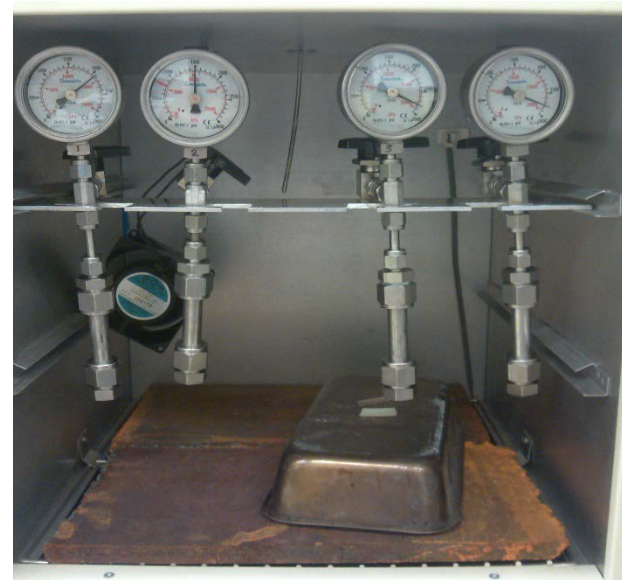
The overall goal of the project is to discover the short-term fluid and rock interaction processes occurring during CO_2 injection in geological reservoirs.

- Determine the mineralogical and chemical changes in the fluid and rock, and how these interactions affect porosity and permeability in different rocks.
- Assess the role of reservoir mineralogy and petrography in controlling geochemical processes during CO_2 injection.
- Investigate the types and rates of supercritical CO_2 - 2% NaCl brine rock reactions.
- Mechanistic modeling of reactivations of natural fractures near injection wellbore due to CO_2 injection

Experimental Systems

Batch Reactors

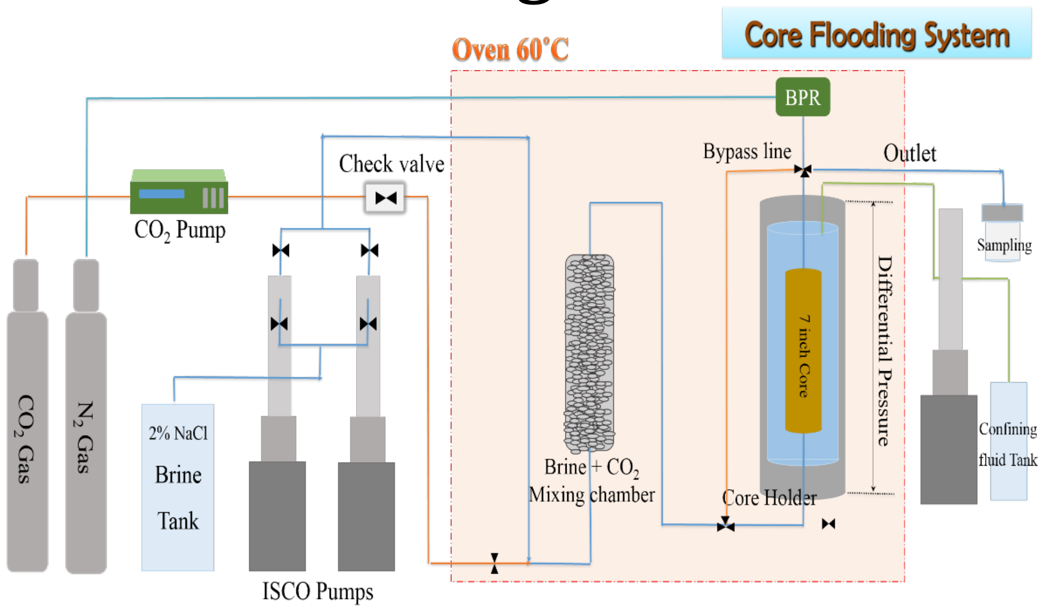




Batch reactor system conditions

- Reaction pressure: 2,400 psi
- Reaction temperature: 60 ℃
- Reaction time: 14 days
- Core samples: Sandstone, Limestone, and Dolomite
- (Powder, fractures, and 0.5 inch core plug)

Core Flooding



Core flooding system conditions

- Core pressure: 2,000 psi
- Confining pressure: 3,000 psi
- Reaction temperature: 60 °C
- Reaction time : 3-14 days
- Cores: Sandstone, Limestone, and Dolomite
- CO_2 : Brine ratio: Variable
- (1.5 inch diameter, 7 inch length)

Analysis Methods

BET, He porosimeter, and Micro-CT

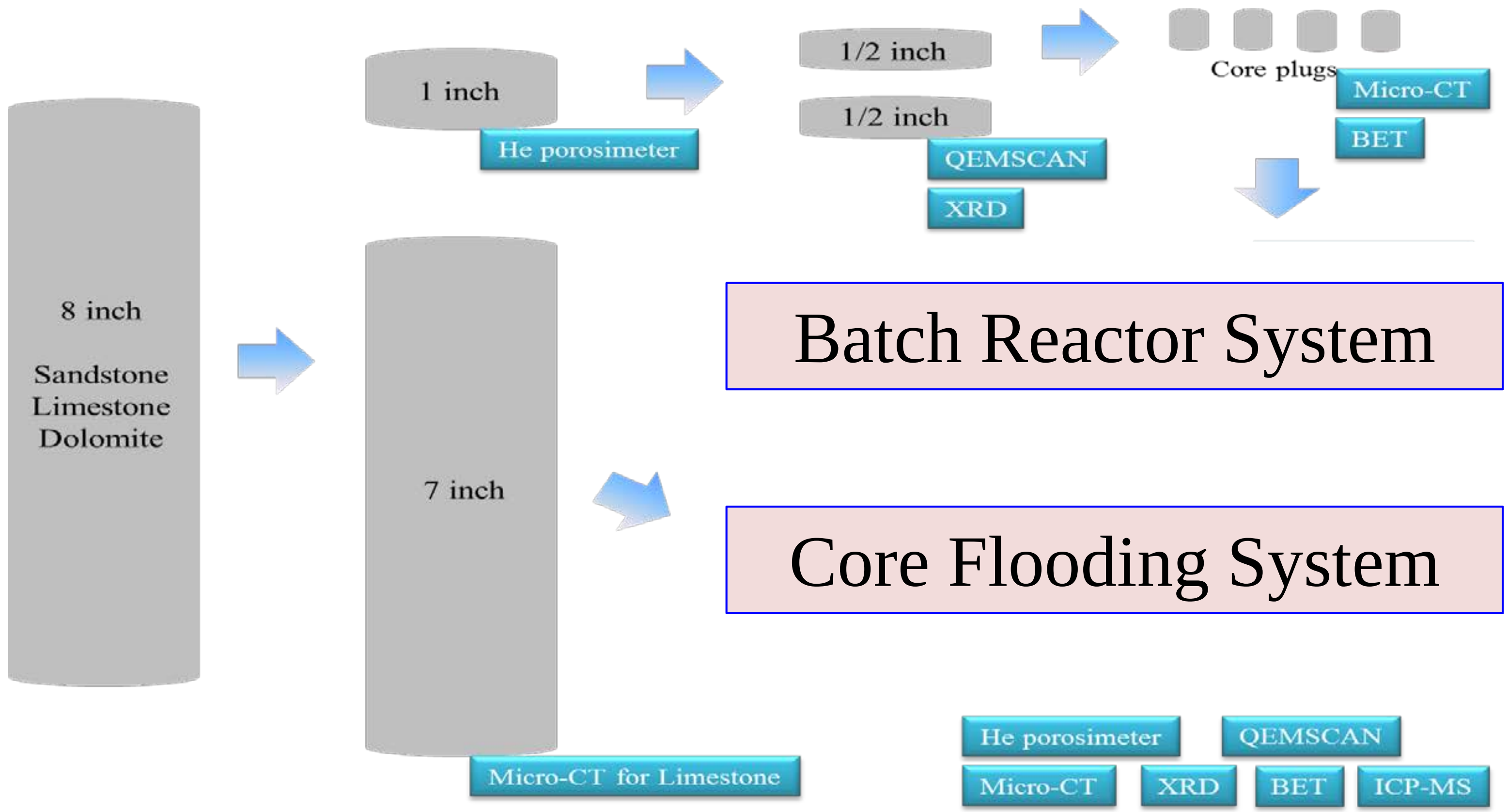
Analyze porosity changes surface area and pore structure

ICP-MS and pH meter

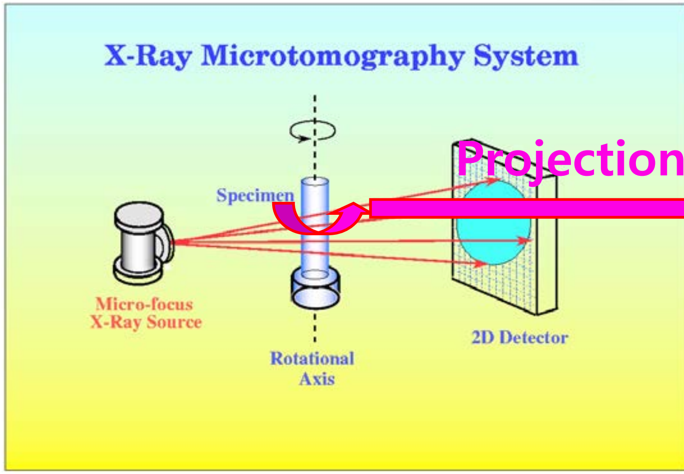
Measure pH and cation concentration of the solution

XRD and QEMSCAN

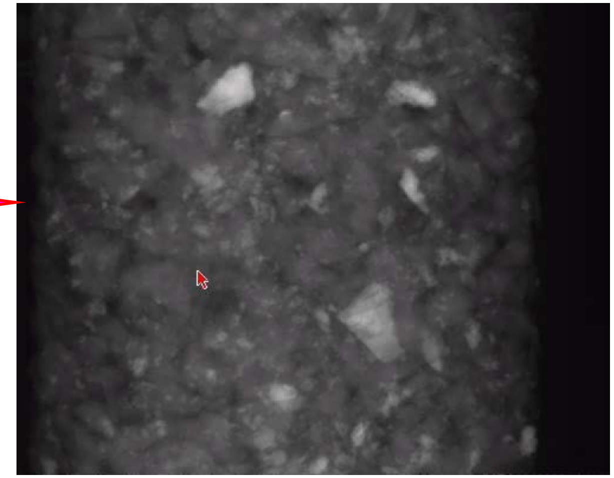
Mineralogical analysis of core samples



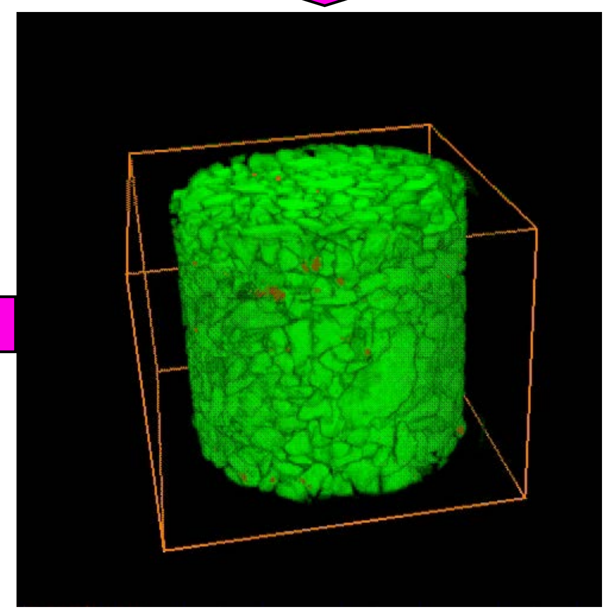
X-ray Micro CT



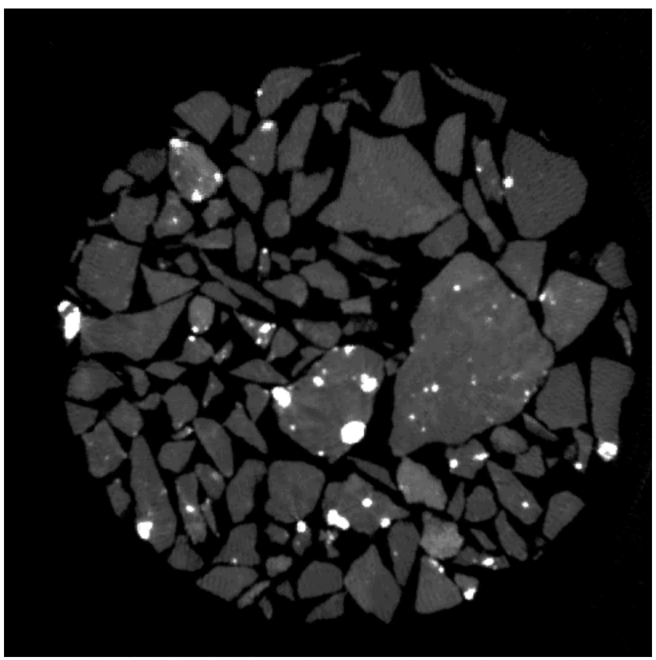
Projection



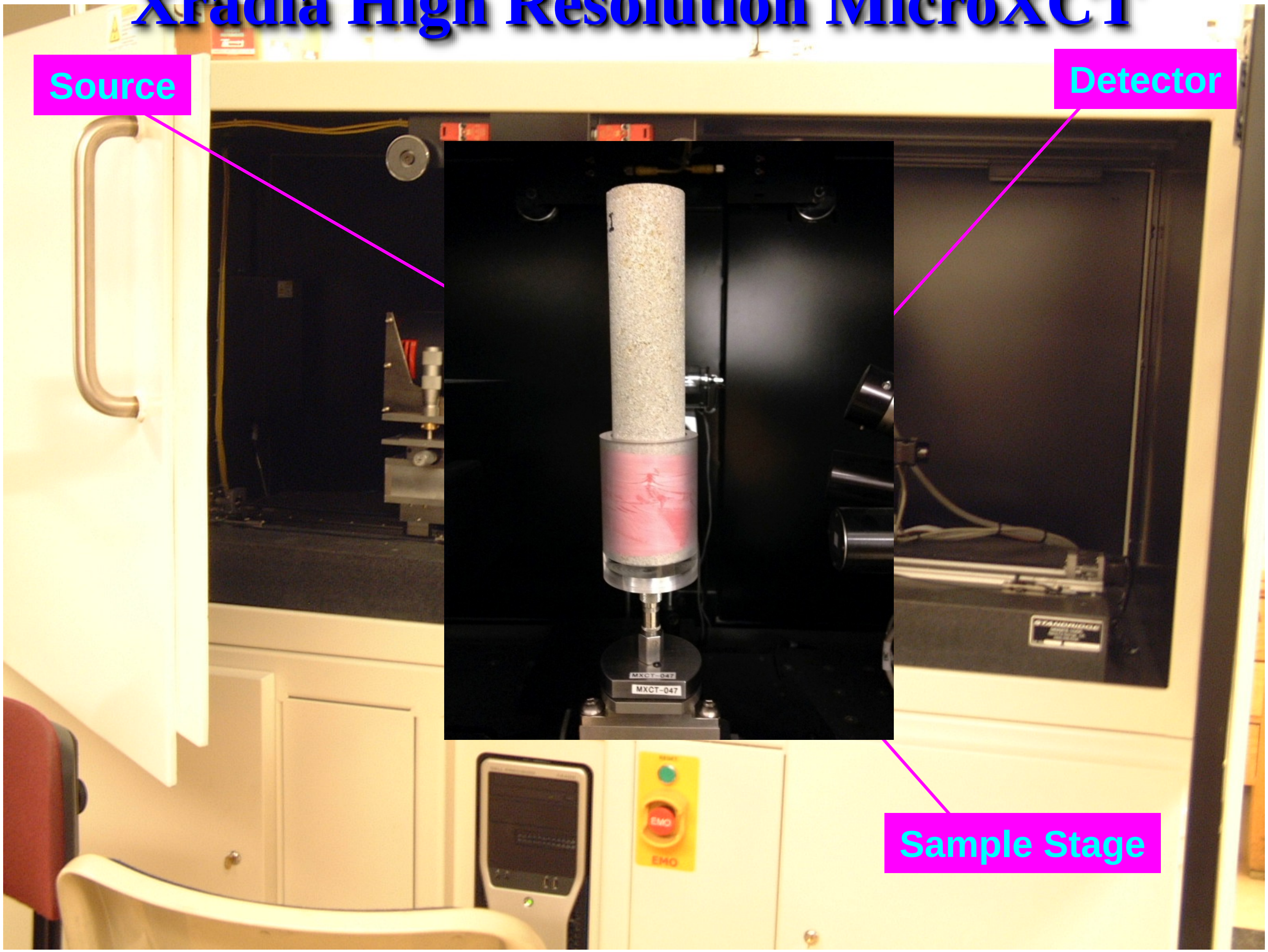
3D View



Slice Views



Xradia High Resolution MicroXCT



Results - Batch

Measurements of the pore size changes using Micro-CT

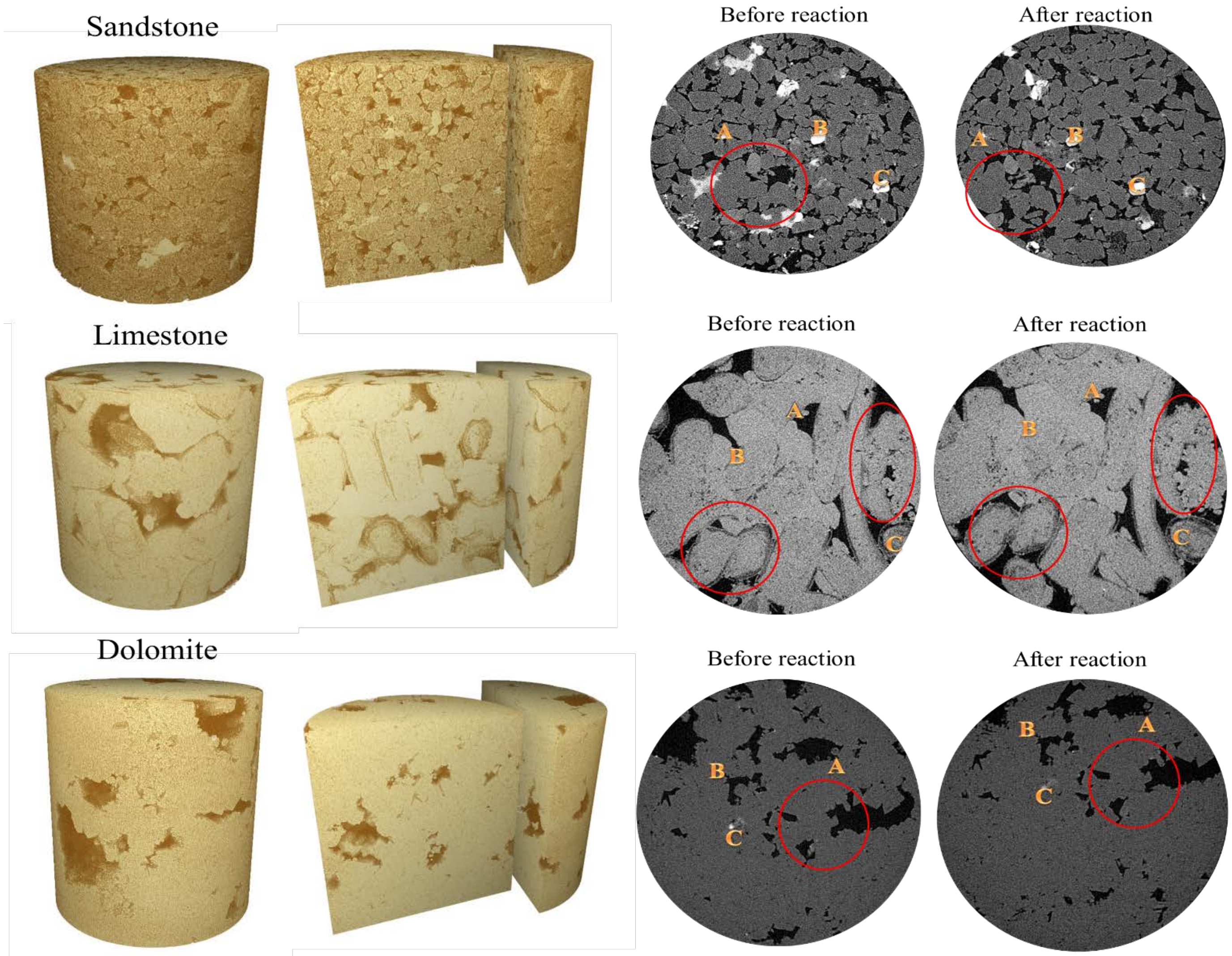


Figure 3. The images of each core plug sample using Micro-CT before and after non-flowing batch reaction 2% NaCl and supercritical CO_2 experiments.

Results - Batch

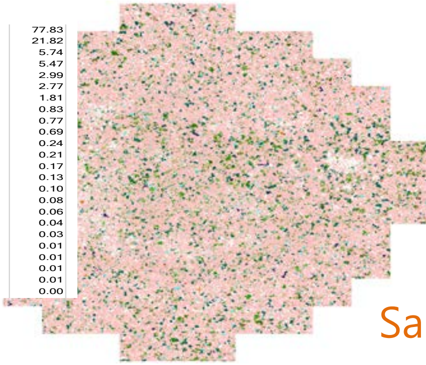
QEMSCAN

XRD

Sandstone

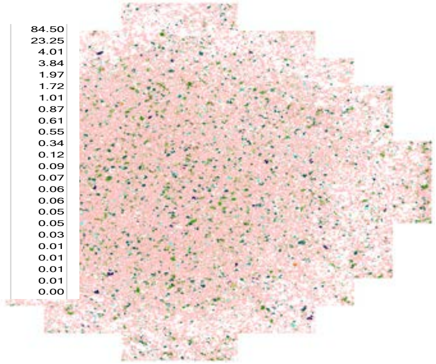
Pre

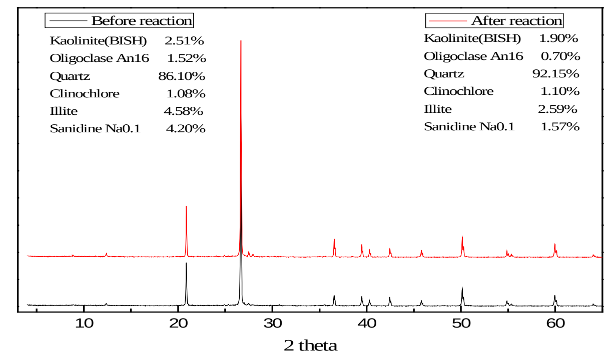
Mineral Name	
Quartz	77.83
Background	21.82
Illite	5.74
Alkali Feldspar	5.47
Kaolinite	2.99
Plagioclase	2.77
Particle Rims	1.81
Chlorite	0.83
Other Silicates	0.77
Smectites	0.69
Ankerite	0.24
Muscovite	0.21
Micrite	0.17
Glauconite	0.13
Siderite	0.10
Biotite	0.08
Rutile	0.06
Fe-oxides	0.04
Unclassified	0.03
Pyrite	0.01
Apatite	0.01
Zircon	0.01
Dolomite	0.01
Calcite	0.00



Post

Mineral Name	
Quartz	84.50
Background	23.25
Alkali Feldspar	4.01
Illite	3.84
Particle Rims	1.97
Plagioclase	1.72
Kaolinite	1.01
Chlorite	0.87
Other Silicates	0.61
Smectites	0.55
Ankerite	0.34
Glauconite	0.12
Micrite	0.09
Siderite	0.07
Biotite	0.06
Fe-oxides	0.06
Muscovite	0.05
Rutile	0.05
Calcite	0.03
Dolomite	0.01
Unclassified	0.01
Zircon	0.01
Apatite	0.01
Pyrite	0.00

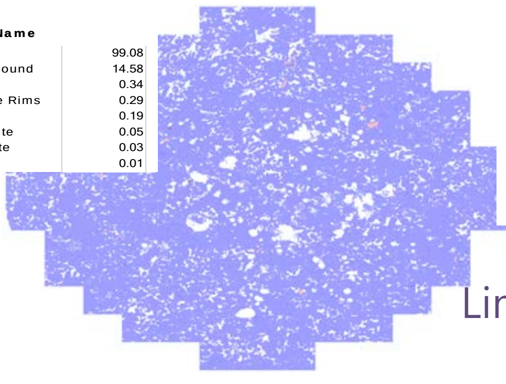




Limestone

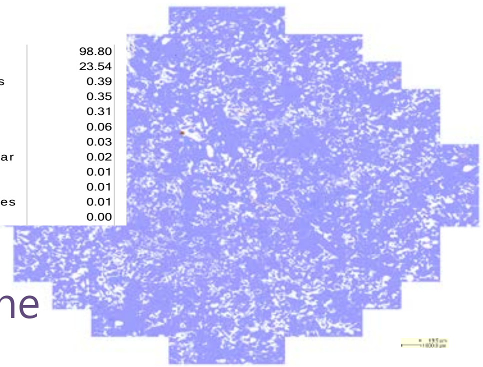
Pre

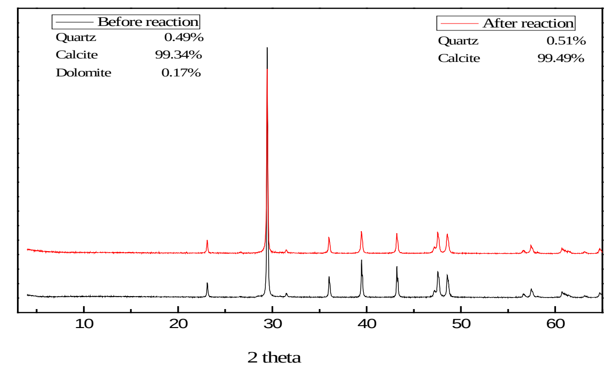
Mineral Name	
Calcite	99.08
Background	14.58
Quartz	0.34
Particle Rims	0.29
Micrite	0.19
Dolomite	0.05
Ankerite	0.03
Apatite	0.01



Post

Mineral Name	
Calcite	98.80
Background	23.54
Particle Rims	0.39
Quartz	0.35
Micrite	0.31
Dolomite	0.06
Ankerite	0.03
Alkali Feldspar	0.02
Illite	0.01
Plagioclase	0.01
Other Silicates	0.01
Apatite	0.00

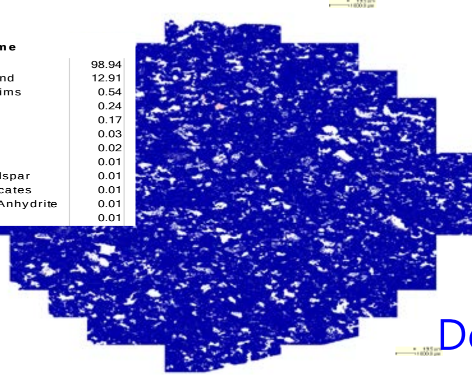




Dolomite

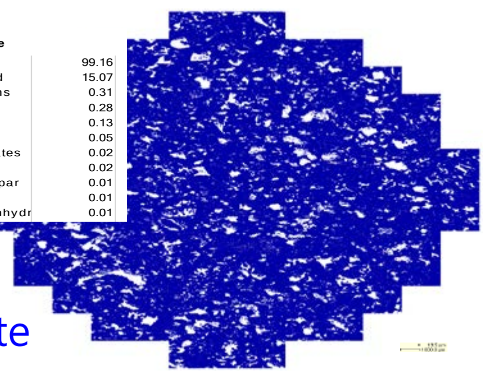
Pre

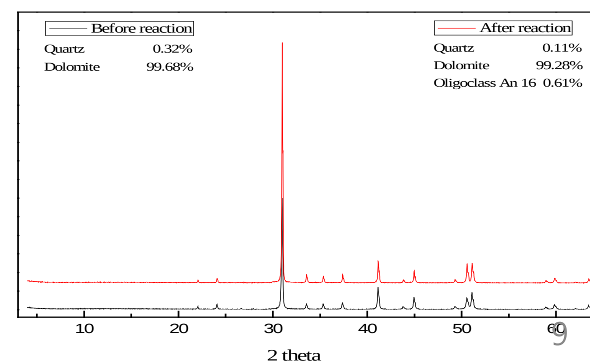
Mineral Name	
Dolomite	98.94
Background	12.91
Particle Rims	0.54
Calcite	0.24
Quartz	0.17
Micrite	0.03
Ankerite	0.02
Pyrite	0.01
Alkali Feldspar	0.01
Other Silicates	0.01
Gypsum/Anhydrite	0.01
Illite	0.01



Post

Mineral Name	
Dolomite	99.16
Background	15.07
Particle Rims	0.31
Calcite	0.28
Quartz	0.13
Micrite	0.05
Other Silicates	0.02
Ankerite	0.02
Alkali Feldspar	0.01
Pyrite	0.01
Gypsum/Anhydr	0.01





Results - Batch

Table 1. ICP-MS results for unreacted and reacted core samples

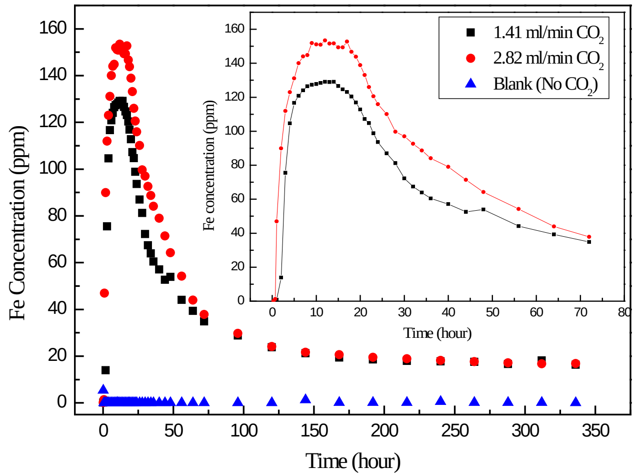
	Ca (mg/kg)	Fe (mg/kg)
Unreacted core plug samples		
LoD	399	7
Sandstone	1703	4655
Limestone	497661	2057
Dolomite	283987	2168
Reacted core plug samples		
LoD	13	0.04
Blank	<13	73.92
Sandstone	154	192.1
Limestone	571	0.08
Dolomite	302	0.08

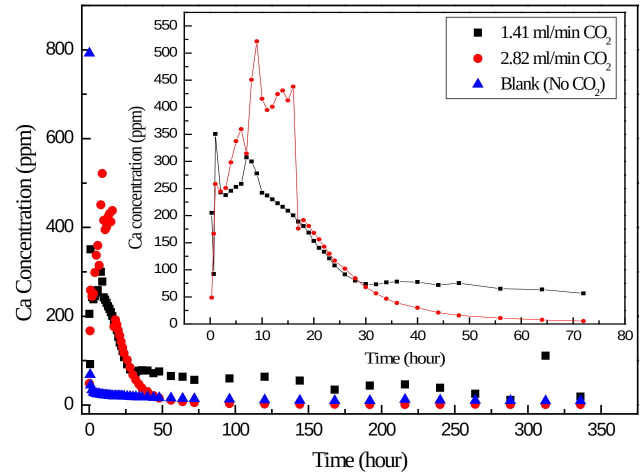
Table 2. Summary of BET results for the core samples of different rock types

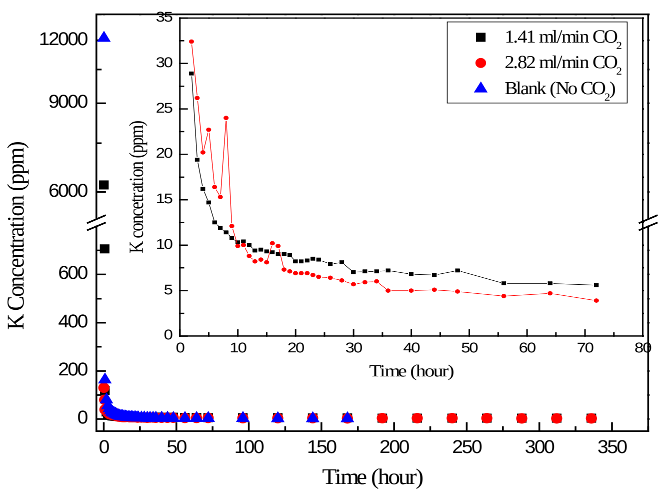
Core plug samples	Surface area (m^2/g)		
	Before	After	Variation
Sandstone	0.8926	1.1095	24.3%
Limestone	0.3235	0.3558	9.98%
Dolomite	0.0023	0.0026	13.04%

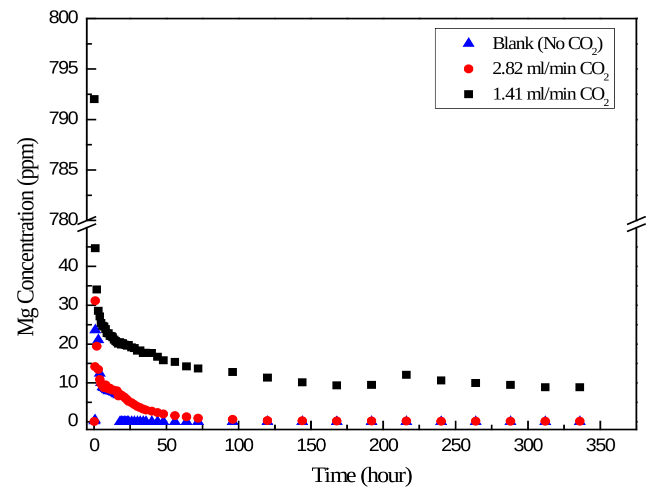
Results – Core Flooding

ICP-MS results of Sandstone solution samples after core flooding (2% NaCl, supercritical CO_2) by time.



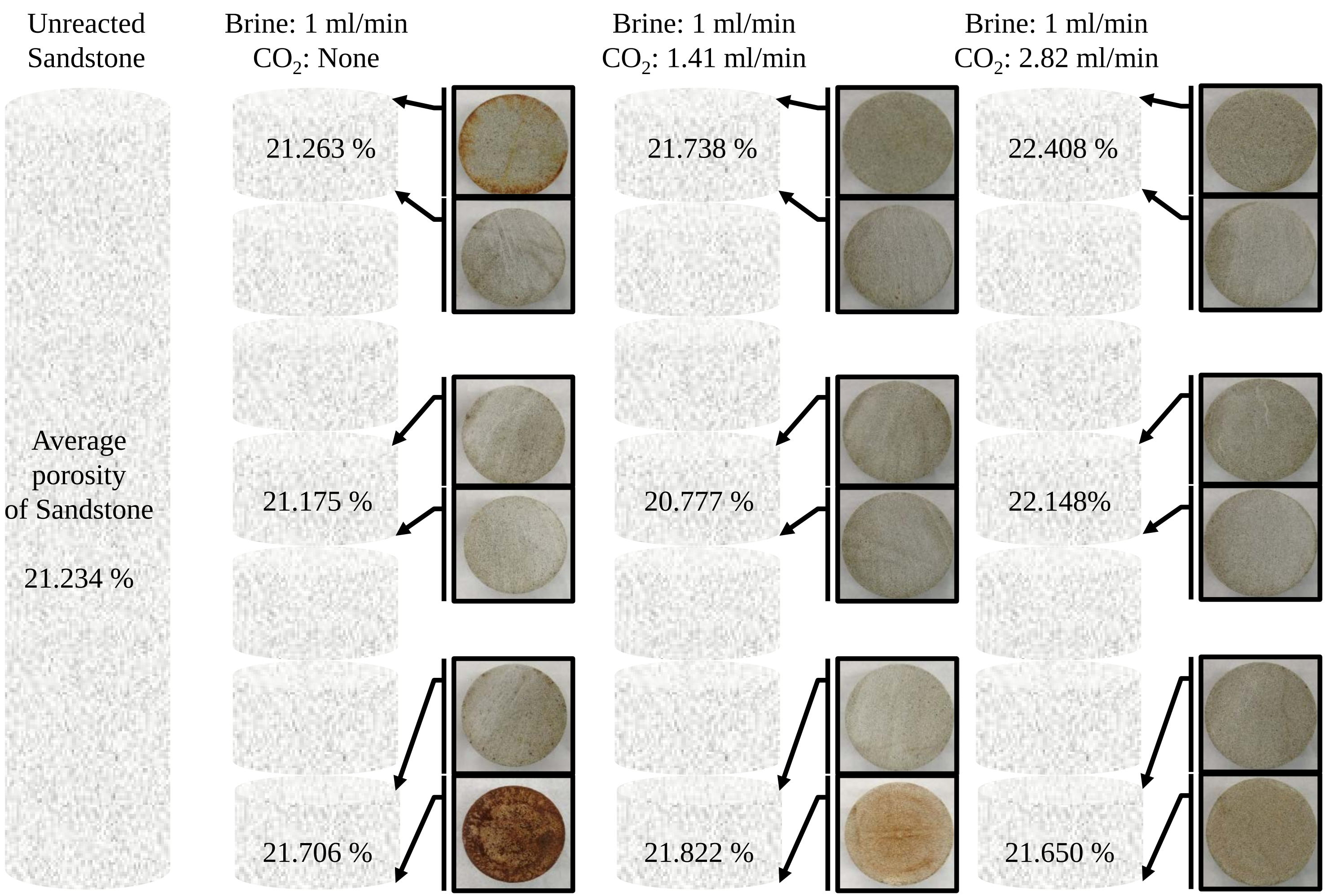






Results – Core Flooding

Entire 7 inch Sandstone core pre- and post- experiment was analyzed by He porosimeter.

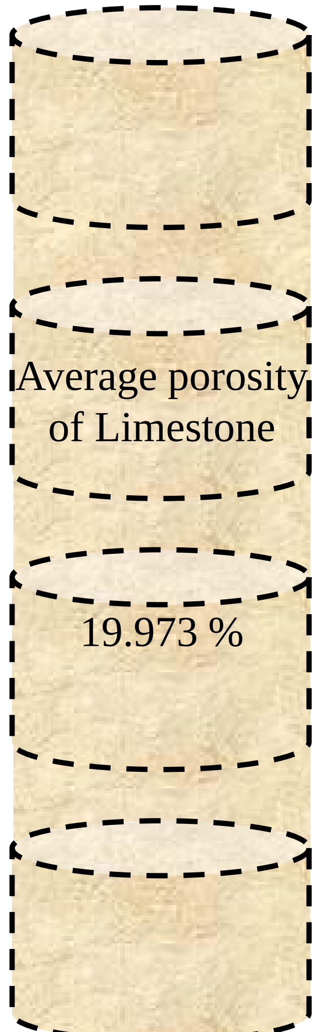


Results - Core Flooding

Flooding Experiment - 2% NaCl brine, supercritical CO_2

Unreacted

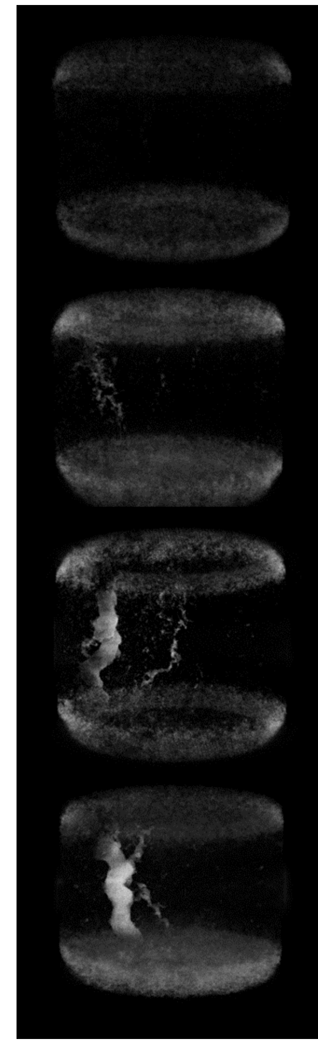
Reacted Limestone



X-ray Micro CT

Unreacted

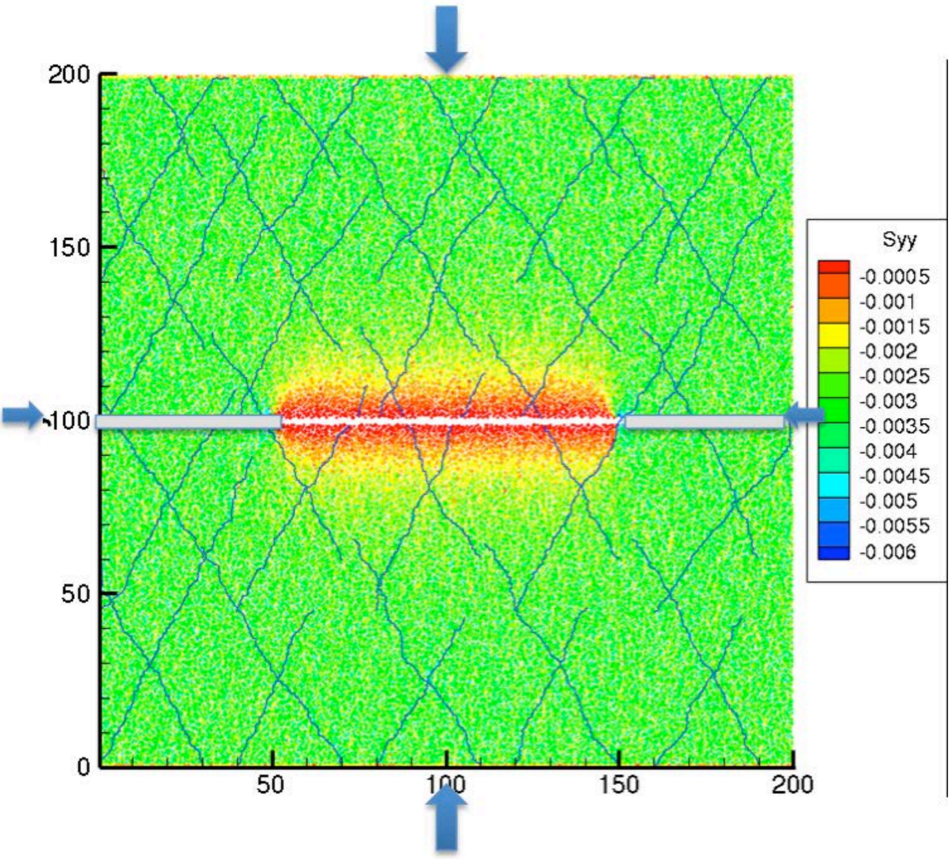
Reacted Limestone



Summary

- We have systematically investigated changes of mineralogy and porosity using XRD, ICP-MS, and Micro-CT. All of these characterizations reveal that consistent changes occur within the properties of rocks in batch reaction during exposure to non-flowing 2% NaCl brine and supercritical CO_2.
- The limestone sample in the core flooding experiment has proven to be much more reactive than the sandstone sample at these conditions. This isclearly demonstrated by the wormhole seen in the Micro-CT images.
- The reactive changes are stimulated by CO_2 injection, and are expected t olead to mechanical property changes of the rocks.

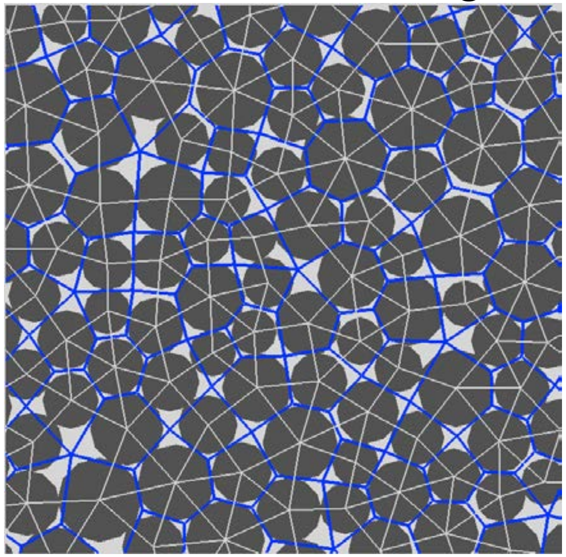
Mechanistic modeling of reactivations of natural fractures near injection wellbore due to CO_2 injection



- **Cemented wellbore with open injection interval**
- **Vertical stress ~10,000psi with H/V ratio of 0.5**
- **Densely fractured reservoir**
- **Natural fractures are assumed to be mechanically closed**
- **Natural fractures have initial permeability of ~$1.4\times10^{-12}m^2$**
- **The reservoir matrix permeability is extremely low,~ $1.4\times10^{-19}m^2$**

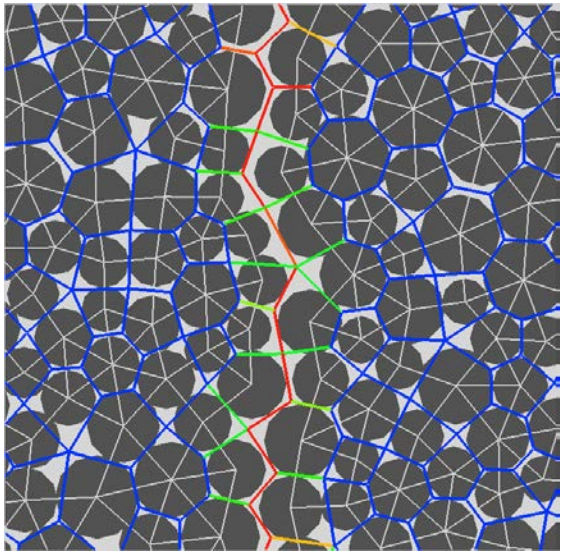
Method: Coupling DEM with Conjugate Network Flow Model

Prior to fracturing



$$q_{ij} = \frac{k_0 \cdot A_{ij}}{\mu} \frac{(P_i - P_j)}{l_{ij}}$$

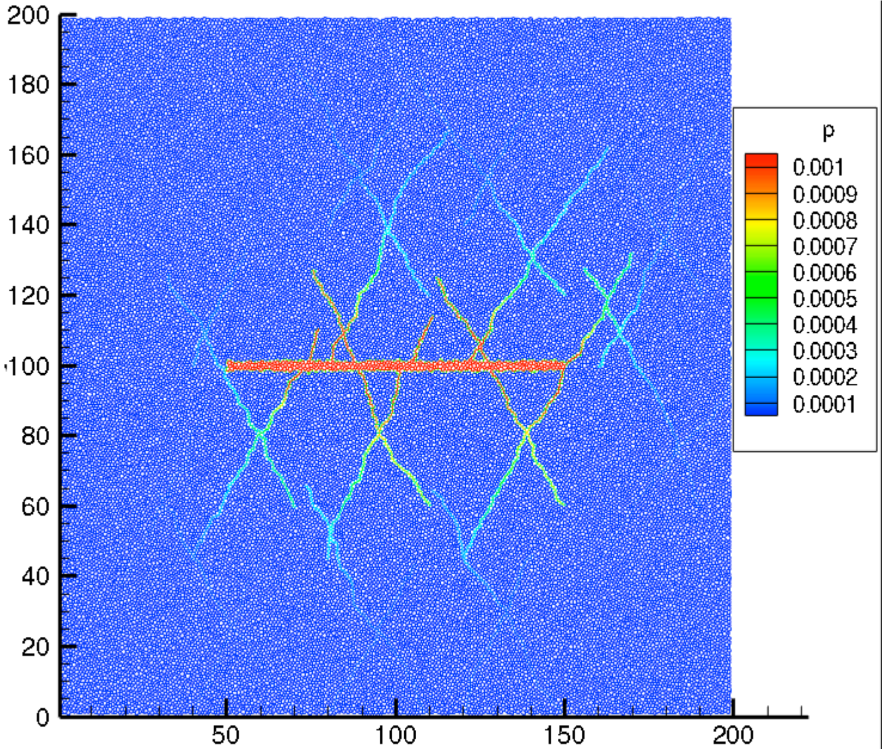
After fracturing



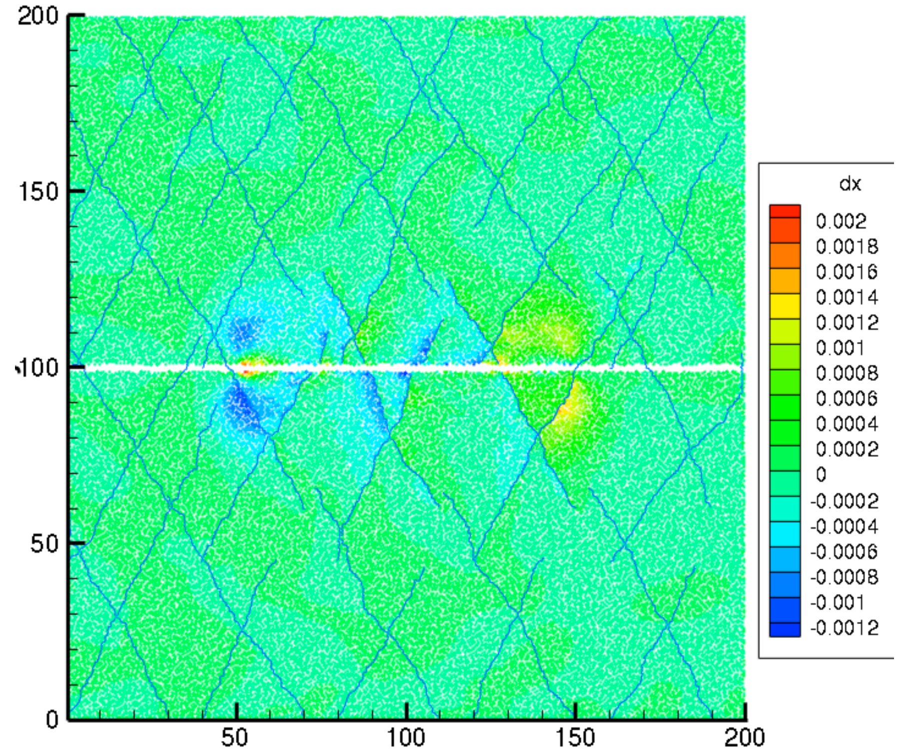
$$q_{ij} = \frac{k_{ij} \cdot b_{ij}}{\mu} \frac{(P_i - P_j)}{l_{ij}}, \quad with\ k_{ij} \approx b_{ij}^2 / 12$$

- Directly calculate apertures of micro-fractures;
- Apertures are used to as direct input for updating permeability of the flow network
- More **PHYSICS**-based hydraulic fracturing model

Simulations on stress and permeability changes

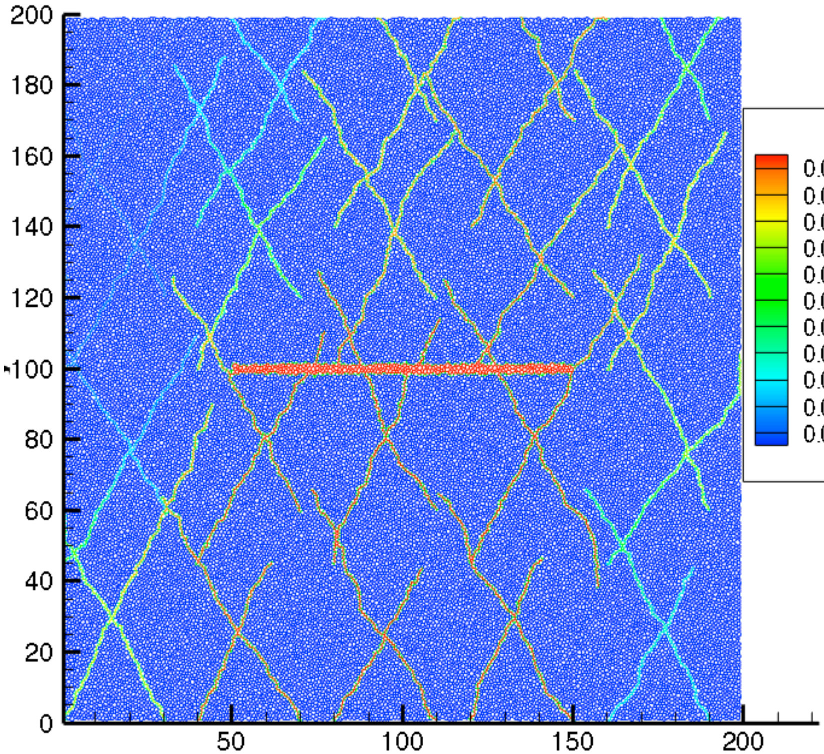


Fluid pressure distribution shortly after the injection was started

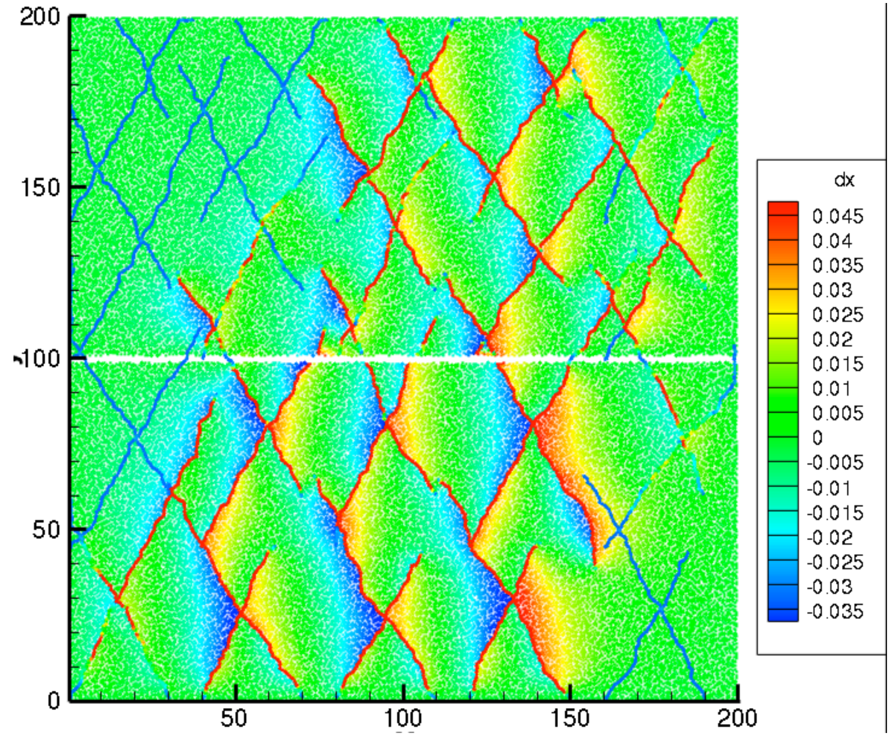


Horizontal displacement field and fracture network colored by fracture permeability

Simulations on stress and permeability changes

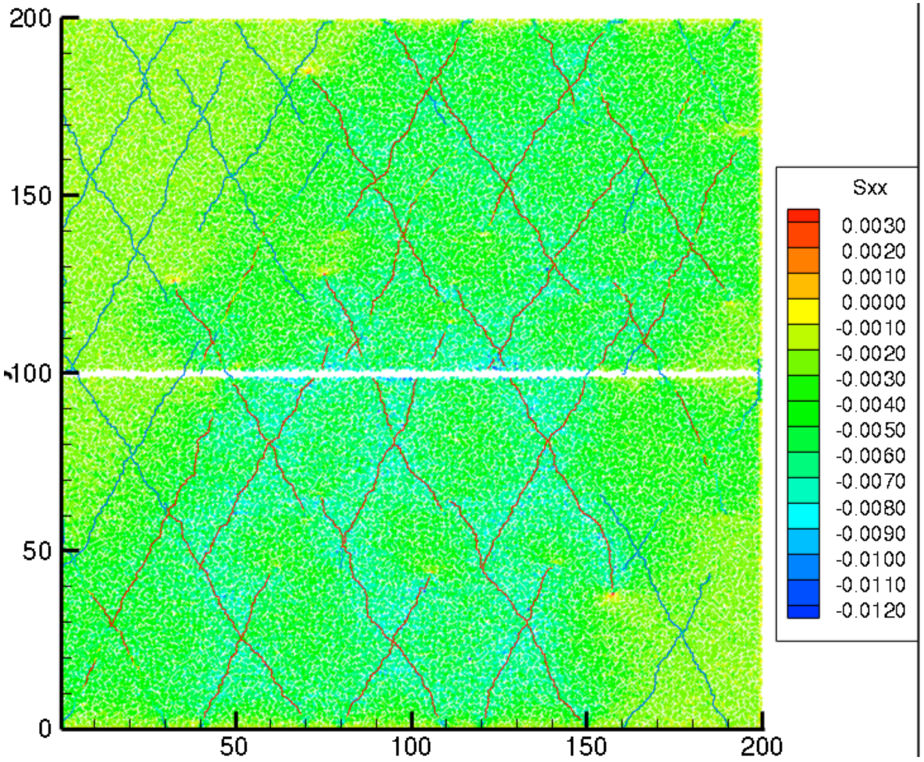


Fluid pressure distribution after flow reach steady-state

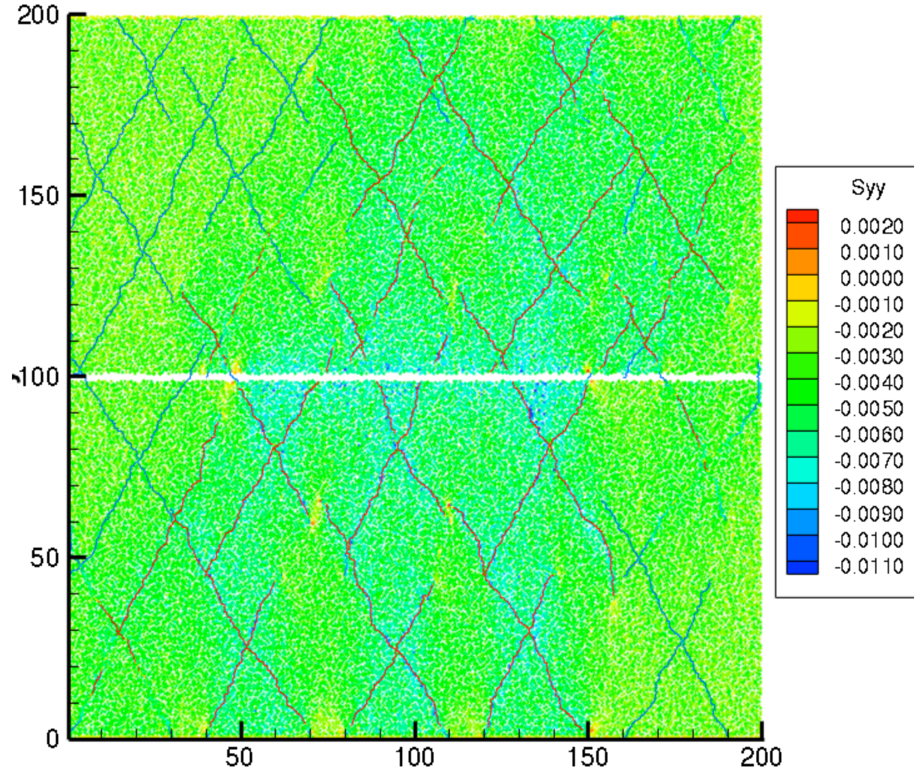


Horizontal displacement field and fracture network colored by fracture permeability

Simulations on stress and permeability changes

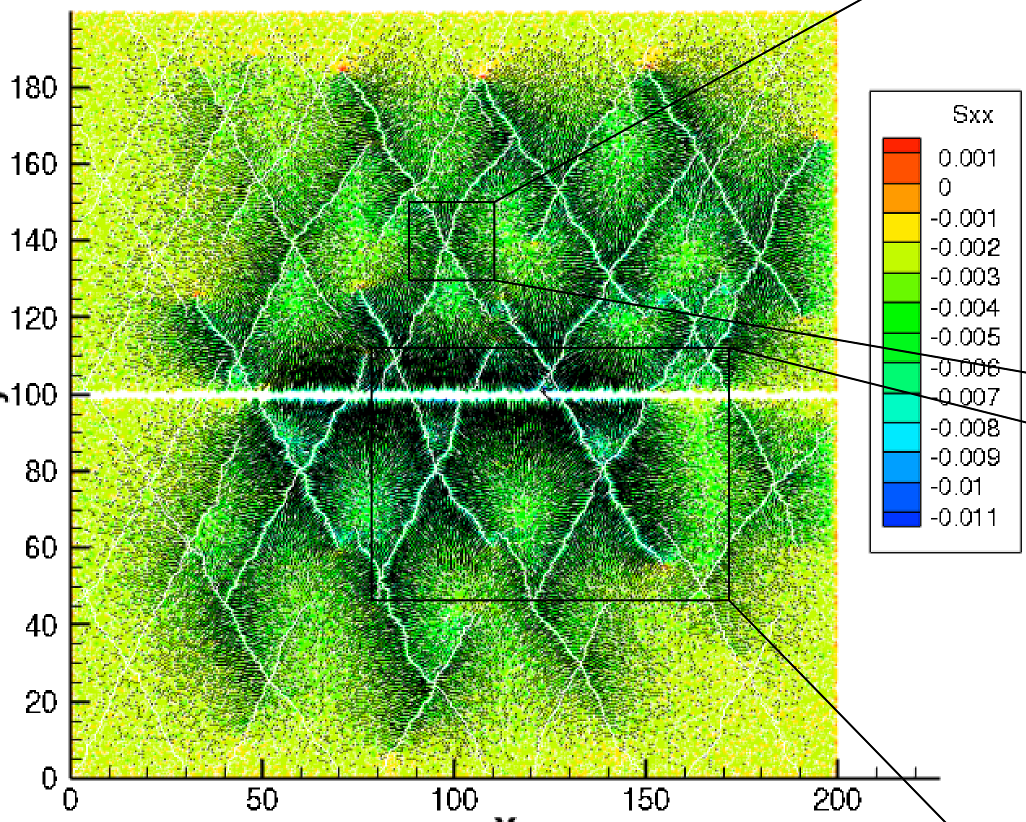


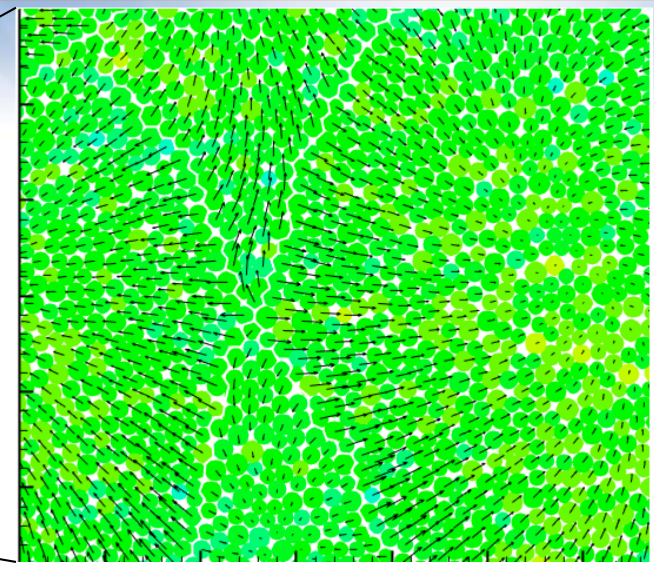
Horizontal stress field during steady flow injection

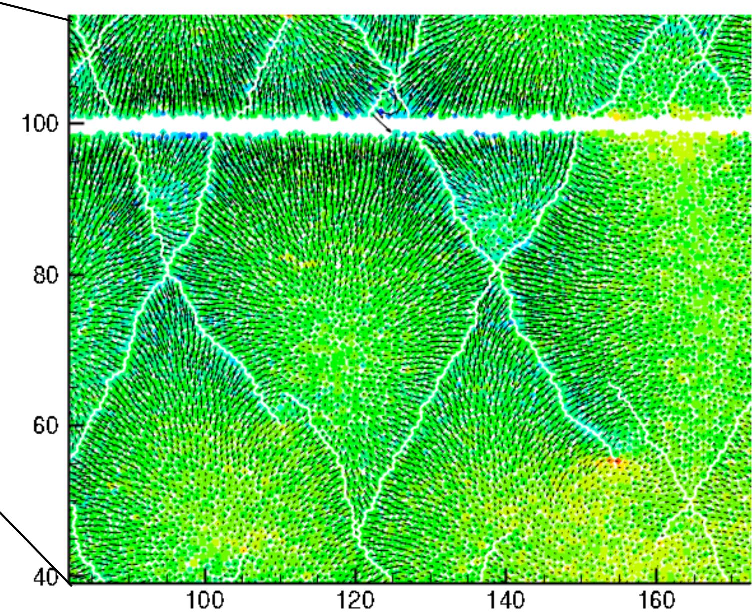


Vertical stress field during steady flow injection

Shear slipping vs. opening?







Displacement vector fields

Next step

- DEM geomechanics model provide to be robust for either fractured or unfractured reservoirs
- Most natural fractures are filled with secondary minerals, and have certain tensile and shear strengths: DEM model must account for such effects in dealing with natural fractures
- Geochemical reactions such as mineral dissolution/precipitation weaken or increase mechanical strength in natural fractures, leading to reactivation of fractures or fracture plugging
- The reasonable approach is coupled DEM-network flow-reactive transport models for hydro-mechanical-chemical processes in fractured reservoir

Thank you