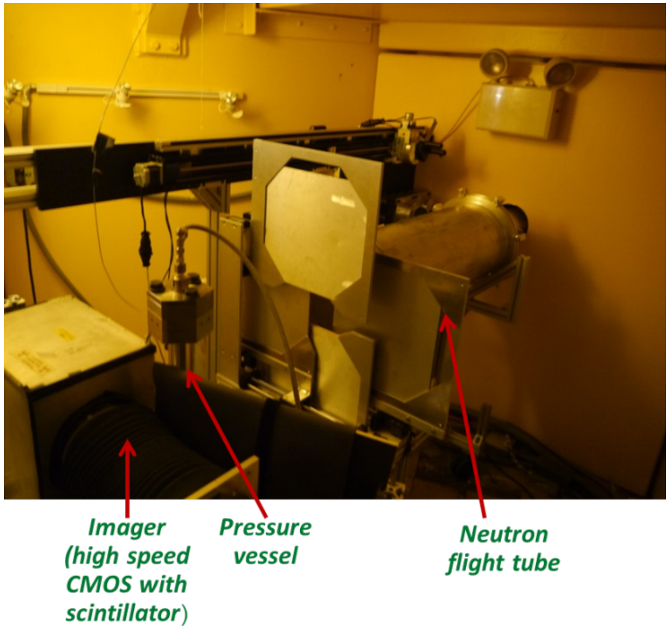

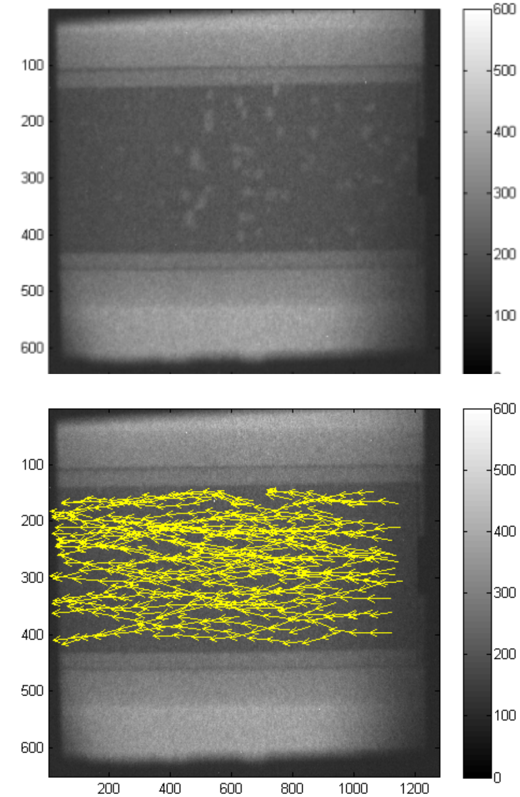

Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments

Project Officer: Sean Porse

Total Project Funding: $1.145M

November, 2017

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Oak Ridge National Laboratory

Relevance/Impact of Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Goals: 1) Develop an experimental capability to image/characterize fluid flow through fractures

2) Develop a unique experimental capability to measure mineral strains within geological samples at EGS-like conditions

Why develop this capability?

- Empirical understanding of EGS through field implementation will be limited due to high costs of field work
- Learning how to do EGS will require a combination of field work, simulation of prospective EGS designs and laboratory experimentation
- Some leveraging of O&G hydraulic fracturing practice will be possible, but the different application lithologies and conditions may require different strategies and methods
- Laboratory capabilities for studying critical EGS processes such as hydraulic fracture process and flow through fractures are limited!

Why Neutrons?

Neutrons can be used to make measurements within materials, through pressure vessels, at EGS-like conditions, to address critical rock mechanics and flow issues that are difficult to study in the field.

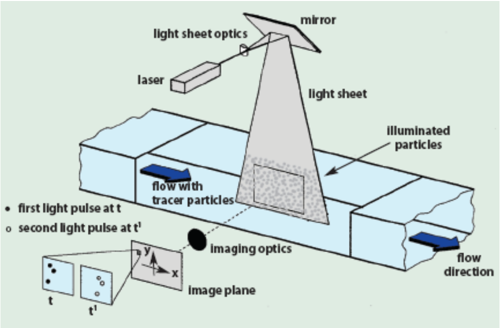
Relevance/Impact of Research

Programmatic Relevance:

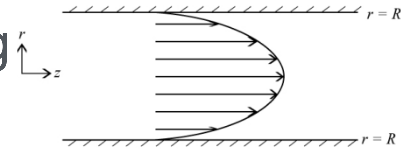
- **Reservoir creation**:
  - Enhancement and validation of hydraulic fracture simulation codes
  - Experimental strain studies of hydraulic fracture with variable pressure, temperature, and triaxial stress state will help optimize stimulation techniques
- **Reservoir operation:**
  - Measurement of flow structure in fractures to improve understanding of reservoir flow
  - Facilitate development of reduced order representation of flow
  - Validation tool for reservoir flow codes
  - Non-invasive quantification of geochemical interactions that affect long term reservoir performance

Impact: *Methods developed and measurements performed in this effort will provide a more complete characterization of physical processes that are critical to design and management of EGS.*

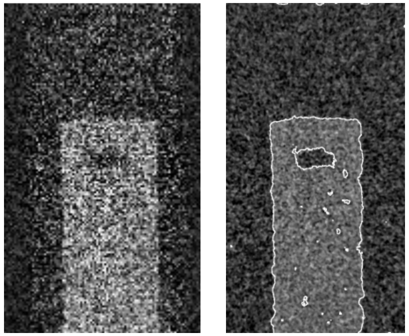
Flow structure imaging and quantification:



- Identify flow features that must be measureable
  - Velocity profiles, special regions such as stagnation points
  - Flow regimes (e.g. laminar or turbulent)
  - Multiphase behaviors



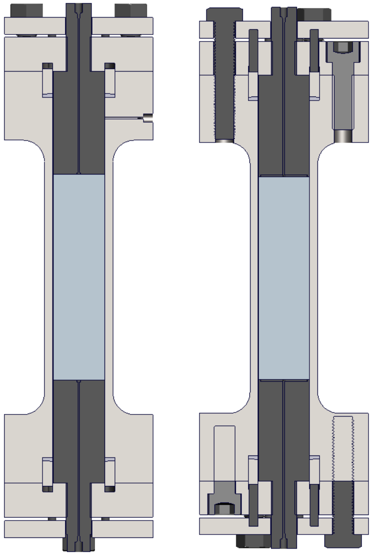
- Develop experimental methods for visualizing/measuring characteristics
  - Neutron imaging details (e.g. flux requirements, exposure times, frame rates, image processing, etc.)
  - Flow structure definition
    - Contrast agents will be used to measure steady-state flow features
      - Select material combinations
      - Develop injection schemes
  - Particle tracking velocimetry within pressure vessel



- Define experiments that help understand flow through fracture effects (E.g. surface roughness effects, aperture variation, tortuosity, etc.)
  - Support validation of flow models or develop new modeling approaches
  - Inform management of operations such as flow degradation and intervention options

Geomechanical characterization using neutron diffraction:

- Identify crystal phases within representative geological materials for which lattice deformations can be measured and equated to macroscopic stresses
- Perform strain mapping experiments of geological samples subjected to uniaxial load tests to confirm that technique is applicable and that diffraction elastic constants can be measured
- Perform proof-of-principle experiments demonstrating that strains can be mapped within geological materials for triaxial stress state, <u>in</u> a pressure vessel
- Perform proof-of-principle experiments demonstrating that mineral strains can be mapped within pressure vessel with both pore and confining pressures
- Refine technique and data analysis to assess accuracy and sources of variability
- <u>Conduct meaningful triaxial stress experiments!</u>
  - Measure critical stress thresholds
  - Compare measured stress distributions to simulated stress distributions for code validation
  - Measure strain in minerals with pore pressure to validate poroelastic material models



Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Define at least two experiments that can be performed using geothermal neutron imaging flow setup to validate commonly used analytical models that describe flow through fractures. (1/2014)	Experiments defined to measure effective permeability values for relevant fracture scenarios including laminar to turbulent flow transition and fracture tortuosity.	1/2014
Complete experiments using contrast fluids or injected particles and definitively confirm that this technique can be used to quantify flow structure of fluid moving through rock fracture. (4/2014)	Identified immiscible fluid for use as contrast agent and imaged fluid flow through core samples. First ever high speed particle imaging velocimetry of water flow demonstration using neutron imaging to investigators' knowledge.	1/2014
Complete design of cell heating hardware to enable testing up to 250C. (3/2014)	Coil design developed for induction heating of cell body.	6/2014
Develop base set of image processing algorithms to quantify velocity gradients within fracture. (6/2014)	Developed Matlab routines to automatically track contrast droplet motion in neutron radiograph sequences.	5/2014
Implement and test high temperature heating capability. (10/2014)	Pressure cell heating system tested to 300°C.	3/2015
Complete set of strain mapping experiments in hydraulically loaded granite samples at varying pressure levels up to fracture. (10/2014)	Strain mapping measurements successfully performed for samples	5/2014
Complete neutron strain measurements of geological samples at temperatures of at least 200°C. (6/2015)	Strain mapping measurements successfully performed for samples	5/2015
Perform neutron imaging flow experiments in Brazilian fractured granite cores. (6/2016)	Experiments performed at NIST beamline. Delays were due to beamline access. Result still being analyzed.	11/2016
Perform neutron strain mapping experiments with pore and confining pressures. (6/2016)	Experiments performed for limestone, marble and granite cores.	4/2016

Neutron imaging results overview:

- All flow through tests in pressure cell performed with engineered fractures using either rock cores or aluminum cores.
  - Goal: Prove experimental setup and methods for capturing detailed flow data
  - Engineered fracture dimensions: 1.59 mm aperture with 31.75 m width
  - Flow velocities up to 30 cm/sec

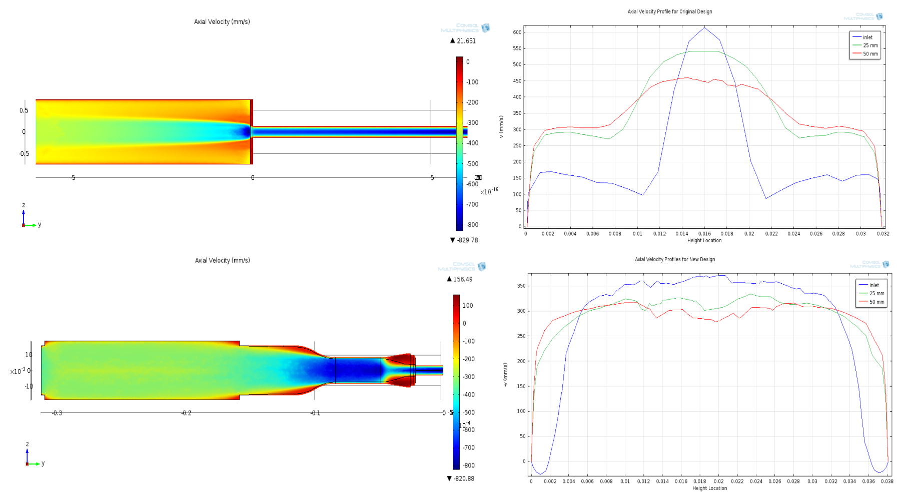
1. Gas/liquid interface experiments – Prove ability to capture multiphase flow details
2. Liquid/liquid interface – Prove ability to capture flow details in steady-state single-phase conditions
3. Precipitation/dissolution evaluation – Experiments performed demonstrating ability to measure both precipitation and dissolution effects in rock cores.
4. Develop complementary simulation framework to relate experiments and high fidelity simulations to reduced order (i.e. reservoir model) parameters.

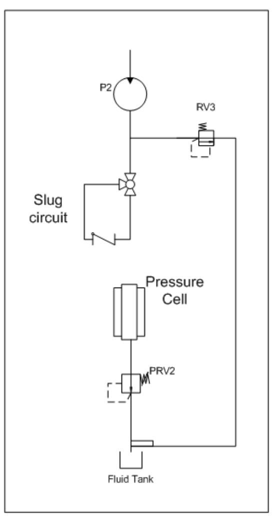
General Conclusion:

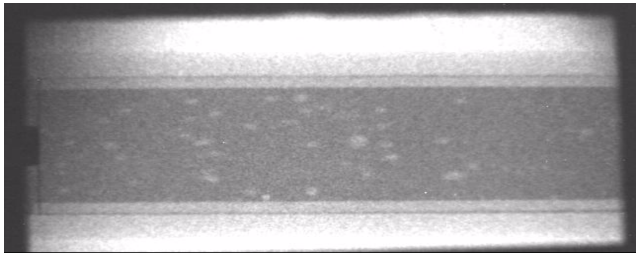
Have successfully overcome major technical challenges and demonstrated high speed particle image velocimetry for neutron radiography

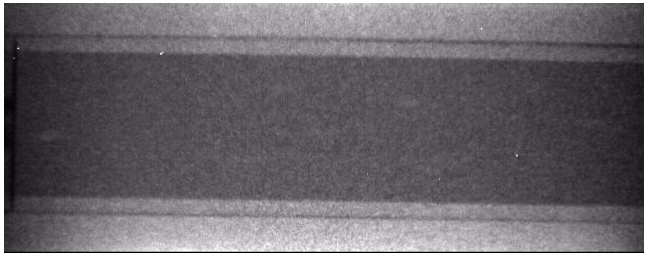
Experimental improvements over course of project

1. Aluminum cell for lower temperature experiments – 60% transmission improvement
2. Fluid flow inlet redesigned
   - Reduced jetting into sample
   - Reduced transverse velocities
3. Introduced needle bubbler injection scheme









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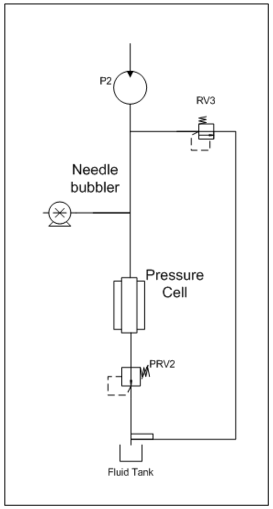

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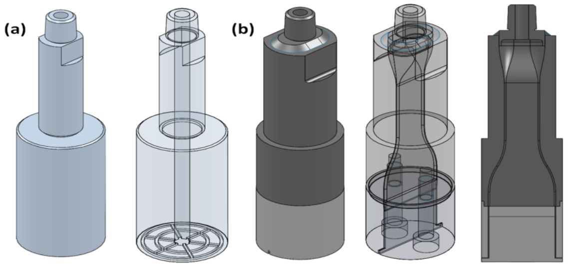

Example experiments and simulation results

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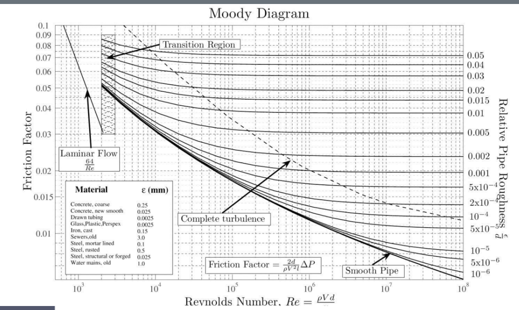
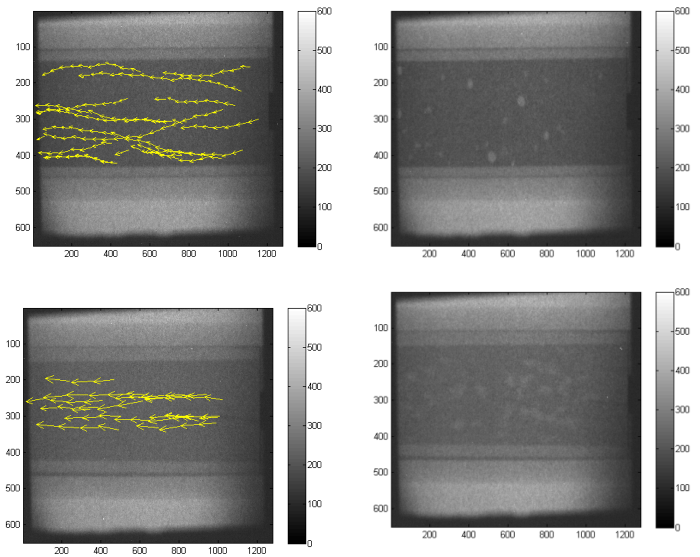
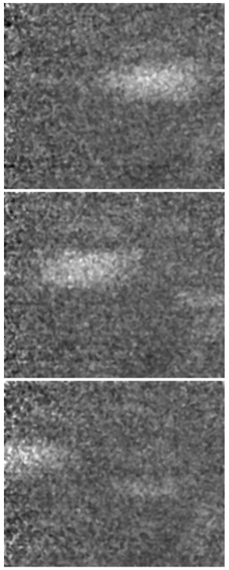
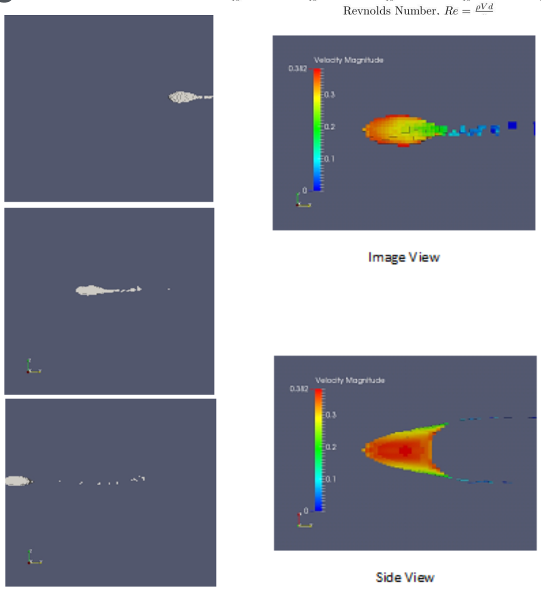
<u>Laminar to turbulent flow transition as function of surface roughness</u>

- Aluminum samples
- Smooth, 0.15 and 0.05 relative roughness
- Simulation using Volume of Fluids method
- Currently exploring lattice Boltzmann simulation methods

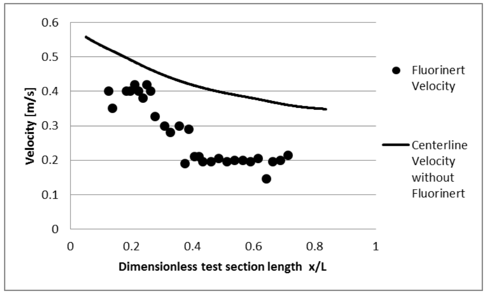




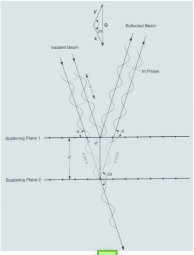




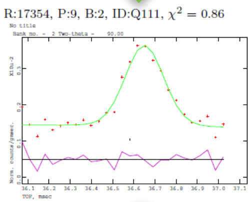
Sample Description	Aperture	Vavg (mm/s)	Vmedian (mm/s)	STDEV (mm/s)
0.65 lpm smooth	1.5 mm	147.9	156.09	35.34
0.825 lpm smooth	1.5 mm	196.11	196.23	21.51
1 lpm smooth	1.5 mm	210.3	211.5	29.1
0.825 lpm medium	0.75 mm	292.02	294	55.35
0.825 lpm rough	0.75 mm	273.99	284.46	63.9



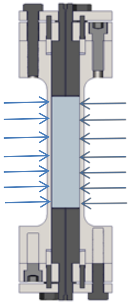
Neutron-Diffraction Strain Measurement Accomplishments Summary



- Experiments performed to date
  1. Uniaxial compression tests
     - Measure repeatability of method and material homogeneity assumptions
  2. Pressure cell experiments
     - Strains internal to sample can be measured through pressure cell
     - Unique capability that would permit mapping of stresses within geological materials at geothermally meaningful conditions (triaxial stress state, elevated temperatures, etc.)!

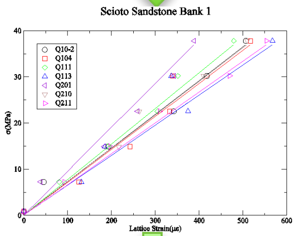


- Measurement details – Westerly Granite and Carthage Marble Samples (5mm x 5mm x 5mm gauge volume)

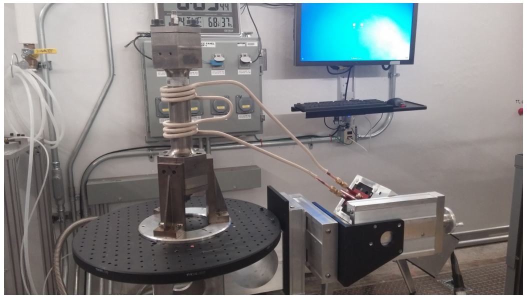


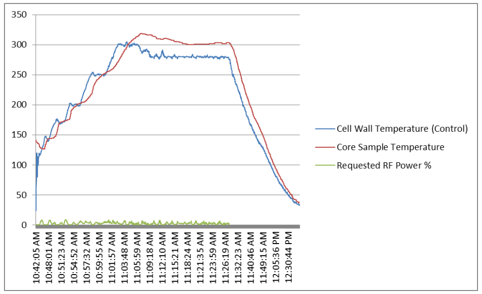
  – Uniaxial tests
    – 3 different points measured over two load cycles to test repeatability and material homogeneity
  – Pressure cell tests
    – Measurement gauge volume of 200 mm^3 (5 mm x 8 mm x 5 mm)

$$\varepsilon_{hkl} = \frac{d_{hkl} - d^0_{hkl}}{d^0_{hkl}}$$



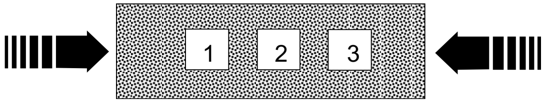
- Pressure cell heating capability demonstrated to 300 degrees C





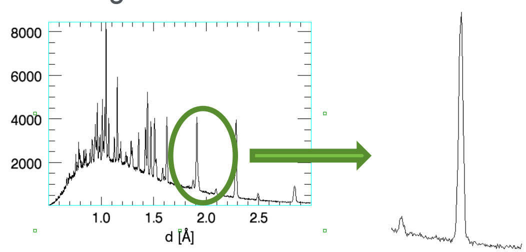
$$\sigma_{ij} = \frac{E_{hkl}}{(1+\upsilon_{hkl})}\left[\varepsilon^{hkl}_{ij} + \frac{\upsilon_{hkl}}{(1-2\upsilon_{hkl})}\left(\varepsilon^{hkl}_{11} + \varepsilon^{hkl}_{22} + \varepsilon^{hkl}_{33}\right)\right]$$

Uniaxial load tests



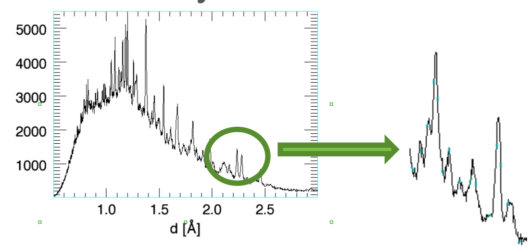
- Experiments show that marble response is homogeneous and repeatable
- Granite is less uniform
- Whole pattern fits significantly more accurate than single peak fits

Carthage Marble

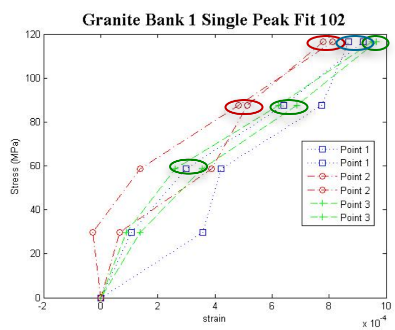


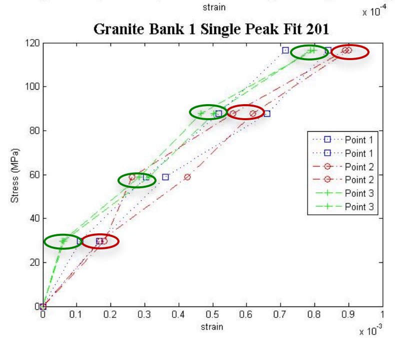
Simple Mineralogy

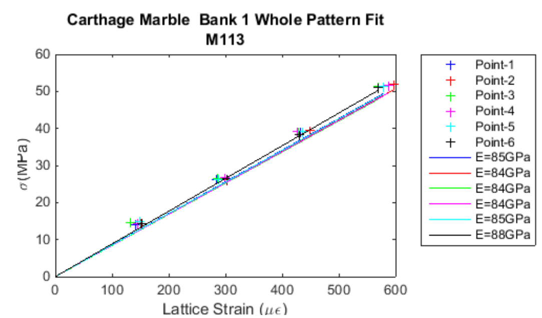
Westerly Granite

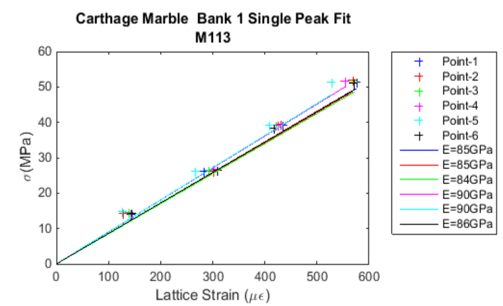


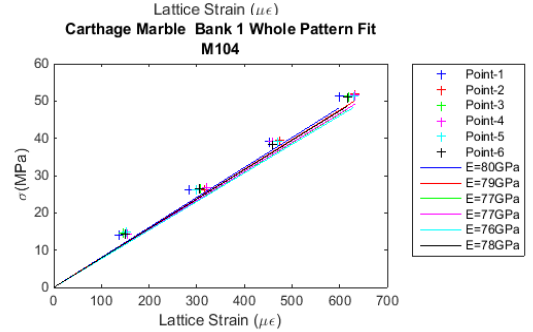
Complex Mineralogy

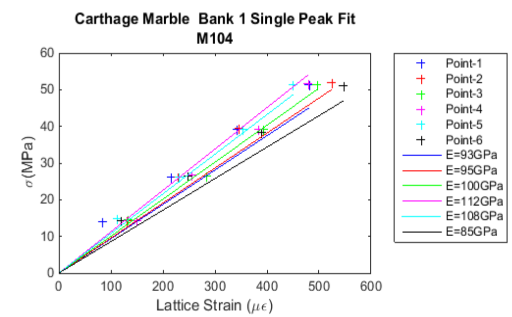










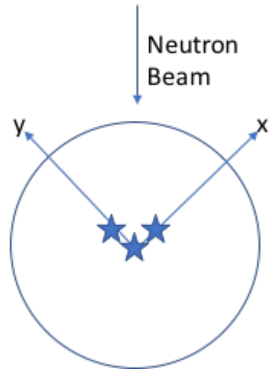


Pore pressure experiments

	Est. Porosity	Est. Permeability	Est. UCS
Carthage Marble	1.5%	2 μD	124 MPa
Indiana Limestone	14 – 19%	2 – 4 mD	35 MPa
Scioto Sandstone	12%	0.01 – 0.1 mD	55 MPa

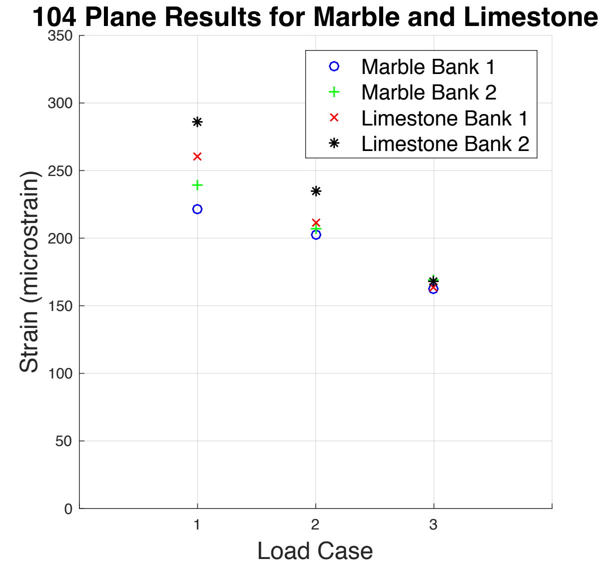
	Confining Pressure	Axial/Pore Pressure
Load Case 1	27.6 MPa	0 MPa
Load Case 2	27.6 MPa	10.3 MPa
Load Case 3	27.6 MPa	20.7 MPa

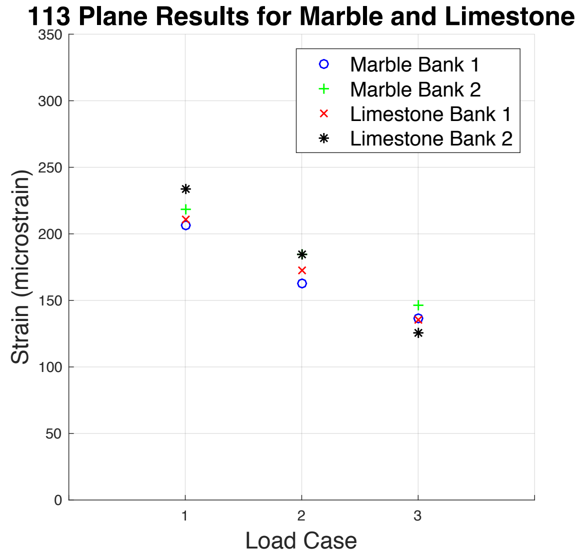
Locations measured within sample



Gauge volume = 6mm x 2 mm x 15 mm

Pore pressure results





- Expected trends measured in experiments
- Strain magnitudes in limestone larger than marble with only confining pressure
- Strain magnitudes become closer with pore pressure

How do the results compare to theory?

	$\alpha = 0$	$\alpha = 0.2$	$\alpha = 0.4$	$\alpha = 0.7$
Strain ratio $\frac{Load\ 2}{Load\ 1}$	0.85	0.80	0.76	0.69
Strain ratio $\frac{Load\ 3}{Load\ 1}$	0.69	0.60	0.52	0.38

Limestone ratio of strains with pore pressure to only confining pressure

	104 Bank 1	104 Bank 2	113 Bank 1	113 Bank 2
10.3 Mpa	0.83	0.87	0.82	0.81
20.7 Mpa	0.63	0.65	0.58	0.53

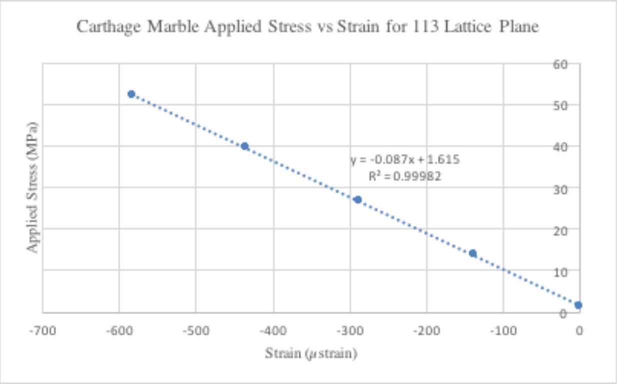
Marble ratio of strains with pore pressure to only confining pressure

	104 Bank 1	104 Bank 2	113 Bank 1	113 Bank 2
10.3 Mpa	0.9	0.79	0.85	0.84
20.7 Mpa	0.69	0.62	0.66	0.63

Terzaghi Effective Stress

$$\sigma'_{ij} = \sigma_{ij} - \alpha p \delta_{ij}$$

$$\epsilon_{ij} = \frac{1+\nu}{E}\sigma'_{ij} - \frac{\nu}{E}\sigma'_{kk}\delta_{ij}$$



- Limestone reported α = .7
  Marble reported α = .2
- Measured strains do not correspond to conventional measurement of α
- But these are lattice strains, not macroscopic strains!

Future Directions

- Project is largely finished and in process of completing documentation

- Recommendations for future work in this area:
  - Neutron imaging work
    - Refine technique for measuring flow through small apertures
    - Utilize experimental method to quantify geochemical models of precipitation and dissolution
    - Utilize experimental method to validate models of fracture and flow evolution in systems with pre-existing fracture networks
    - Transition technique to broader community
  - Neutron strain measurement work
    - Develop technique for calculating strains in minerals with low crystal symmetry
    - Perform experiments in polymineralic materials to inform development of improved micromechanical models of bulk properties
    - Transition technique to broader community

Research Collaboration and Technology Transfer

- Have educated Pioneer Natural Resources, an unconventional Oil & Gas independent, on the potential applications of neutron imaging and diffraction for geophysical characterization and are currently formulating a work scope for characterizing shales.
- Pressure cell and techniques have been applied to study fluid movement in geological specimens for DOE BES program.
- Research has been presented at relevant conferences within R&D community

Mandatory Summary Slide

Neutron imaging of flow

- Successful demonstration of ability to measure single phase and multi-phase flow through samples within pressure vessel
- Particle imaging and tracking algorithms able to quantify particle velocity vectors
- A reduced-order model correlation approach has been formulated and demonstrated on a simple case
- Demonstrated ability to measure precipitation and dissolution within geological samples

Neutron strain measurement

- Feasibility established for triaxial stress loading, with pore pressure, strain mapping in actual geological materials within pressure cell
- Technique appears to be useful for quantifying localized variation in mechanical response of heterogeneous materials – potentially can be used to build better material models
- Technique may also be useful for providing insight into intergranular effects that influence material failure – no such direct observational capability with conventional rock mechanics load testing