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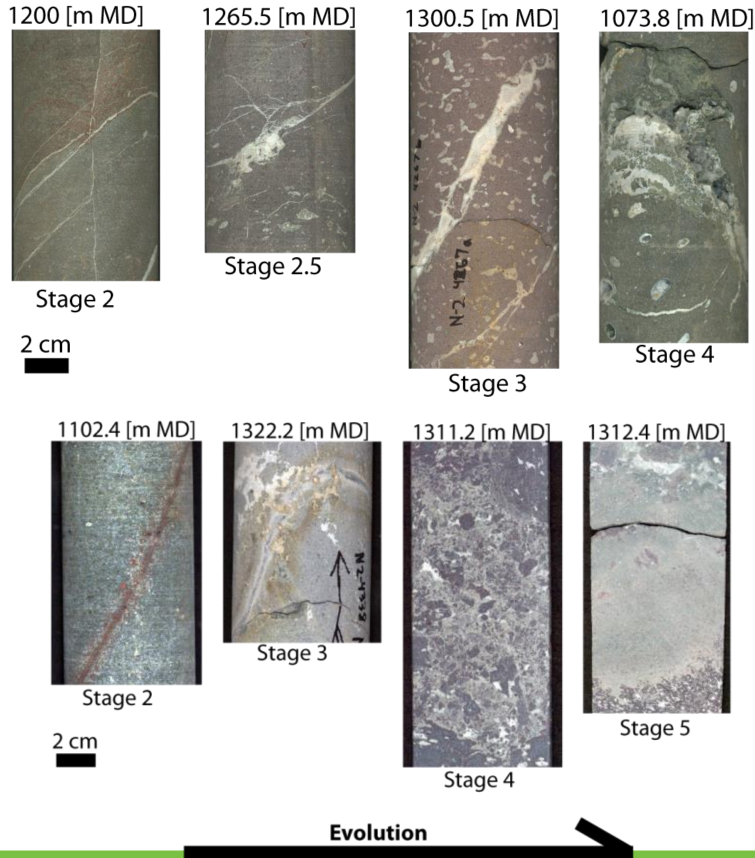

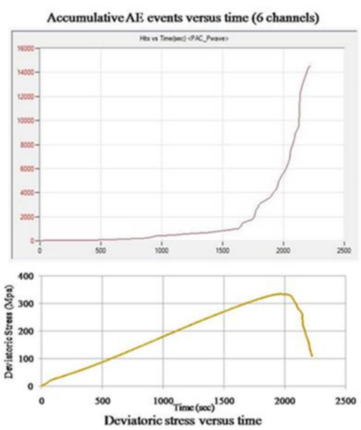

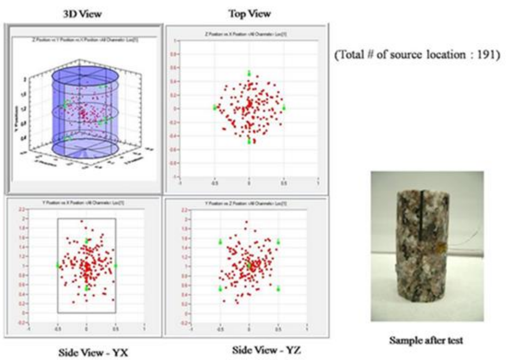

Development of a Geological and Geomechanical Framework for the Analysis of MEQ in EGS Experiments

Principal Investigator
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The University of Oklahoma

EGS Component R&D › Induced Seismicity

This presentation does not contain any proprietary confidential, or otherwise restricted information.

May 2015

Relevance/Impact of Research

- The objective of this project is to develop a framework for investigating processes that contribute to the occurrence of seismicity in enhanced geothermal systems with particular reference to the Newberry demonstration experiment and the potential Geysers EGS demonstration experiment

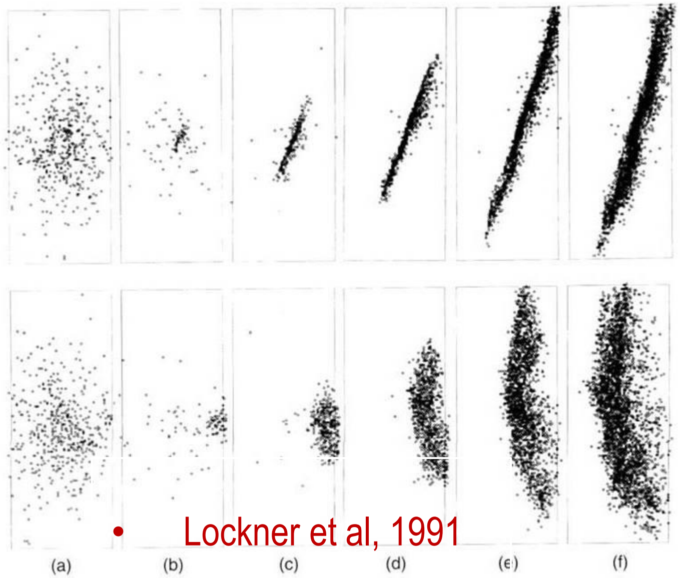
- We will use an integrated geological and geomechanical approach to identify the causal mechanisms of MEQs, and to relate their occurrence to accompanying changes in rock mass characteristics

Relevance/Impact of Research

- Help remove barriers for prediction of reservoir's response to stimulation: Induced Seismicity
  - Contribute to securing the future with Enhanced Geothermal Systems
  - Permeable zones have to be created by stimulation, a process that involves fracture initiation and/or activation of discontinuities
  - Rock stimulation can be accompanied by multiple micro-seismic events
  - Improve understanding of the relation between the location of the MEQ and fluid flow based on geological/geomechanical criteria that can then be used as a model for study of other EGS sites

Scientific/Technical Approach

- Combined geological and geomechanical approach to asses reservoir response to stimulation, and to identify causal mechanisms of MEQs; relate MEQ occurrence to resulting permeability characteristics
  - (i) characterize petrophysical and geomechanical properties of type rock from Newberry and the Geysers using rock deformation experiments under various pressure & temperature conditions



- Lockner et al, 1991

Scientific/Technical Approach

(ii) Study natural fractures in the Newberry to establish a fracturing history and the behavior of the fracture during slip:

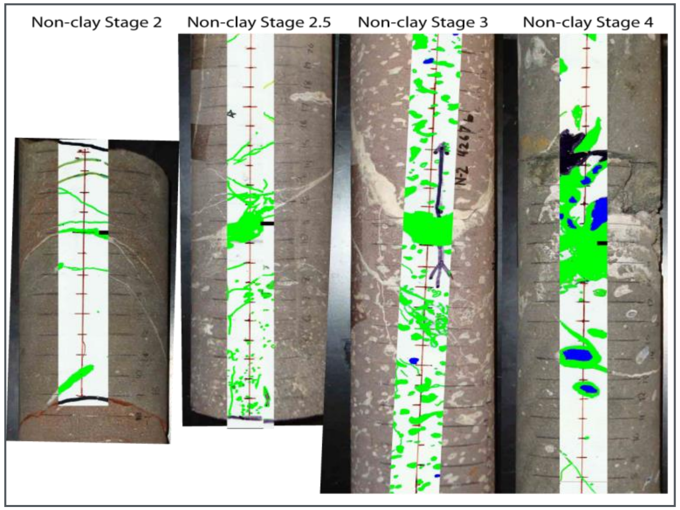
- Assess the geometry and survival of asperities during slip using initial porosity and the minerals present along the surfaces of the fracture
- Understand the role of fluid flux and chemical reactivity in the pores & along fractures

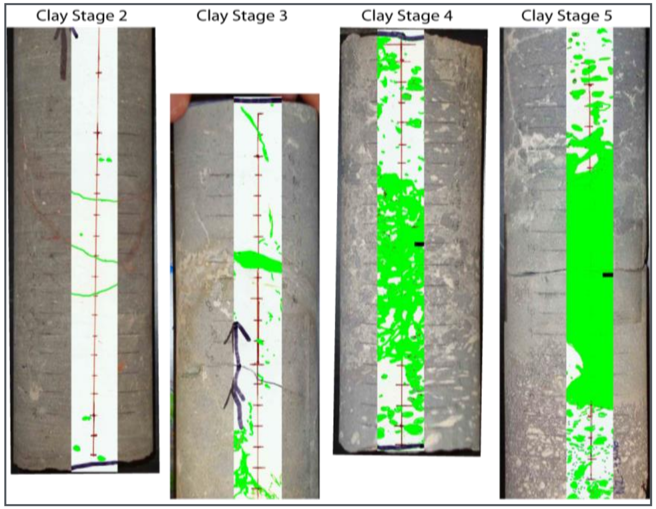
(iii) Study generation of MEQ’s under a triaxial stress state, characterize permeability during injection

(iv) Identify the mechanisms associated with MEQ’s in relation to maintenance of natural fracture permeability

- Using analytical and numerical tools benchmarked by observations of naturally and experimentally deformed samples

- **Core collection, preparation, rock mechanical testing**
- **Petrophysical characterization include**
  - Thin section preparation and analysis; porosity, permeability measurement; quantified of the variation in porosity and pore geometry as a function of distance from the slip surface; quantified textural evolution of fractures via thin section analysis
  - Petrographic analysis was used in conjunction with X-Ray diffraction (XRD) analysis to identify the mineralogy of the host rock and the respective fracture zone in each core sample (composition from 85 % plagioclase and 10% quartz to 25% plagioclase and 50% quartz. The plagioclase) and X-Ray Fluourescence (XRF) to define the elemental chemistry of the host and fault rock
    - Figures show Macroscopic porosity mapping of faults containing non-clay and clay-enriched fault rocks via 2 cm-wide transect of cores. Green solid color denotes healed crack porosity, and solid blue represents open porosity. Brown tick-marks on transparency photo equal 1 cm.





N2-3617 to 4339 ft

Accomplishments, Results and Progress

- Calibration of testing apparatus; Protocol for multi-stage compression test
- Tests on aluminum, steel, and Berea SS, etc. samples
- Development of elastic and failure properties for all core plugs (N1-4013-4014; N1-4348-4349; N2-4281; N2-4219.5; OXY 72-3)
- High-resolution scanning of some samples to explore pore volume structure before and after failure

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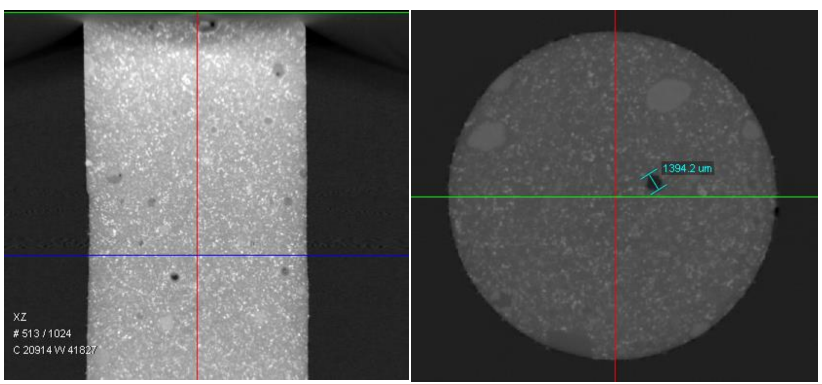
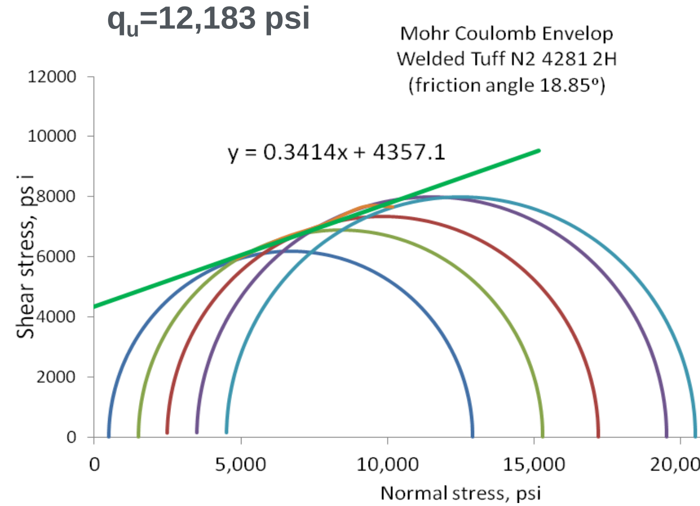
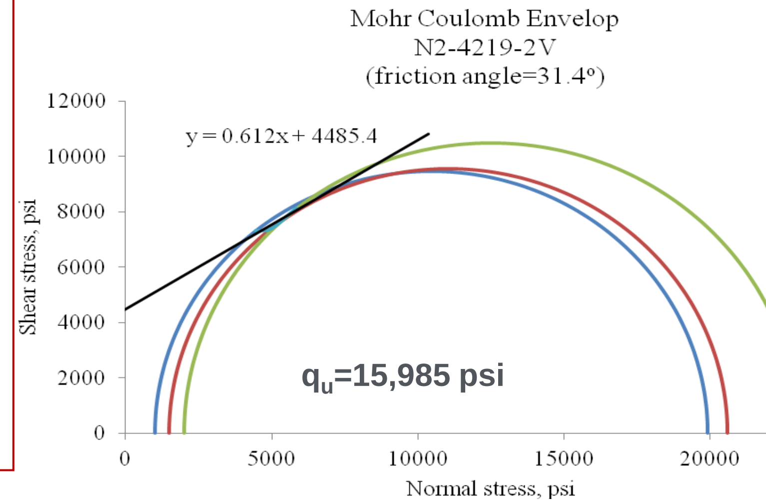






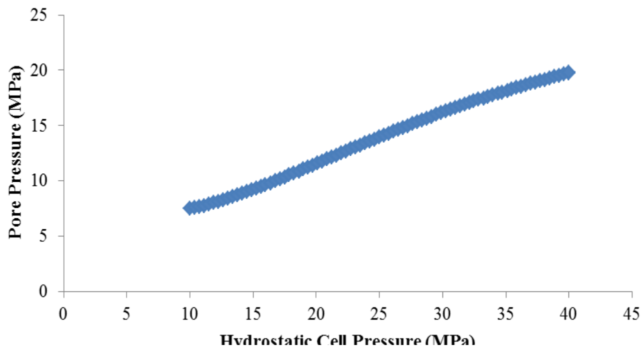
Accomplishments, Results and Progress

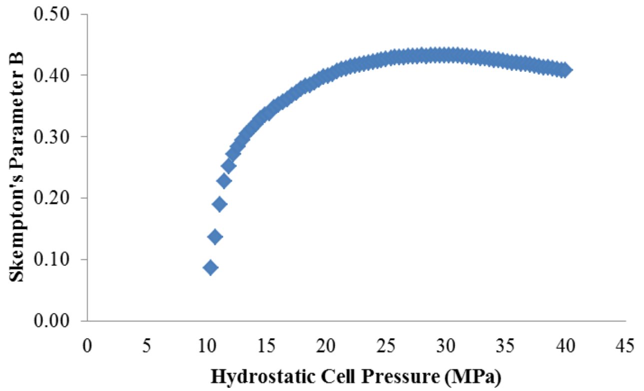
- **Poroelastic parameters measured:**

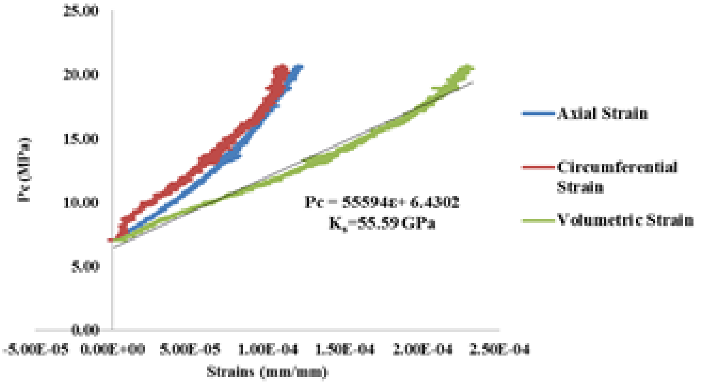
Drained and Undrained test for specimen N1-4013-3H. Skempton's B values for N1-4013-3H.
Unjacketed test: Grain compressibility for Welded Tuff N1-4348-1V.

Rock Specimen	Skempton's Parameter, B		
	This work	Hart	Akbarnejad-Ghassemi
Berea Sandstone	0.64	0.84	0.55
Indiana Limestone	0.52	0.4	0.46

Rock Specimen	K (GPa)		K_s (GPa)		α		Compared author (s)
	This work	Others authors	This work	Others authors	This work	Others authors	
Berea Sandstone	10.13	4.0-12.5/ 0.95	34.72	47.2/ 29.8	0.71	0.8	Chajlani/Hart
Indiana Limestone	14.28	20.83	74.9	76.9	0.81	0.84	Chajlani
Westerly Granite	16.24	15-25	48.01	N/A	0.66	0.60	NER
Welded Tuff N1-4348-1V	2.33	8.68-20.28*	55.6	N/A	0.96	N/A	*Hooke's Law

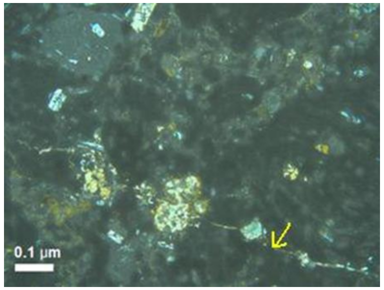


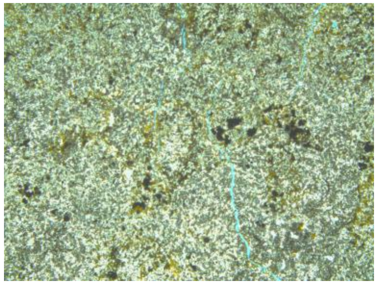


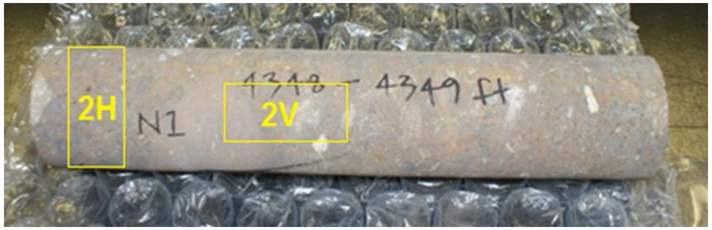


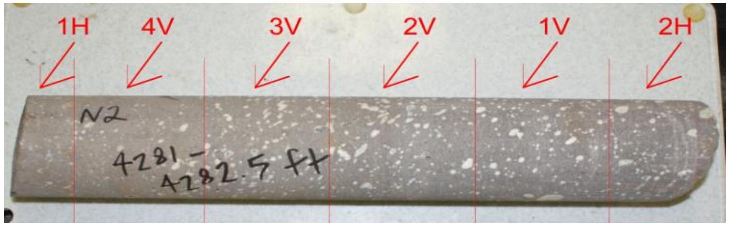
Accomplishments, Results and Progress

- Rock mechanical heterogeneity, implications for MEQ distribution or lack there of.





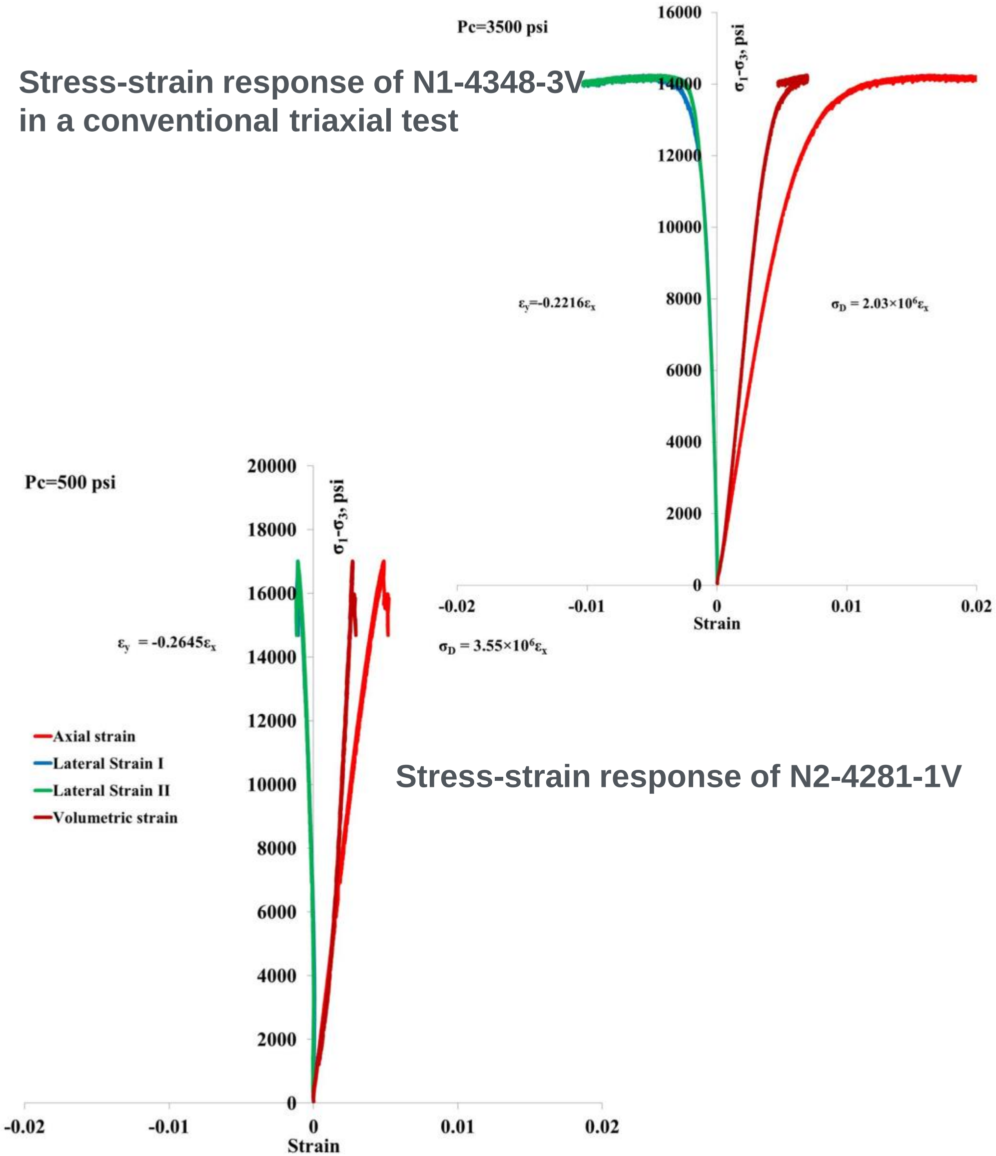


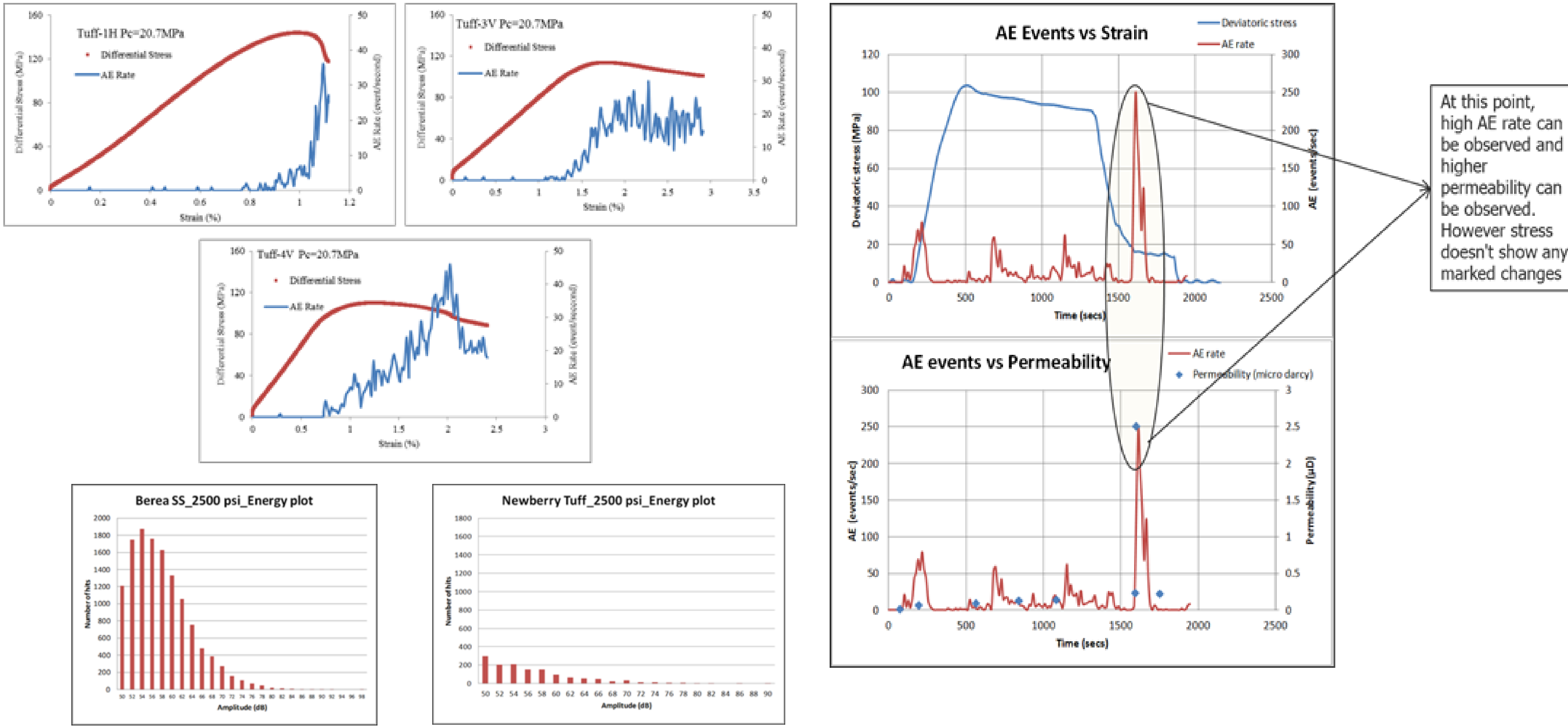


- Brittle vs Ductile Response

Stress-strain response of N1-4348-3V in a conventional triaxial test

Stress-strain response of N2-4281-1V



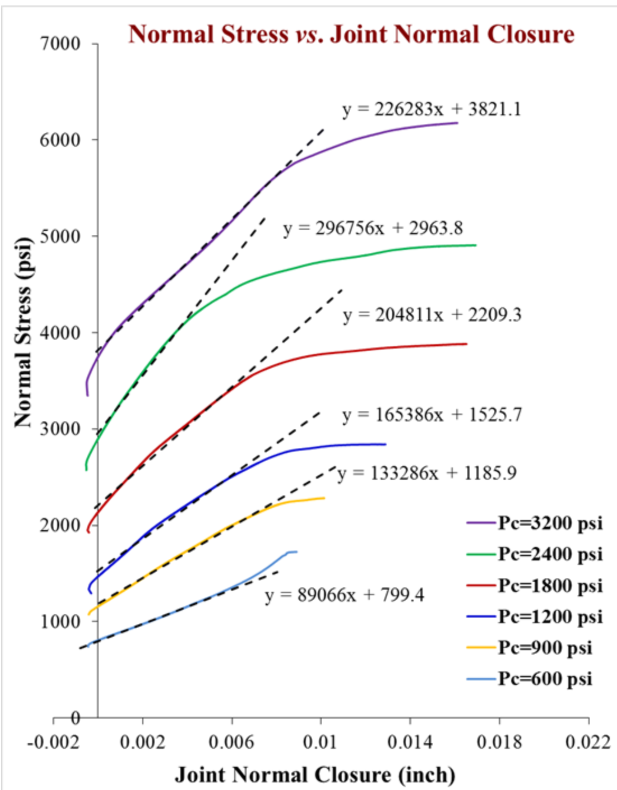


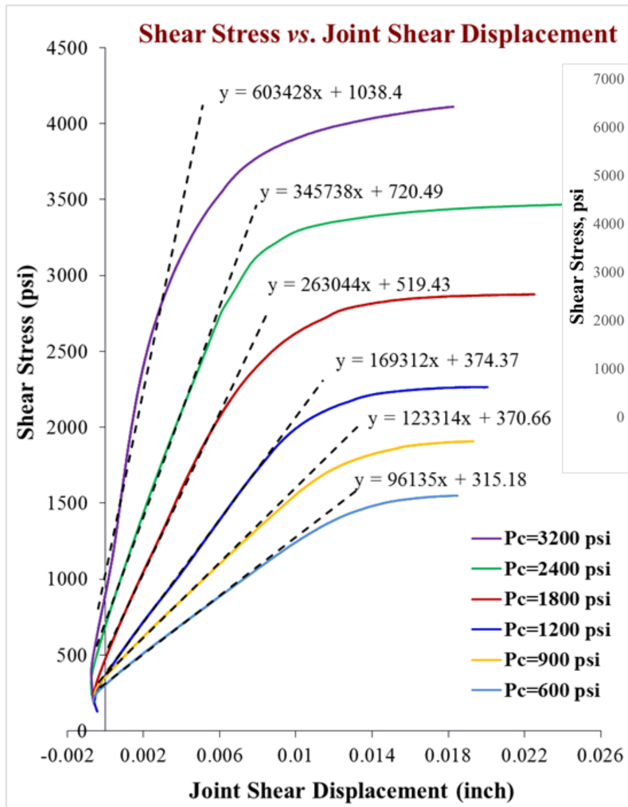
Differential stress and AE rate versus axial strain (Tuff-1H), (Tuff-3V), (Tuff-4V). Triaxial testing under 21 MPa confining pressure, 0.02%/min strain rate and 6-channel AE monitoring.
On the right: Permeability (nitrogen gas) generation and AE events during rock failure.
Bottom left: Comparison of acoustic energy from a relatively brittle sandstone and relatively ductile tuff sample.

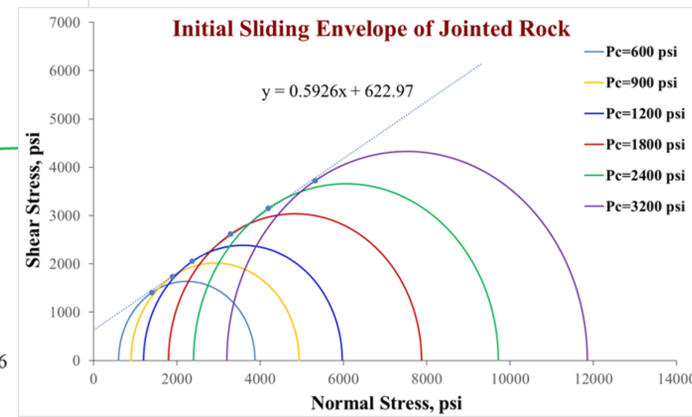
Accomplishments, Results and Progress

Stiffness Properties for Jointed Rock

Peak Normal Stress (psi)	1004 (6.92 MPa)	1867 (12.88 MPa)	2537 (17.49 MPa)	4052 (27.94 MPa)	5423 (37.39 MPa)	7353 (50.70 MPa)
Peak Shear Stress (psi)	1022 (7.05 MPa)	1761 (12.14 MPa)	2105 (14.51 MPa)	3151 (21.73 MPa)	3905 (26.93 MPa)	4778 (32.94 MPa)
Normal Stiffness (psi/in)	89066 (24.18 MPa/mm)	133286 (36.18 MPa/mm)	165386 (44.89 MPa/mm)	204811 (55.60 MPa/mm)	296756 (80.55MPa/mm)	226283 (61.42 MPa/mm)
Shear Stiffness (psi/in)	96135 (26.1 MPa/mm)	123314 (33.47 MPa/mm)	169312 (45.96 MPa/mm)	263044 (71.40 MPa/mm)	345738 (93.85 MPa/mm)	603428 (163.80 MPa/mm)



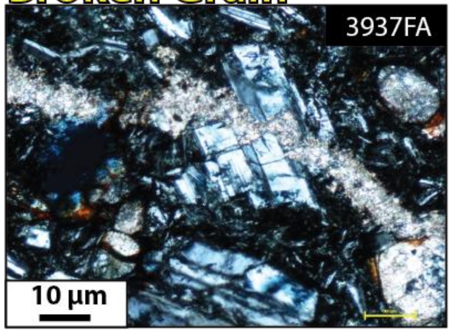




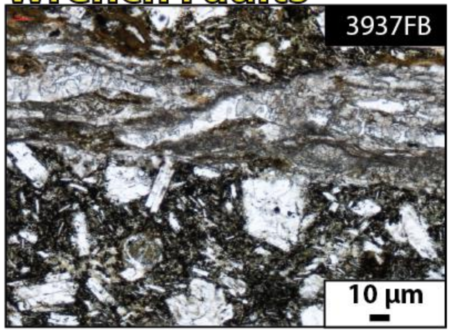
Dilation Accompanying Repeated Slip

Geologic Slip Indicators

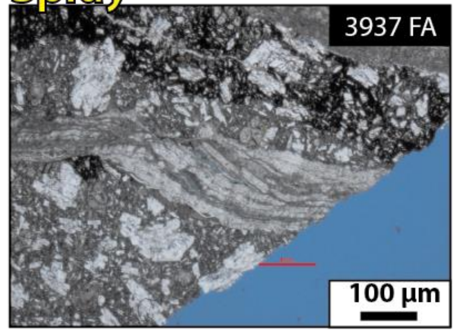
Broken Grain

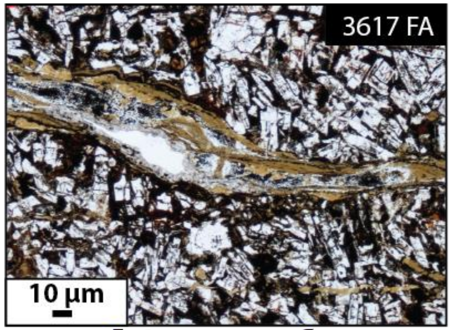


Wrench Faults

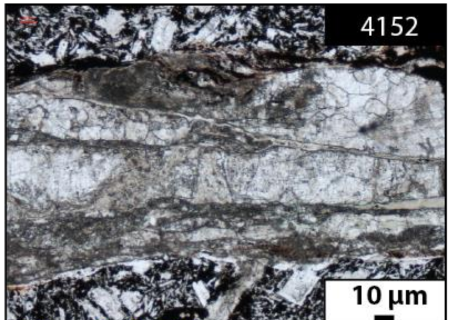


Splay



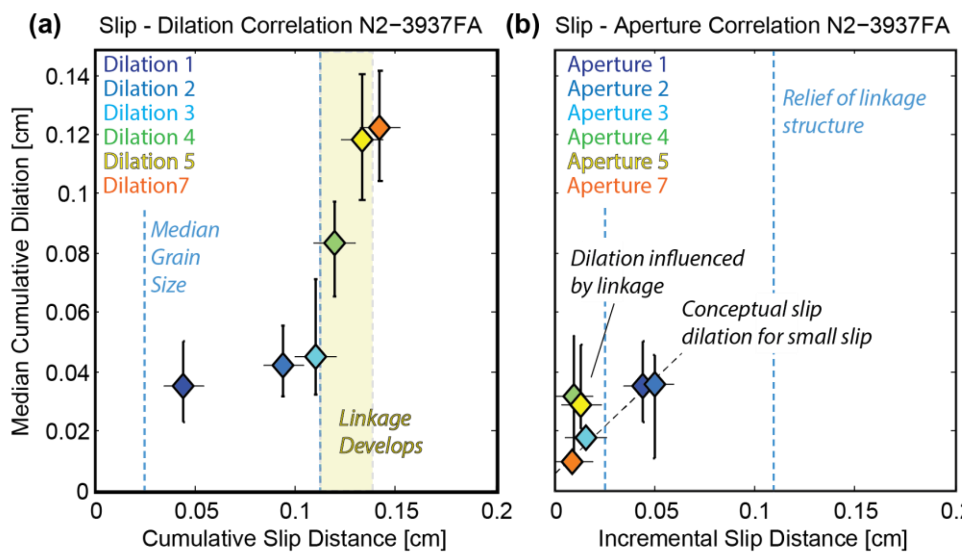


Matching Surfaces



Riedel Shears

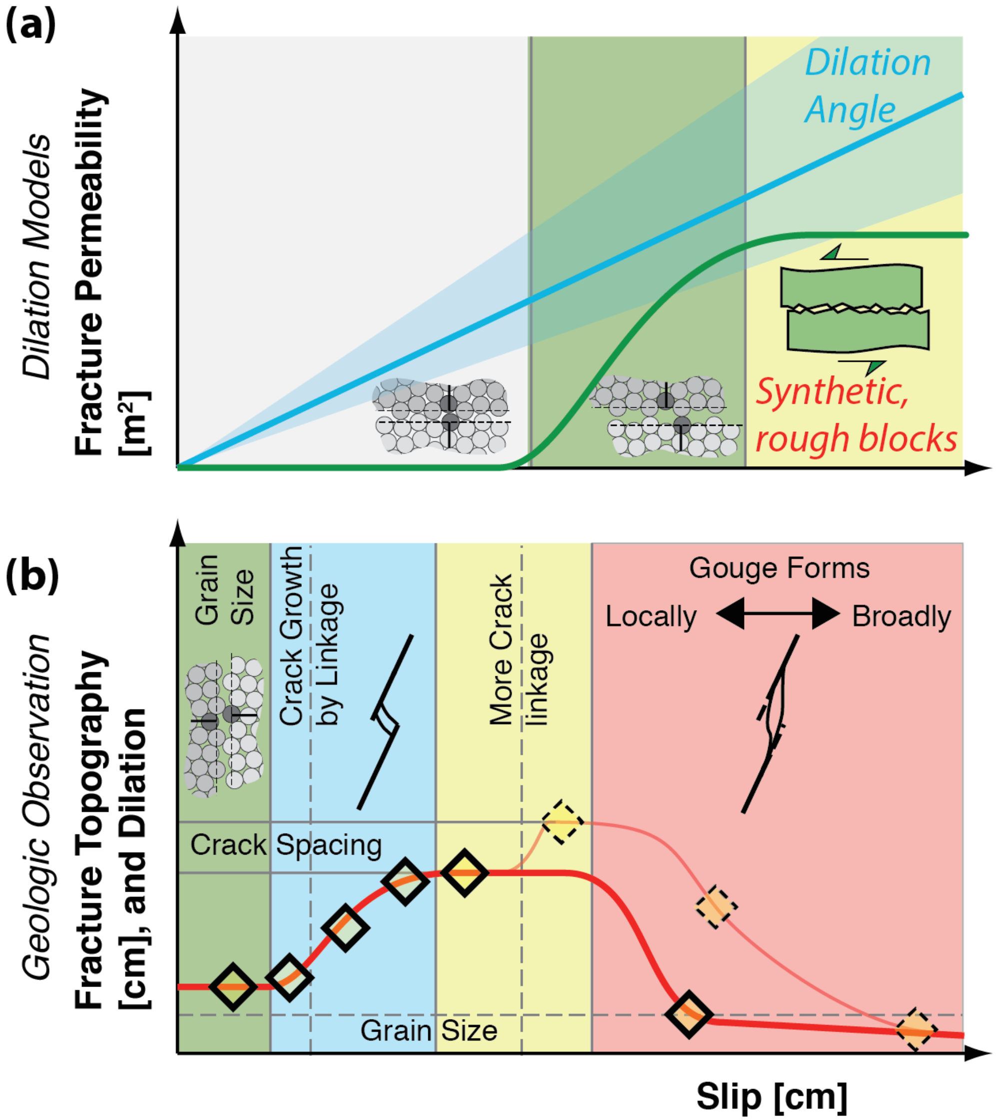
Slip Dependence of Dilation



Slip-Dilation Model and Implications

Implications:

- Provides basis for assessing individual slip and cumulative slip dilation
- Documents fracture life cycle under *in situ* conditions including: slip, healing, reactivation, growth
- Identifies and tests critical controls on initial and evolved roughness that controls dilation
- Can be related to earthquake moment: $M_0 = GAu_{avg}$
- Integrated with the larger **Core and MEQ Project**, this places induced seismicity into a well constrained context that related:
  - Geologic Characteristics
  - Rock Mechanical Properties
  - Relationship to permeability change



Accomplishments, Results and Progress

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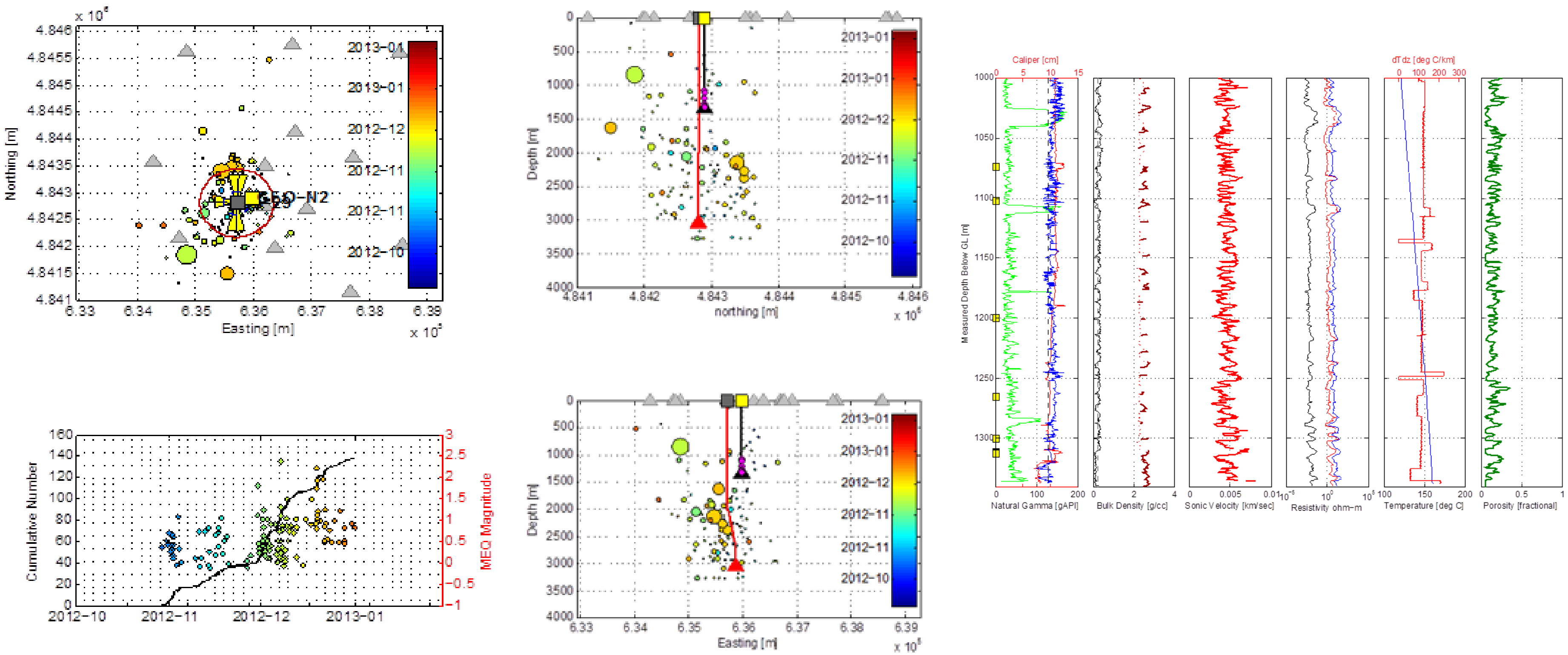

Figure (upper): S-N and W-E cross sections of seismicity from first stimulation attempt at Newberry (new records from recent 2014 stimulation will be addressed next). Core locations in Geo-N2 (yellow square) are shown as magenta diamonds. The cross sections indicate that micro-earthquake activity occurred in the vicinity of Geo –N2 (both in terms of map position and depth relative to the core samples).

Accomplishments, Expected Outcomes and Progress

- Geomechanics tests and petrophysical studies have been used to characterize various lithological units that might be encountered during stimulation
- Results show reservoir heterogeneity with distributed brittle, ductile zones
- Overall, rock mechanics/geological data help understand the distribution of observed MEQ .
- The study will be used to catalog a set of geological and geomechanical conditions that are responsible for generation of MEQ, and to help identify fracturing type, permeability structure

Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Geologic & Geomechanical studies for understanding reservoir response to injection: Rock elastic and poroelastic properties, strength, density, petrological and petrophysical characterization	Determine rock mechanical properties, failure envelop for all rock types; Established correlation with petrophysics	10/2012
Study dilatancy of natural fractures during shearing; and the mechanisms accommodating deformation. Develop a preliminary stress model and stimulation design using core from Newberry	Quantify 3D pore geometry using high resolution CT-scanning, quantify fault rock texture and composition at the micron scale using SEM (need to analyze additional fracture samples).	10/12
Investigate MEQ/porosity/permeability in injection experiments	Lab protocol, procedure development, tests performed on sandstones, granite	10/12
Integrated field, literature, and lab, and numerical studies to catalog a set of geological and geomechanical conditions that are responsible for generation of MEQ, and to help identify role of poro-mechanical processes	Ongoing	

Future Directions

- key activities for the rest of the project completion (2015)
  - Continue to study dilatancy of natural fractures during shearing. Understand fracturing style, potential for shear/dilation permeability increase with respect to lithology. Correlation of fracture roughness, stage, and the spatial distribution of pore characteristics including size, density, and shape which could be related to the equivalent permeability of a fracture.
  - Conduct hydraulic fracture/ injection experiments in the lab under stress to study the nature of fracturing in response to different injection rates and stress levels and temperatures.
  - Triaxial testing with AE (location and source) using larger samples are planned to characterize source type .
  - Characterize fractures that result from fluid injection; correlate with the recorded acoustic emissions.
  - Use digitized geophysical property logs to (a) assess measurements of in situ porosity, (b) rock strength, (c) refine a local stress model to aid in correlation of observed induced seismicity
  - Integration of these results with mechanical properties from triaxial testing
  - Integrated literature, lab (and numerical), with field results from the stimulation phased of EGS well NWG 55-29 By AltaRock Energy.

Summary Slide

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- Established geomechanical characteristics of various lithologies from core and geological study;
  - Porosity distribution; Mineralogy; Quantify 3D pore geometry using high resolution CT-scanning, quantify fault rock texture and composition at the micron scale using SEM
  - Deformation and strength properties, Vp, Vs
  - Poroelastic properties
  - Preliminary stress model developed using the results of this work
  - Natural fracture properties
  - AE vs permeability change
  - Slip/dilation relations
  - More but we have no space to show

- Current correlation of the catalog of geological and geomechanical properties prove useful for describing the distribution of MEQ from injection experiment and identifying permeability structure

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Actual /Est. End Date
4/1/2010	5/31/2013	6/15/2010	12/31/2013 08/31/2015

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$1,061,245	$546,197	$1,350,000	$1,100,000	$1,262,500	$450,000

- The project is behind schedule to say the least. We started late (funds not allocated); PI and research team moved to OU but significant delays in the project have resulted from difficulties in transferring the primary project contract between the DOE and Texas A&M to the University of Oklahoma, and related subcontracts to Temple University. This has prevented availability of funds necessary to continue the research, resulting in a gap in research activities.
- Although slowed down, experimental work has been ongoing. Geological analysis also has been on-going.

Supplemental

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1. Wang, J., Jung, W., Li, Y., Ghassemi, A. 2015. Geomechanical Characterization of Newberry Tuff. Geothermics, EGS Special issue (under review).
2. Wells, O.L., and Davatzes, N.C. 2015. The History of Dilation Across Natural Fractures Due to Evolving Surface Roughness. Proc. 40th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford.
3. Li, Y., Wang, J. Jung, W., Ghassemi, A. 2012. Mechanical Properties of Intact Rock and Fractures in Welded Tuff from Newberry Volcano. Proc. 37th Stanford Geothermal Workshop, January 30 - February 1, 2012.
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5. Cladouhos, T., S. Petty, G. Foulger, B. Julian, and Fehler, M. 2010. Injection Induced Seismicity and Geothermal Energy, GRC Transactions, 32, 1213-1220.
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7. Davatzes, N.C., Hickman, S., Fetterman, J.A., Cladouhos, T. 2012. Newberry EGS Demonstration, USA: Overview and Structural Analysis. International Geothermal Congress, Freiburg, Germany.