Basic Energy Sciences

Roundtable Discussion on
Foundational Research Relevant to SubTER

Don DePaolo
Associate Laboratory Director for Energy Science
Lawrence Berkeley National Laboratory
BESAC July 8, 2015

Presentation Overview

- **What is SubTER?**
  - National Lab working group
  - Four “Pillars” of the initiative
- **BES Roundtable discussion – May 22, 2015**
  - Roundtable results and report overview
- **Grand challenge – imaging stress distributions**
  - What is the problem, and what are the opportunities?
- **Priority Research directions and cross cutting themes**
  - Advancing experimental, theoretical, and computational capabilities suggest new advances are possible
- **Relationship to 2007 Basic Research Needs Report**

National Laboratory "Big Idea" Summit: March, 2014

- **DOE asked the National Lab Chief Research Officers to develop a set of "Big Ideas" to be considered for FY16 investment**
- **Laboratories developed multi-lab teams for 8 ideas:**
  - Advanced Manufacturing
  - Nuclear Energy
  - Climate
  - Energy/Water
  - ***Subsurface*** → **SubTER***
  - Grid
  - Energy Systems Integration
  - Transportation
- **Summit meeting: March 12-13, 2014**

Department of Energy
National Laboratory Ideas Summit
March 12-13, 2014
Crystal City Gateway Marriot

March 12, 2014

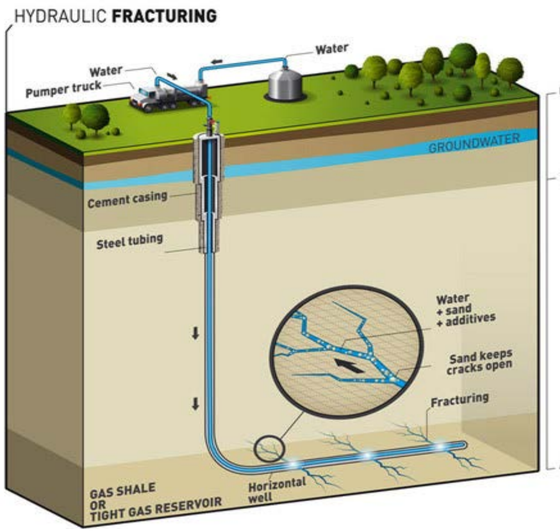
Time	Topics	Speakers & Location
7:45 am	**Registration**	
8:30 am	**Opening remarks**	Mike Knotek Deputy Under Secretary for Science & Energy *Plenary room*
10:30 am	**Break**	
10:45 am	**Sustainable and secure water management:** A sustainable and secure energy/water nexus through superior decision tools and technologies	Speakers TBD *Plenary room*
11:25 am	**Climate change science and adaptation:** Ensuring regional energy and water resilience to climate change	Speakers TBD *Plenary room*
12:05 pm	**Deli lunch (Provided)**	*Plenary room*
1:05 pm	**Accelerating materials to manufacture:** Beyond Edison: Taking Materials from Lab to Market Twice as Fast	Speakers TBD *Plenary room*
1:45 pm	**Systems integration:** The optimization of energy systems across multiple pathways (electricity, thermal, fuel, water, communications) and time and space scales (campus, city, region).	Speakers TBD *Plenary room*
2:25 pm	**Creating an adaptive and intelligent U.S. electric grid:** Evolve the electric grid so that it incorporates clean and distributed energy, adapts to climate and demographics change, eliminates large-scale and long-term blackouts and keeps electricity bills affordable	Speakers TBD *Plenary room*
3:05 pm	**Sustainable transportation:** A consumer-driven carbon neutral ground transportation fleet that is fueled by renewable domestic sources	Speakers TBD *Plenary room*
3:45 pm	**Break**	
4:00 pm	**Subsurface:** Control of subsurface fractures and fluid flow	Speakers TBD *Plenary room*

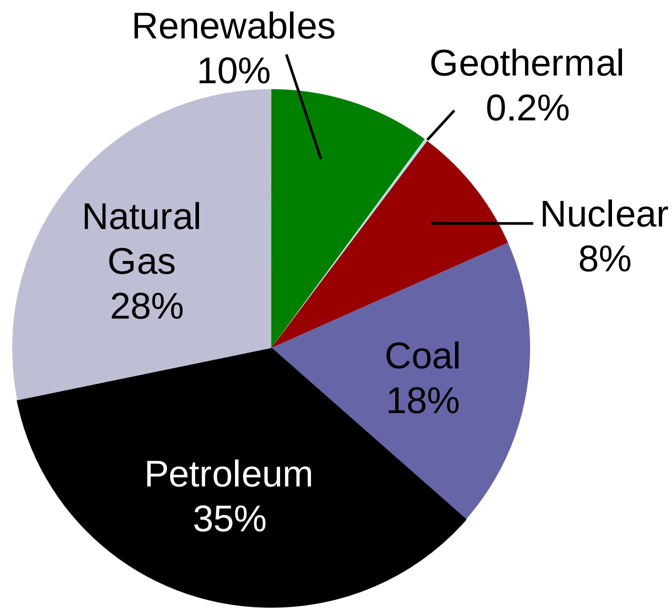
March 13, 2014

SubTER: **Subsurface **T**echnology and **E**ngineering **R**D&D Crosscutting Team*

Subsurface Engineering: Critical for current & future energy systems

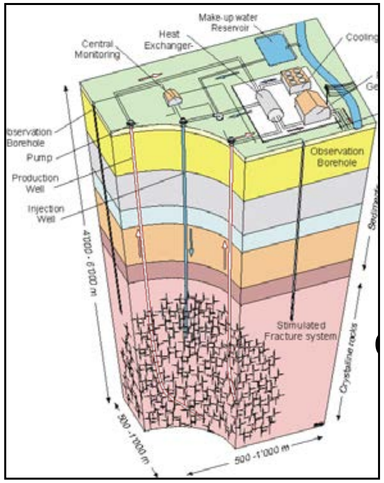
Shale hydrocarbons



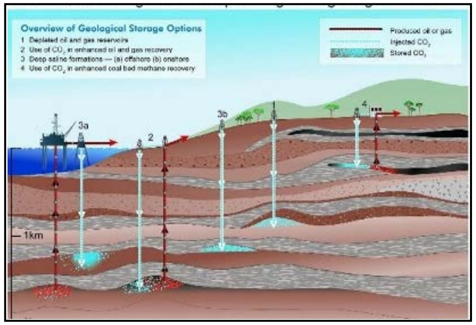


Primary Energy Use by Source, 2014

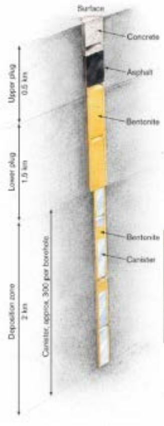
Enhanced geothermal

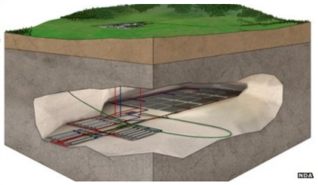


CO_2 Storage

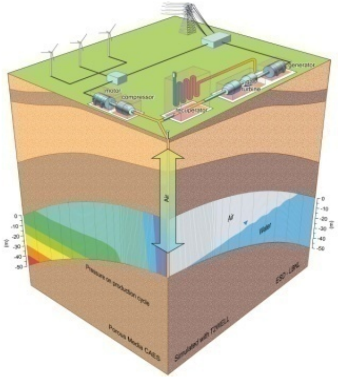


Nuclear waste storage



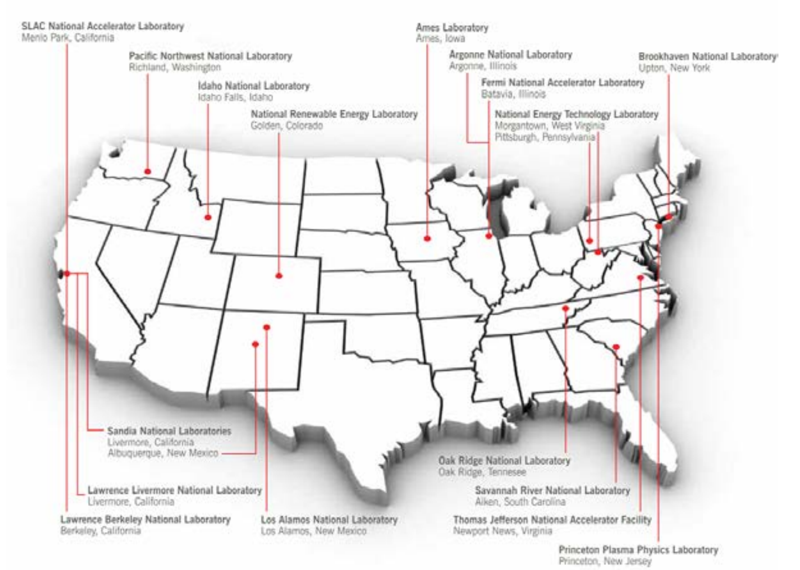


Compressed Air Energy Storage



SubTER Working Team: 13 Laboratories

ANL: Randall Gentry
BNL: Martin Schoonen
INL: Earl Mattson, Hai Huang, Rob Podgorney
LANL: Rajesh Pawar, Melissa Fox, Andy Wolfsberg
LBNL: **Susan Hubbard (co-lead)**, Curt Oldenburg (deputy), Jens Birkholzer, Tom Daley
LLNL: Roger Aines, Jeff Roberts, Rob Mellors, Susan Carroll
NREL: Charles Visser
NETL: Grant Bromhal, Kelly Rose
ORNL: Eric Pierce, Yarom Polsky
PNNL: Alain Bonneville, Dawn Wellman, Tom Brouns
SLAC: Gordon Brown, Mark Hartney
SNL: **Marianne Walck (co-lead),** Doug Blankenship (deputy), Susan Altman, Moo Lee
SRNL: Lisa Oliver, Ralph Nichols



SubTER Theme:
Adaptive Control of Subsurface Fractures and Fluid Flow

Wellbore Integrity

- Improved well construction materials and techniques
- Autonomous completions for well integrity modeling
- New diagnostics for wellbore integrity
- Remediation tools and technologies
- Fit-for-purpose drilling and completion tools (e.g. anticipative drilling, centralizers, monitoring)
- HT/HP well construction/ completion technologies

Subsurface Stress & Induced Seismicity

- Measurement of stress and induced seismicity
- Manipulation of stress and induced seismicity
- Relating stress manipulation and induced seismicity to permeability
- Applied risk analysis of subsurface manipulation

Permeability Manipulation

- Physicochemical fluid-rock interactions
- Manipulating flowpaths
- Characterizing fractures, dynamics, and flows
- Novel stimulation methods

New Subsurface Signals

- New sensing approaches
- Integration of multi-scale, multi-type data
- Adaptive control processes
- Diagnostic signatures and critical thresholds

Energy Field Observatories

Fit For Purpose Simulation Capabilities

BES Roundtable on Foundational Research / SubTER

- **Purpose:** Convene national lab, university and industry experts in the geosciences to brainstorm basic research areas that *underpin the goals of the broader SubTER Technology Team efforts*, and are *currently underrepresented* in the BES research portfolio. The output goal is a document with *prioritized research questions* and descriptive narrative that could inform future BES research directions or a potential follow-on workshop.
- **Participants:** By invitation only, approximately 12-15 external scientists (DOE laboratories, university and industry). Two co-chairs will help select participants and lead the discussion. Several (3-5) Federal Program Managers from BES, EERE and FE will attend as observers. Total meeting size limited to about 20.
- **Logistics:** DOE Germantown, May 22, 2015 (9:00 – 5:00 pm)
- **Target report completion date**: July, 2015

BES Roundtable Participants

National Laboratory

- Don DePaolo (Co-chair), Associate Laboratory Director for Energy Sciences, LBNL
- Ben Gilbert, Staff Scientist, LBNL
- Joe Morris, Group Leader for Computational Geosciences, LLNL
- Steve Pride, Staff Scientist, LBNL
- Kevin Rosso, Laboratory Fellow and Associate Director for the Chemical and Material Science Division , PNNL
- Andrew Stack, Staff Scientist, ORNL
- Marianne Walck, Vice President California Laboratory and Energy Climate Programs, SNL

University

- Nicholas Davatzes, Associate Professor, Temple University
- Peter B. Kelemen, Professor and Chair Dept. of Earth & Environmental Sciences, Columbia
- Kate Maher, Assistant Professor of Geological Sciences, Stanford
- Catherine A. Peters, Professor Dept. of Civil and Environmental Engineering, Princeton
- Laura Pyrak-Nolte (Co-chair), Professor of Physics, Purdue
- Wen-lu Zhu, Associate Professor Department of Geology, University of Maryland

Industry

- Joanne Fredrich, R&D Manager, BP
- James R. Rustad, Scientist, Corning

Outline - Results of the Roundtable Discussion

Grand challenge

- Imaging subsurface stress distributions and geochemical processes

Priority Research Directions

- Nanoporous geomaterials – reactivity, flow and mechanics
- Chemical-mechanical coupling in stressed rocks
- Reactive Multiphase Flow in Fractured Systems

Crosscutting themes and approaches

- Advanced computational methods for heterogeneous time dependent geologic systems
- Architected geomaterials to address heterogeneity and scaling

Grand Challenge: Imaging subsurface stress and geochemistry

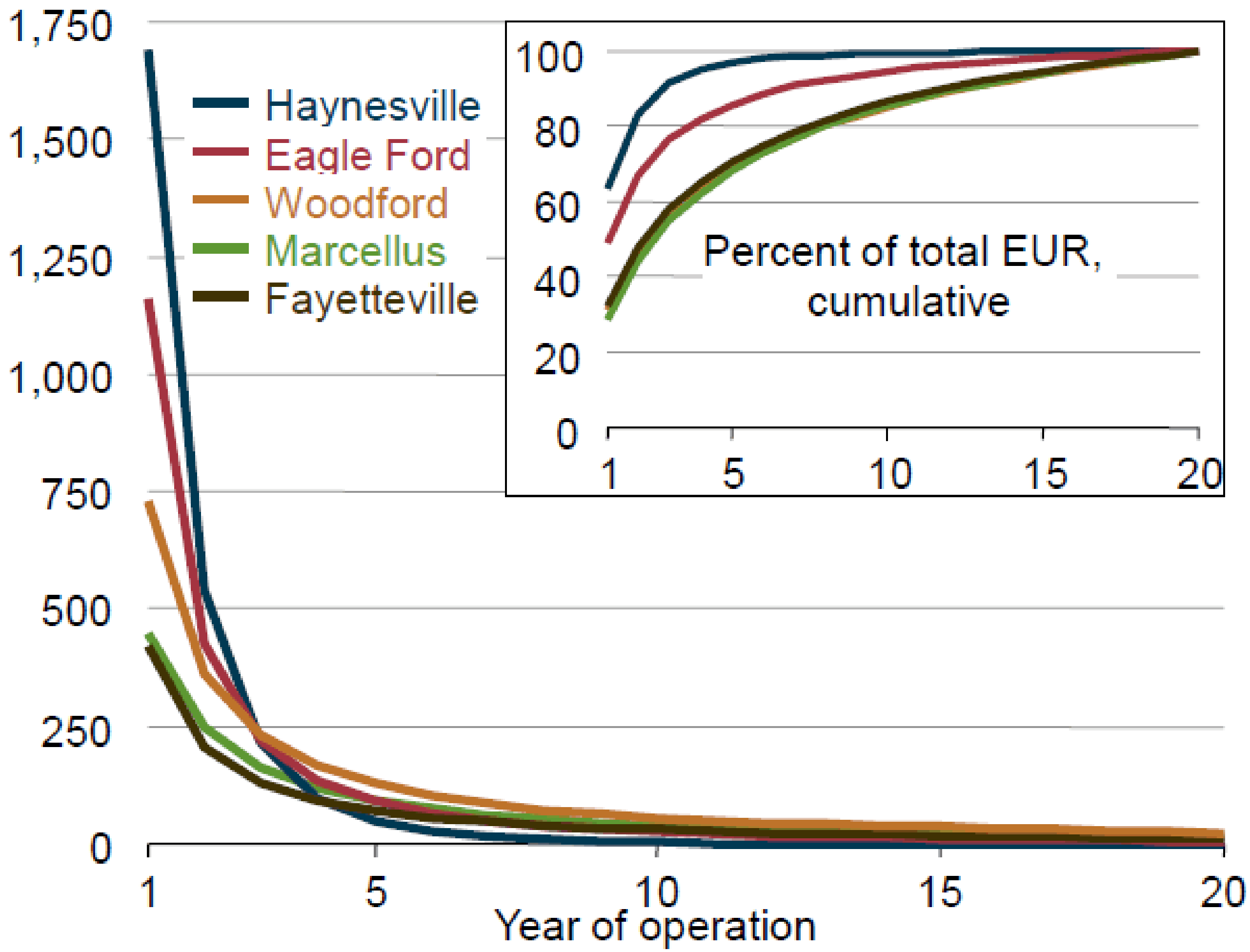
- **Problem:**
  - The responses of rocks to stresses imposed by fluid injection are determined not only by the rock properties, and the existence of faults and fractures, but by the *ambient state of stress*
  - Stress can be inferred from measurements in boreholes, but *cannot be determined in 3D away from boreholes*, and is difficult to monitor *as the system is perturbed*
- **Opportunity**
  - *Multi-modal imaging* of the subsurface combined with geologic structure, surface deformation, borehole data and *advanced computing* could lead to new capabilities to "image" stress in 3D and 4D
  - Improved knowledge of stress distribution could be major factor in *maximizing yield and minimizing negative impacts*

Fractures and fluid flow in the subsurface are a ubiquitous issue

Conceptualization of hydrofracture for oil and gas extraction from "tight" formations (fine-grained, micro- to nanoporous sedimentary rocks).

What do fracture patterns actually look like? Do fractures stay open? How long? What volume of rock is accessed? How do fluids move into the fractures and into the well?

Average production curves for shale gas wells from major formations



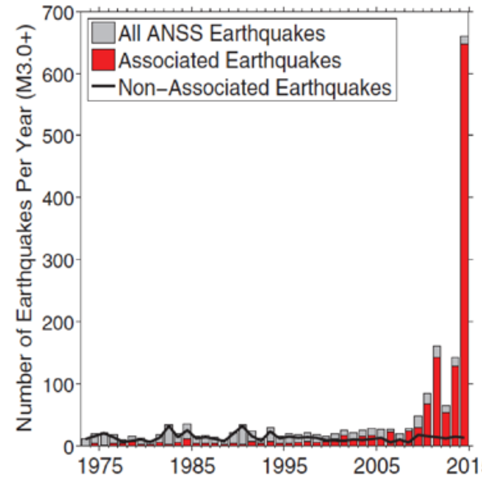
http://naturalgasnow.org/

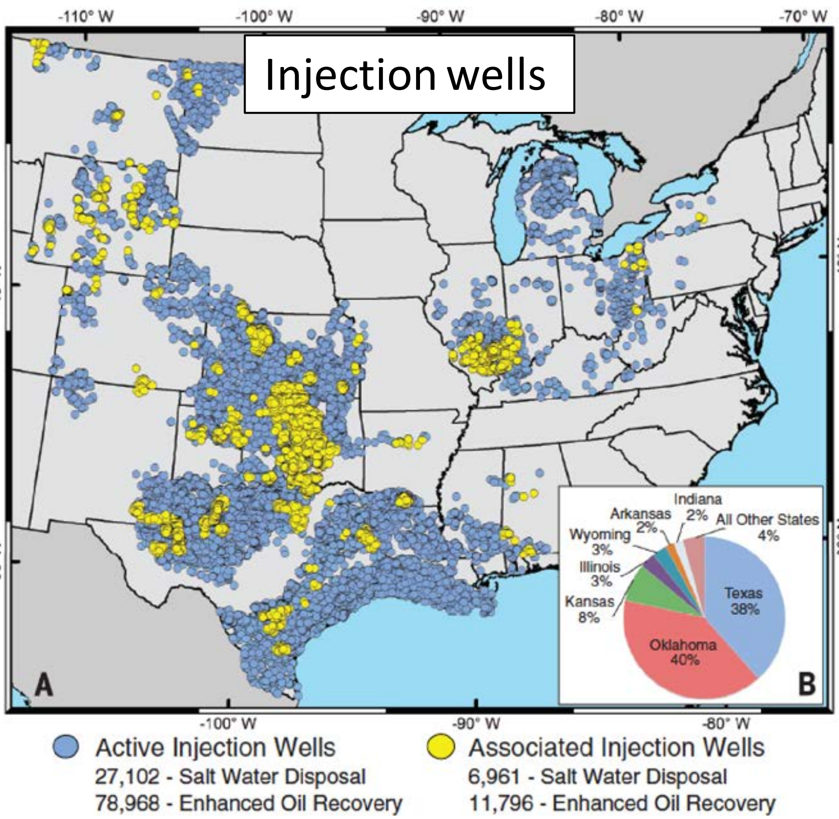
Induced seismicity in central U.S.

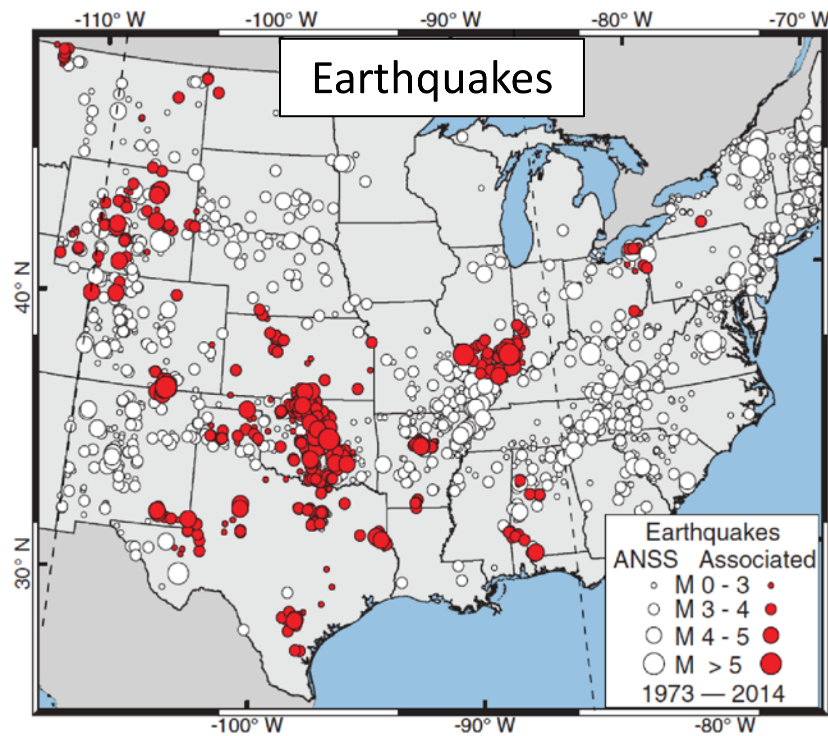
High-rate injection is associated with the increase in U.S. mid-continent seismicity

M. Weingarten,[1*] S. Ge,[1] J. W. Godt,[2] B. A. Bekins,[3] J. L. Rubinstein[3]

Weingarten et al., Science, 2015

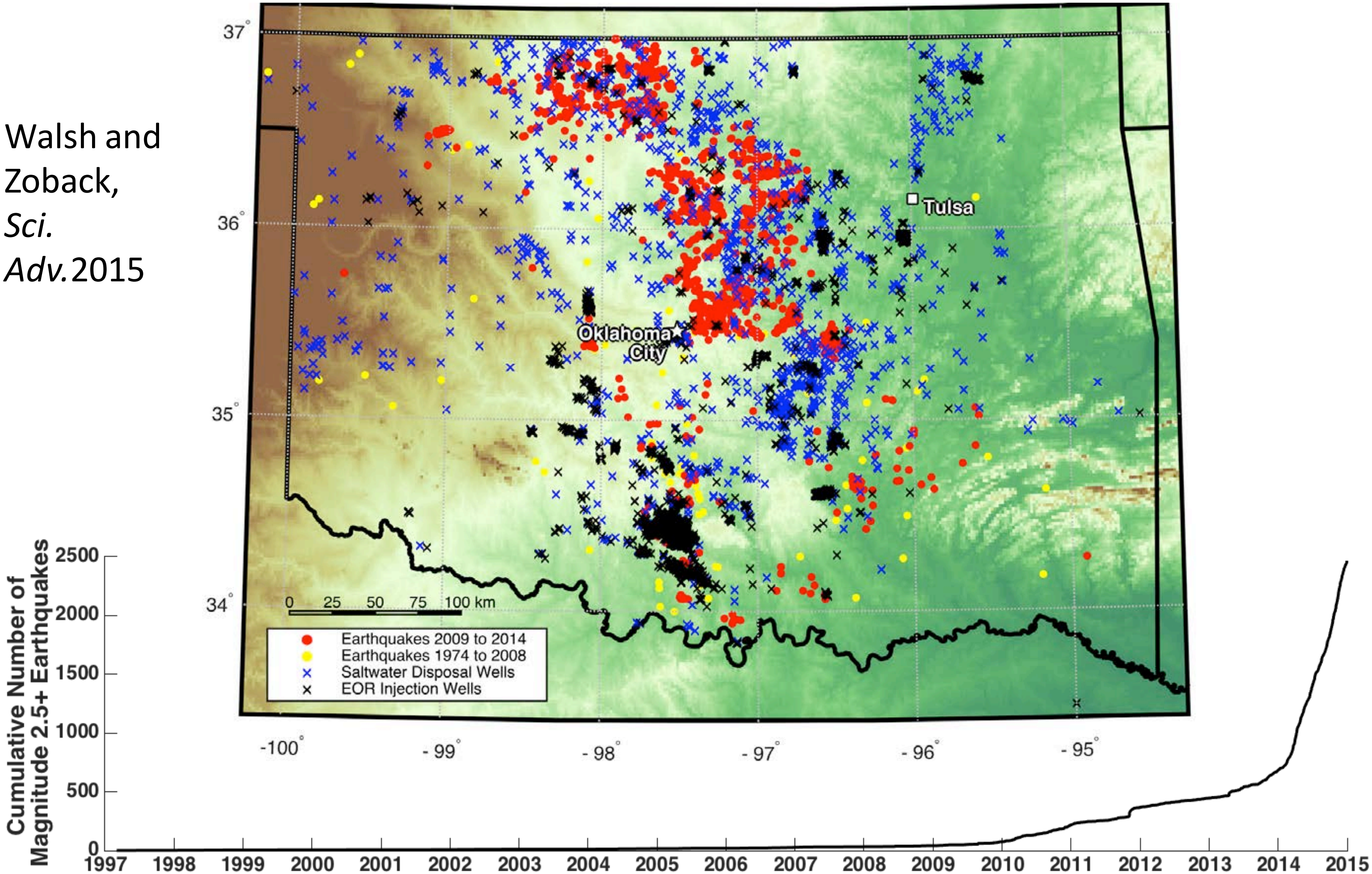






Earthquakes (red) and Disposal wells (blue) in Oklahoma

Walsh and Zoback, *Sci. Adv.* 2015



Induced Seismicity – the general idea…

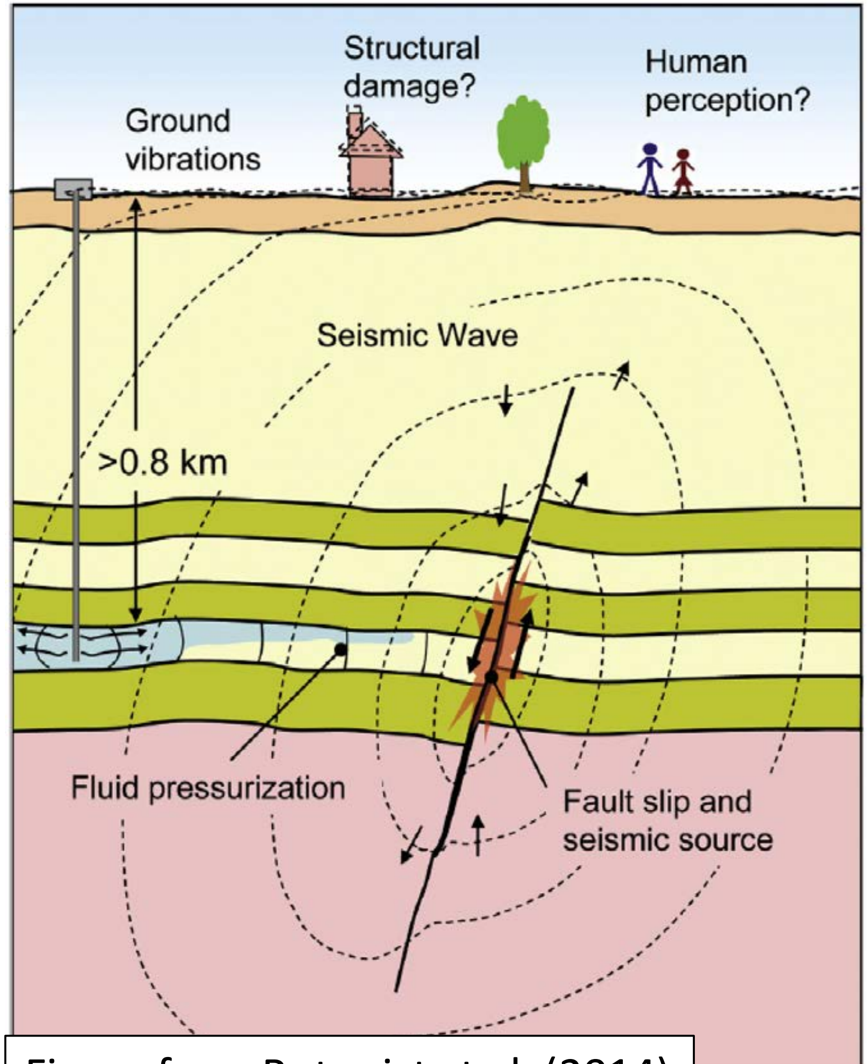
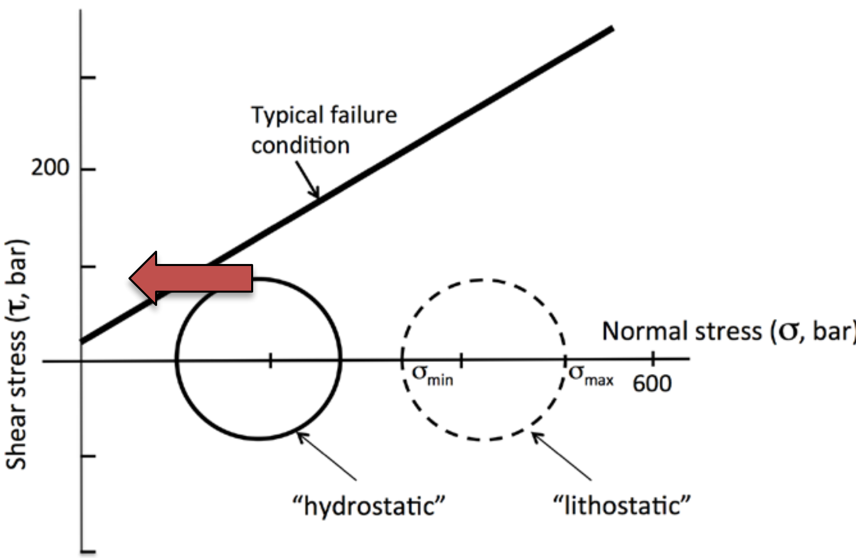


Figure from Rutquist et al. (2014)

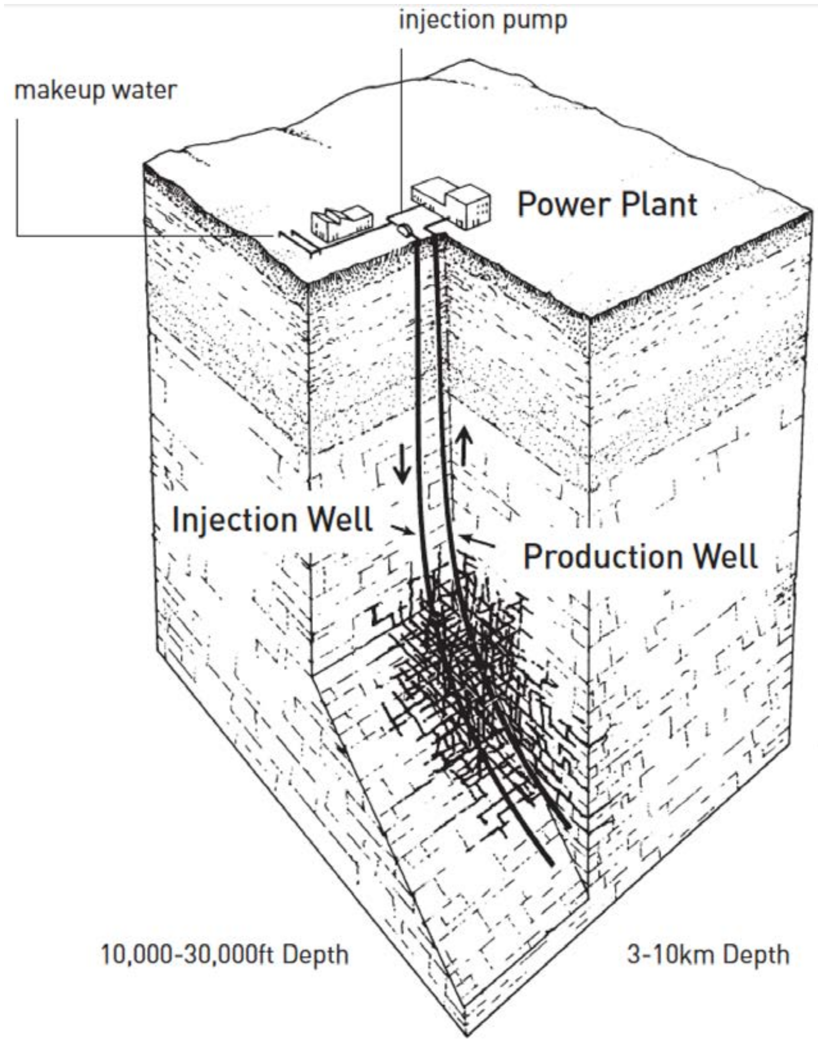
Fluid injection requires “overpressure” to force fluids into porous rocks

Increased fluid pressure from injection affects a much larger volume of the subsurface than that actually contacted by the new fluids.

Increased fluid pressure decreases the “normal” stress on faults, allowing them to slip and produce earthquakes



Enhanced Geothermal Systems require control of fractures and fluid flow

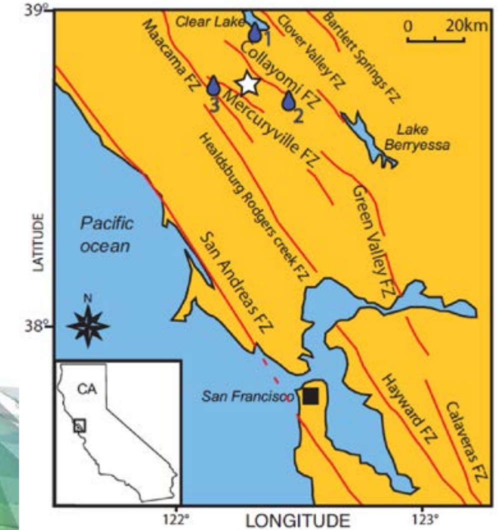


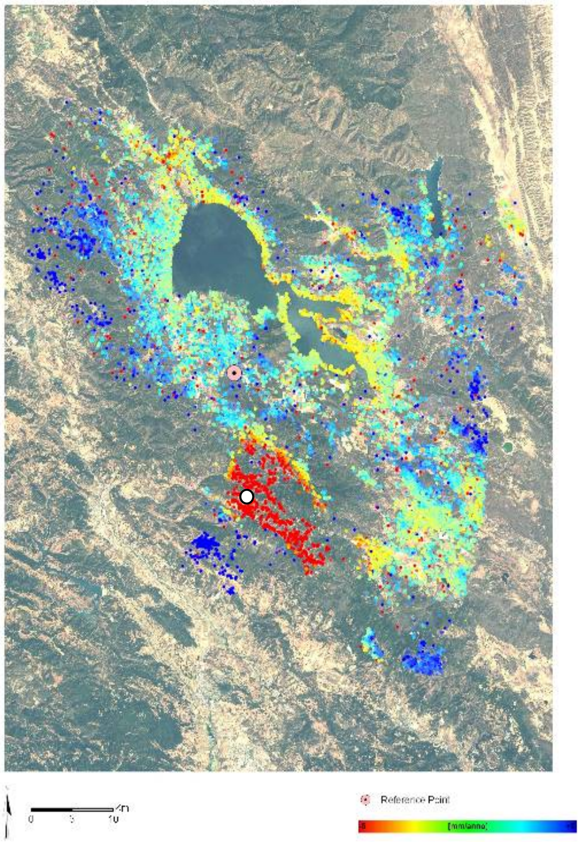
What is EGS

- Artificially create/enhance a fracture network by hydraulic fracturing and/or chemical mechanisms in high temperature, low permeability rock.
- Transfer heat to surface by circulating fluid through the fracture network with injection and production boreholes.

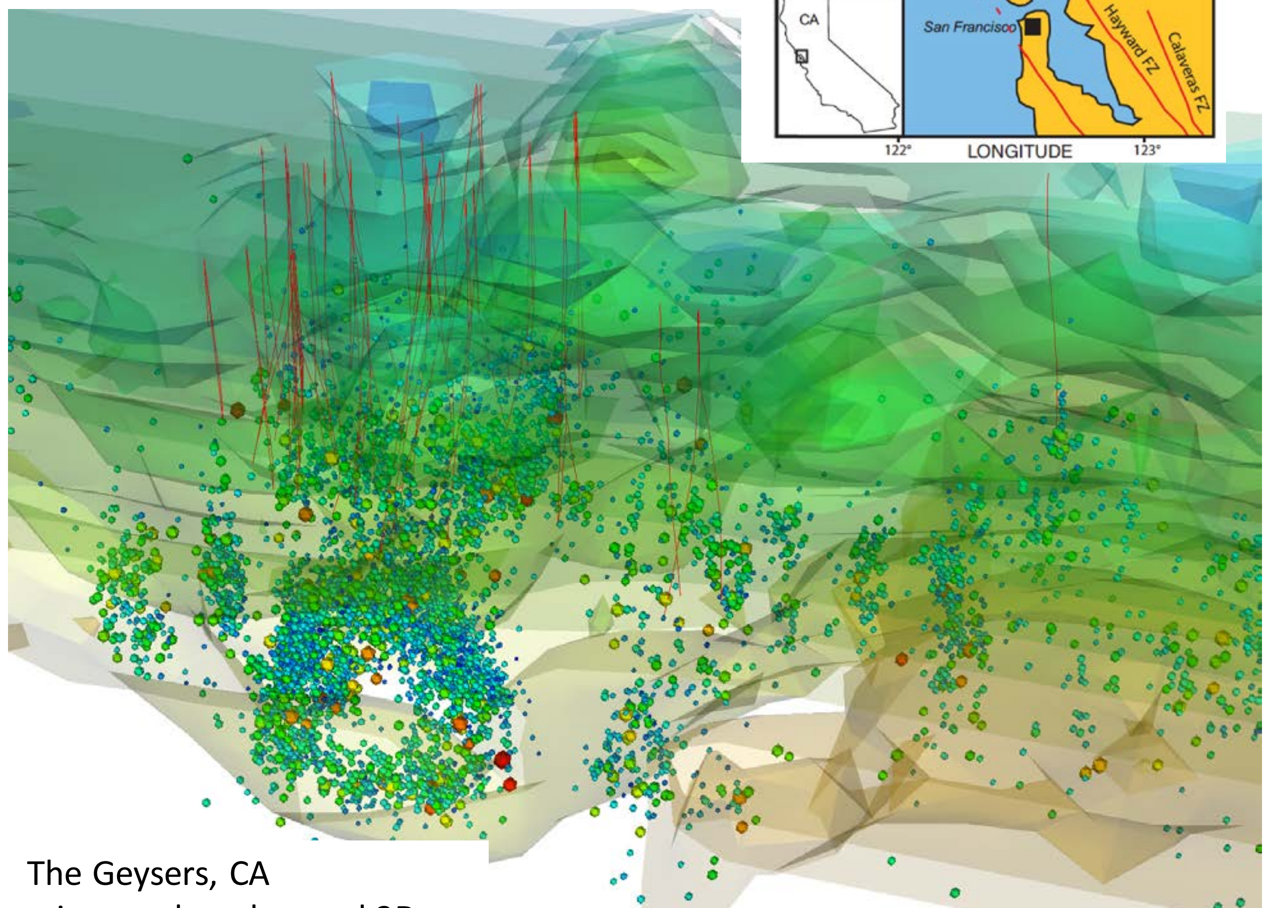
Experimental projects in U.S., U.K., France, Japan, Australia, Sweden, Switzerland, Germany.

The Geysers geothermal field in Northern California is “enhanced’ in that fluid is being added to a natural system





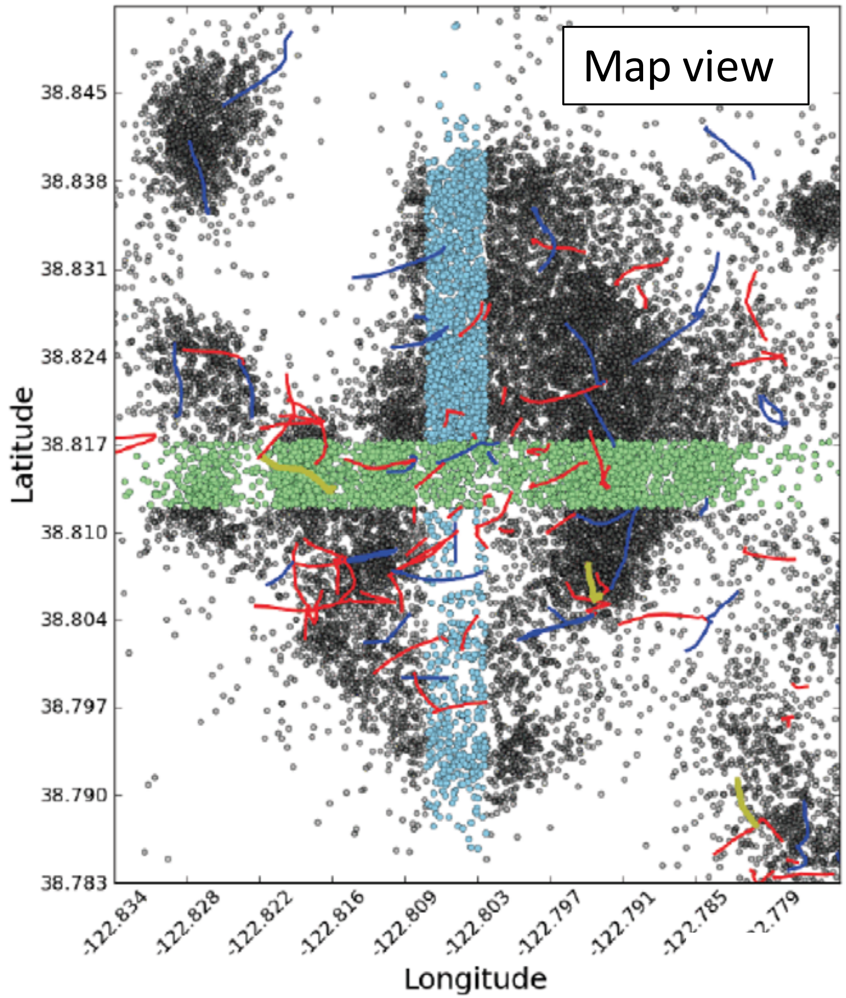
Annual surface deformation
-5 (red) to +5 (blue) mm/yr



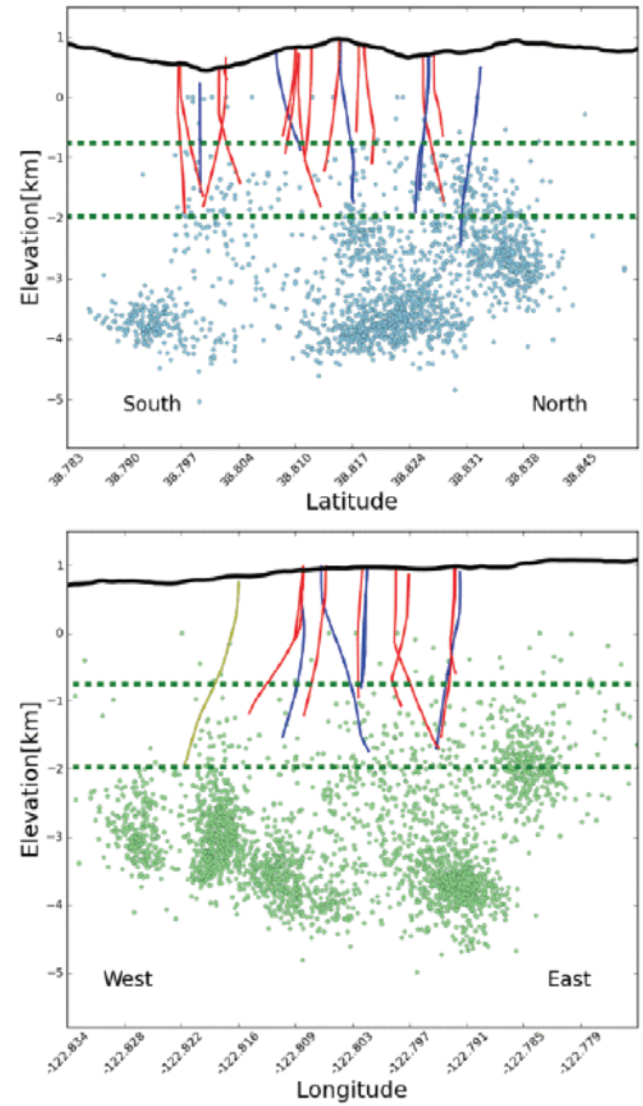
The Geysers, CA
microearthquakes and 3D
Velocity Structure

Geysers earthquakes are not clustered at the points of injection

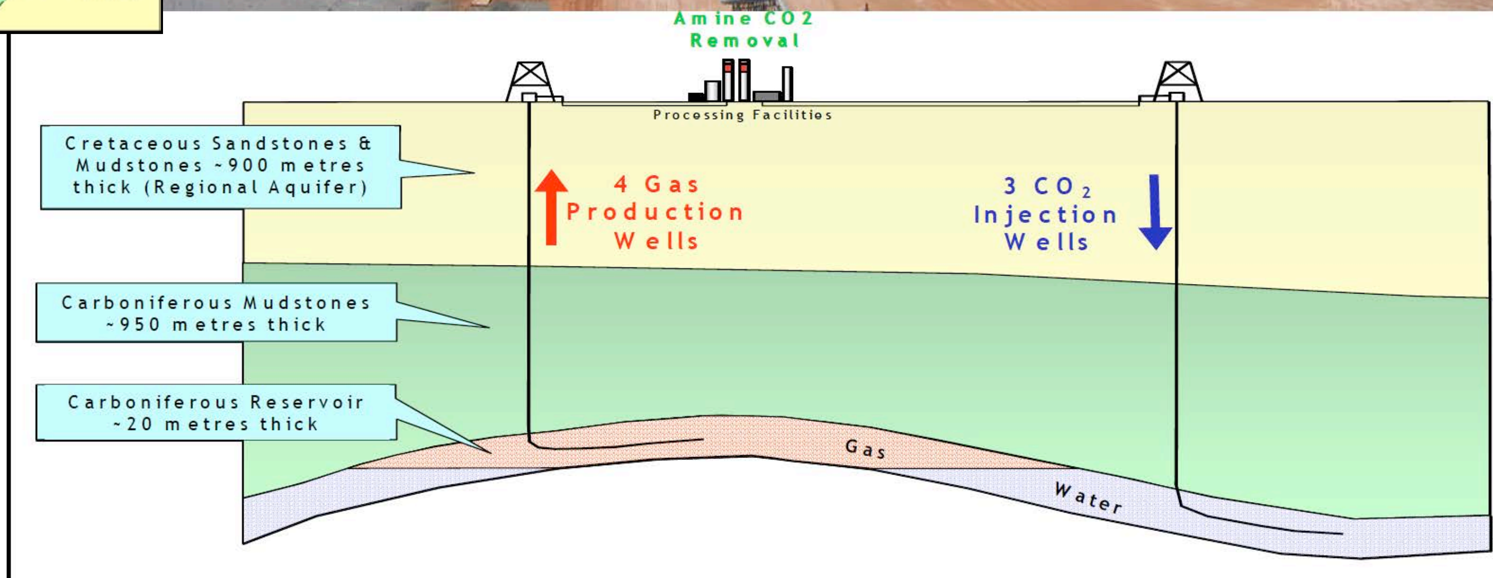
Microearthquake locations



Cross sections

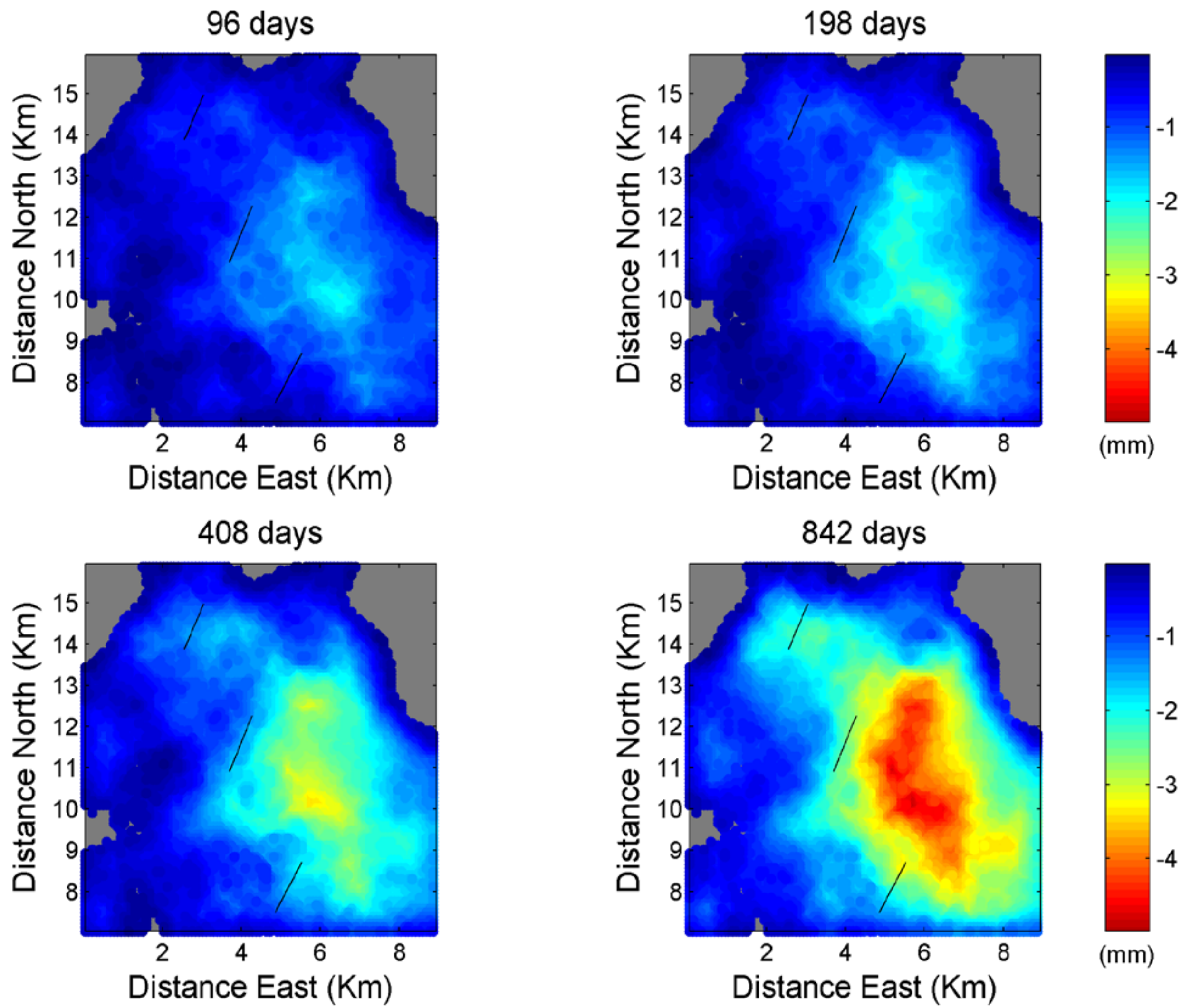


CO_2 storage experiment at Krechba gas field in Algeria: Another way to observe deformation related to subsurface stress distribution – ground surface uplift



CO_2 separated from natural gas re-injected at 1.9 km depth

Ground surface uplift (in mm) following injection of CO_2 at 1.9 km depth at the Krechba gas field, In Salah, Algeria (*Vasco et al.*).



Data obtained using InSAR. Surface-displacement data provides low-resolution but important constraints on how subsurface stress is evolving.

Outline - Results of the Roundtable Discussion

Grand challenge

- Imaging subsurface stress distributions and geochemical processes

Priority Research Directions

- Nanoporous geomaterials – reactivity, flow and mechanics
- Chemical-mechanical coupling in stressed rocks
- Reactive Multiphase Flow in Fractured Systems

Crosscutting themes and approaches

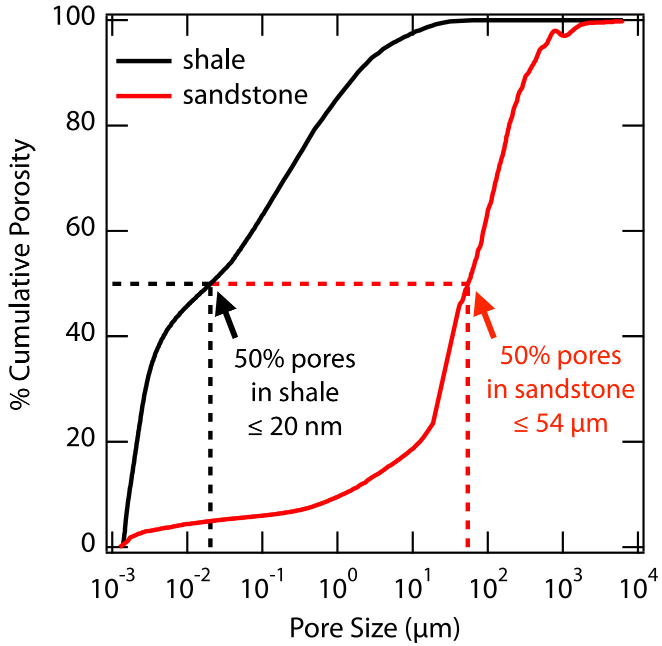
- Advanced computational methods for heterogeneous time dependent geologic systems
- Architected geomaterials to address heterogeneity and scaling

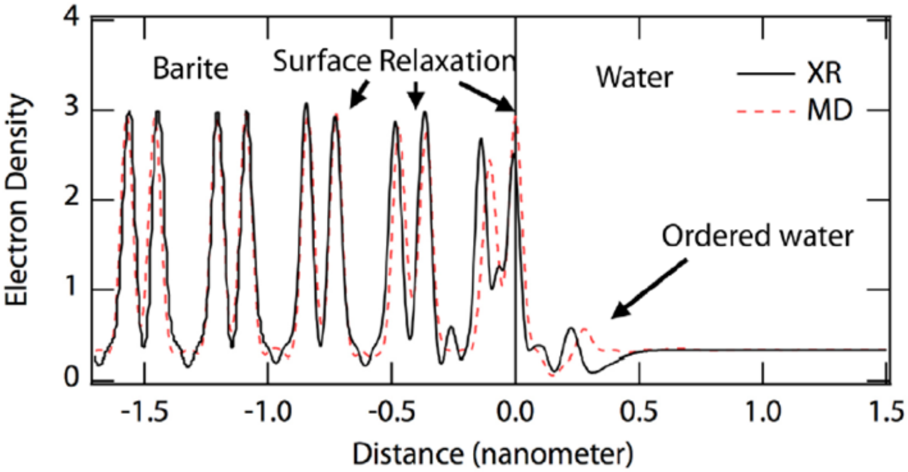
Nanoporous geomaterials – reactivity, flow and mechanics

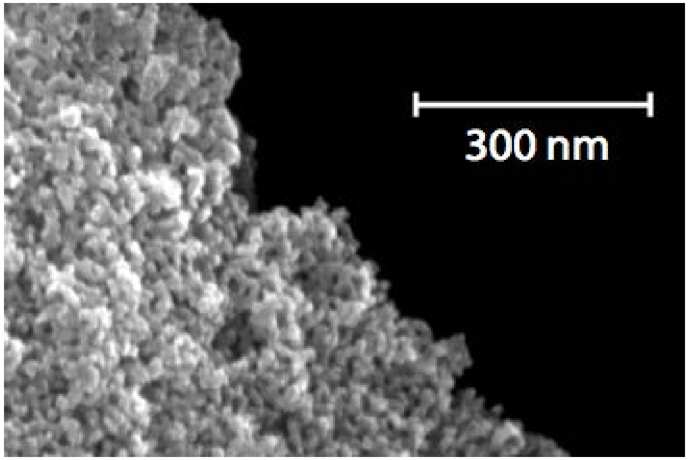
Shale (s.l.) has become a critical energy material……

- **Problem:**
  - Nanoporous geomaterials (e.g. shale) have properties that are critical for many subsurface engineering issues
  - The properties of nanopores, their effects on contained fluids and gases, and the behavior of nanopore networks are poorly known
  - The chemical/mechanical response of nanoporous geomaterials to perturbations is a particular challenge
- **Opportunity**
  - Advanced molecular models for nanoscale phenomena
  - New characterization techniques – Xrays and neutrons – for studying nanoscale features and processes
  - New experimental techniques for studying nanoporous materials

Nanopores can be a large fraction of pore space

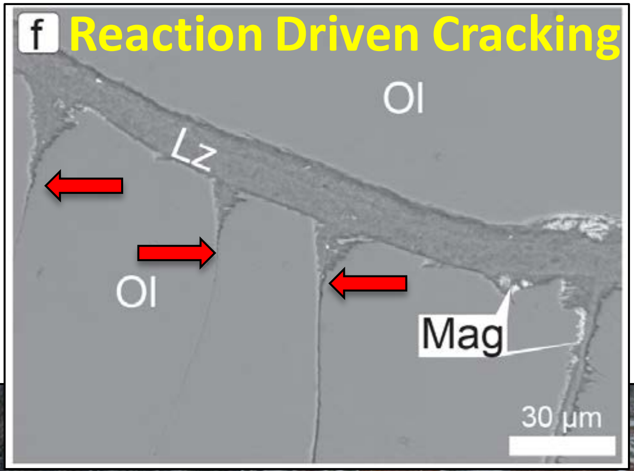






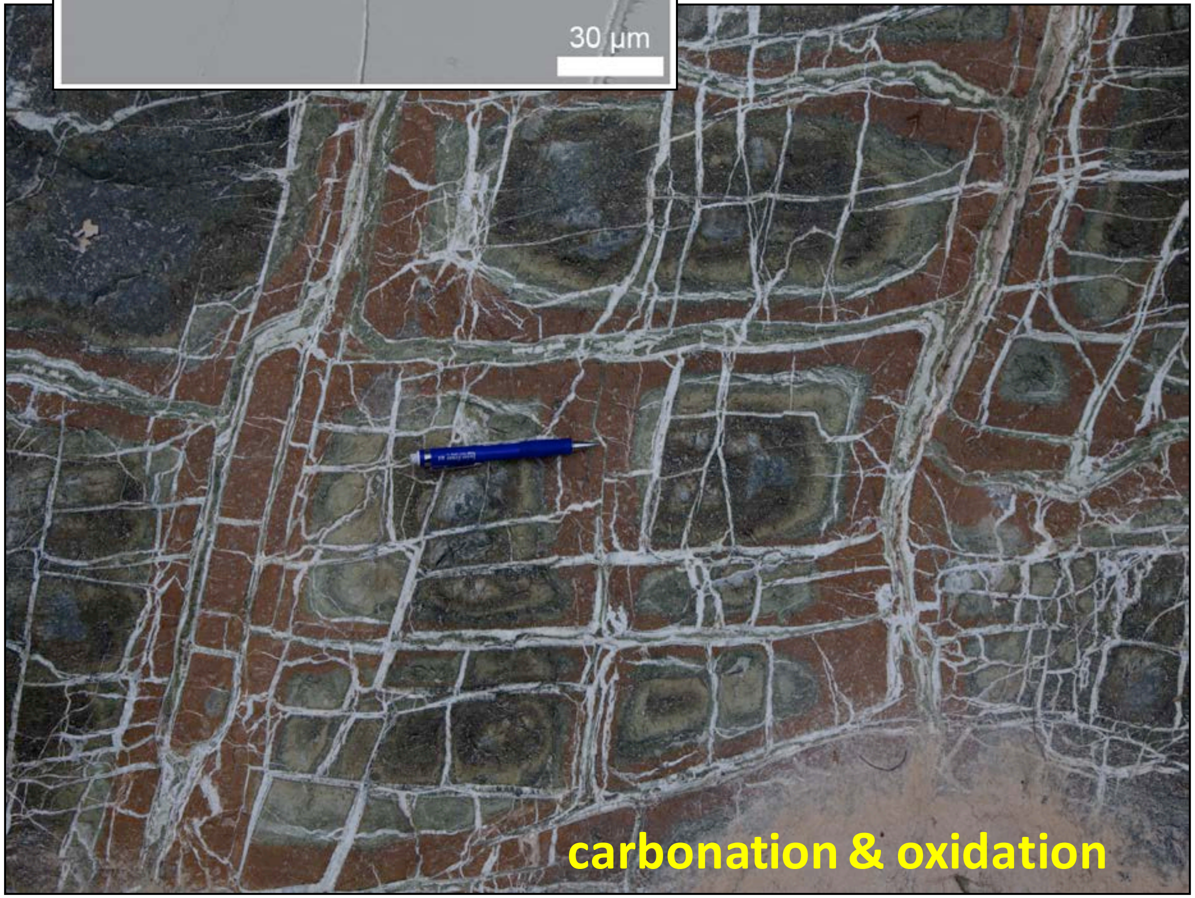
Chemical-mechanical coupling in stressed rocks

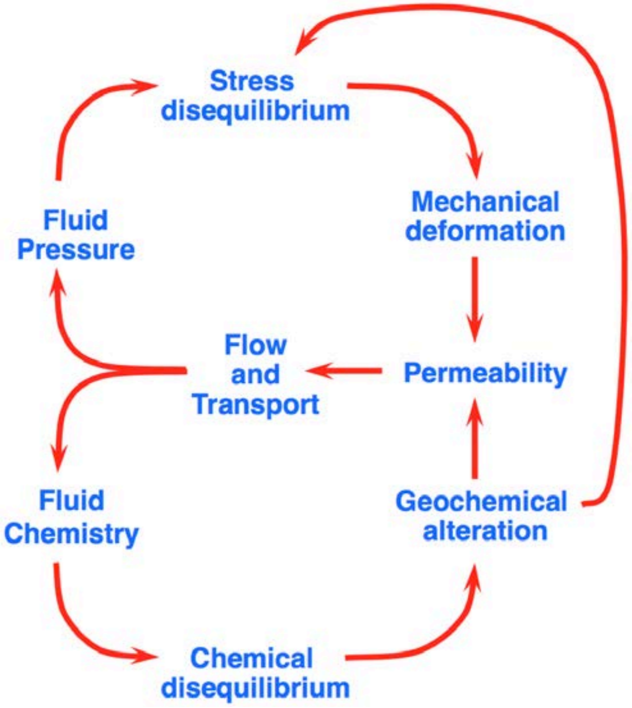
- **Problem:**
  - Response of fluid-saturated rocks to induced stresses can be both physical and chemical.
  - Reactive chemistry and deformation can be mutually reinforcing or attenuating
  - Models are limited by knowledge of constitutive properties of the rocks (multi-mineralic and heterogeneous on many scales), and by mathematical algorithms that capture the feedbacks
- **Opportunity**
  - New capabilities for measuring rates of chemical reactions and 3D imaging of response to applied stresses (Xrays, neutrons)
  - Increased computing power combined with algorithm development
  - New purpose-built experimental systems designed to be compatible with imaging tools for real time monitoring of experiments



Chemical-mechanical coupling models are needed for measuring and monitoring stress distributions.

Stress must be inferred from observed material responses



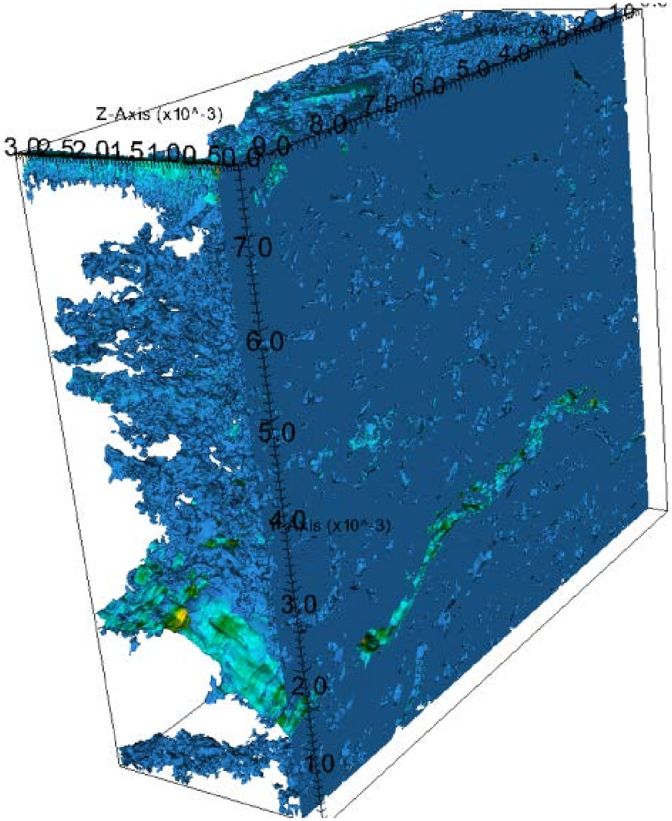


Components of a coupled modeling strategy
Detwiler, 2015

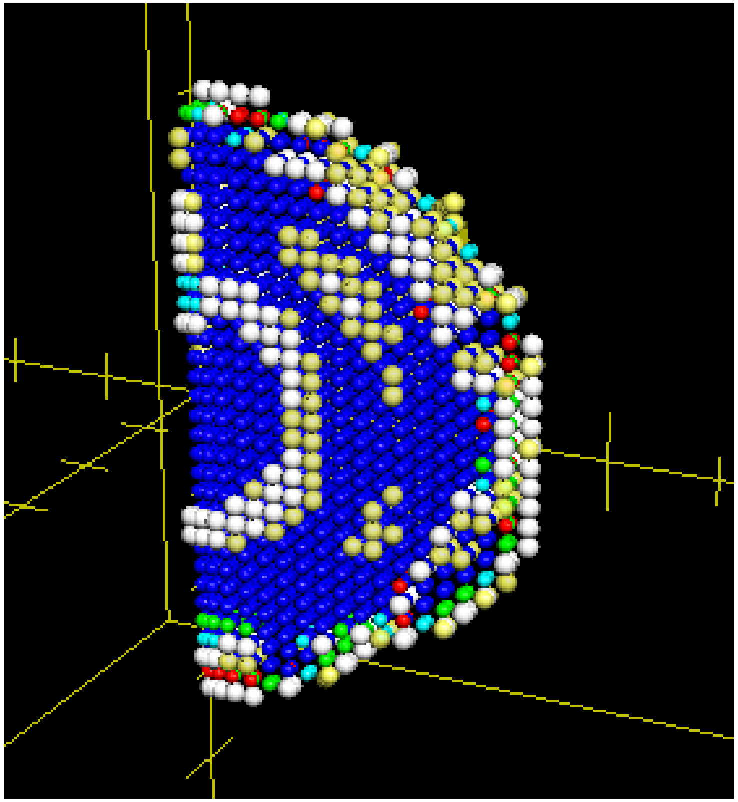
Advanced computational methods

- **Problem:**
  - Forecasting the response to stresses caused by fluid injection requires treatment of thermal, hydrological, mechanical and chemical (THMC) effects concurrently
  - Formulation of the physics and chemistry, feedbacks, knowledge of constitutive relations and allowance for time-dependent properties (e.g. fracture development & growth) can be done only in a rudimentary, approximate way
- **Opportunity**
  - Recent development of advanced numerical algorithms, discretization techniques, and computation power allow for direct simulation
  - Improving database on material properties, chemical-mechanical coupling, mineral-fluid reaction rates

Advanced computational methods



Simulation of flow in a previously imaged sample of fractured Marcellus shale using 60,000 cores of NERSC Hopper and the software package Chombo-Crunch.



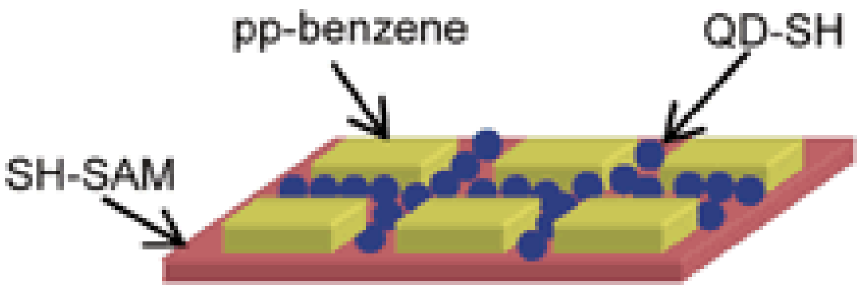
Simulation of permeability in a hydraulic fracture. The permeability variation ranges from over 10^4 times the initial permeability (blue) to 1.1 times the initial value (yellow).

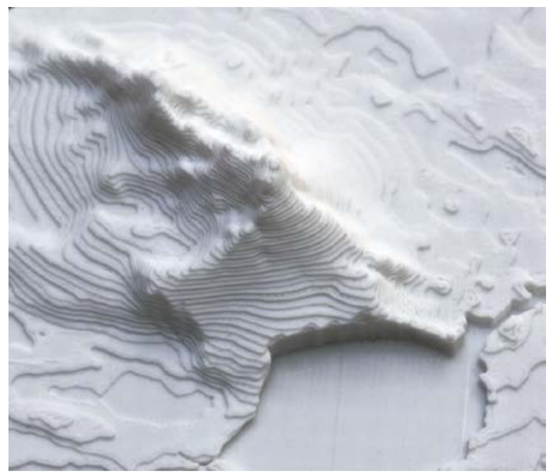
Architected Geomaterials

- Systematically addressing heterogeneity and complexity

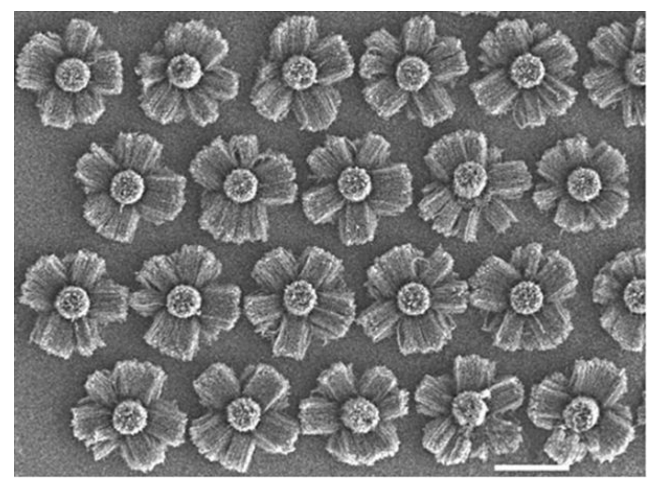
- **Problem:**
  - The step from controlled laboratory experiments to heterogeneous natural materials a giant leap!
  - Interactions between mineral and porosity heterogeneity, mesoscale structures, fractures and chemical reactions are difficult to study systematically
- **Opportunity**
  - New capabilities for making artificial materials that approximate natural features, but have limited complexity, may allow coupled processes to be studied more systematically
  - Advanced imaging methods can be used to characterize experiments, and provide a computational grid for model development and verification

Architected Geomaterials:
- controlled complexity





Advances in 3D printing, patterning functionalized surfaces and micro-electronic fabrication provide a new opportunity to make geo-like materials in the laboratory to explore the effects of chemical and structural heterogeneity in a controlled, repeatable manner.



BES Roundtable – SubTER Matrix

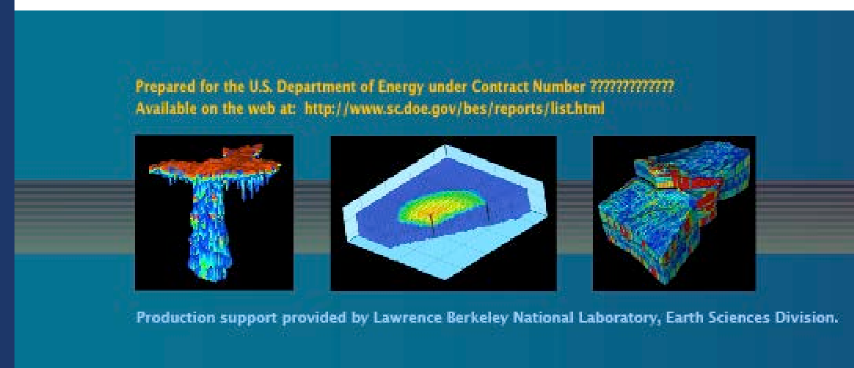
	Wellbore Integrity	**Subsurface Stress & Induced Seismicity**	**Permeability Manipulation**	**New Subsurface Signals**
Advanced computation		X	X	X
Nanoporous geomaterials	X		X	
Reactive multiphase flow	X	X	X	
Chemical-mechanical coupling		X	X	X
Architected geomaterials	X	X	X	X
Imaging Stress and Geochem. features		X	X	X

Relationship to Basic Research Needs Workshop

Workshop:
Feb. 20-24, 2007

Report published:
July 10, 2007

http://www.sc.doe.gov/bes/reports/list.html



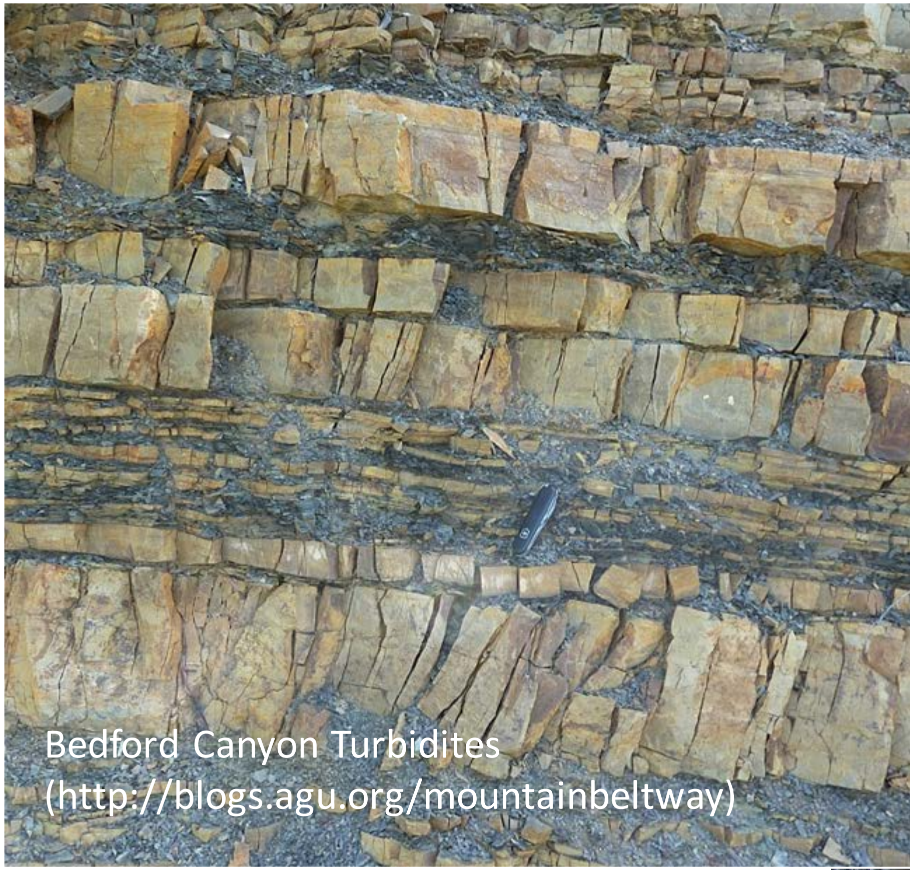
Focus was on carbon sequestration and nuclear waste

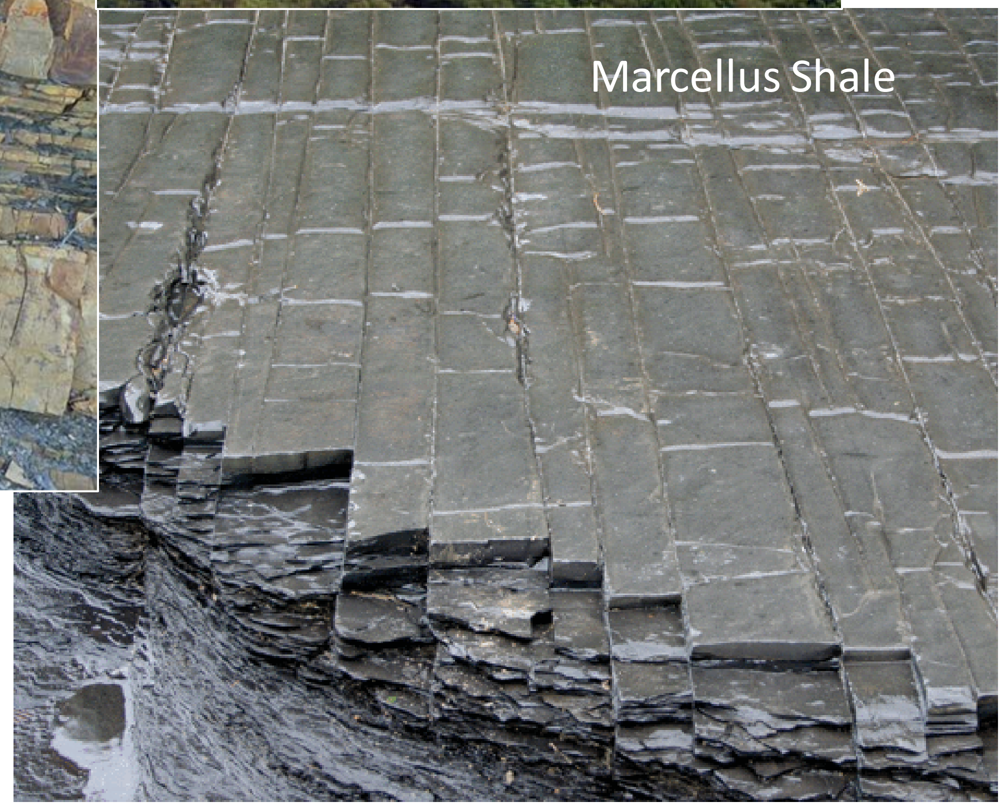
Basic Research Needs for Geoscience, February 20-24, 2007

Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment
Microscopic basis of macroscopic complexity - scaling	Mineral-fluid interface complexity and dynamics	Develop and test methods for assessing storage capacity and for monitoring containment of CO_2 storage	Develop site selection criteria
Highly reactive subsurface materials and environments	Nanoparticulate and colloid chemistry and physics	Develop remediation methods to ensure permanent storage	Develop storage and operating engineering approaches
Thermodynamics of the solute-to-solid continuum	Dynamic imaging of flow and transport	Demonstrate procedures for characterizing storage reservoirs and seals	Storage demonstrations
Computational geochemistry of complex moving fluids within porous solids	Transport properties and *in situ* characterization of fluid trapping, isolation and immobilization	Integrated models for waste performance prediction and confirmation	Apply assessment protocols and technologies for the lifecycle of projects
Integrated analysis, modeling and monitoring of geologic systems	Fluid-induced rock deformation	Radionuclide partitioning in repository environments.	Evaluate release of radionuclide inventory from the repository
Simulation of multi-scale systems for ultra-long times	Biogeochemistry in extreme subsurface environments	Waste form stability and release models.	Assess corrosion/ alteration of engineered materials
		Incorporate new conceptual models into uncertainty assessments.	Long-term safety/risk assessment for emplacement of energy system by-products.

Office of Science

FE, RW, EM, EERE


Bedford Canyon Turbidites
(http://blogs.agu.org/mountainbeltway)


Marcellus Shale

Thank You

Additional reference slides

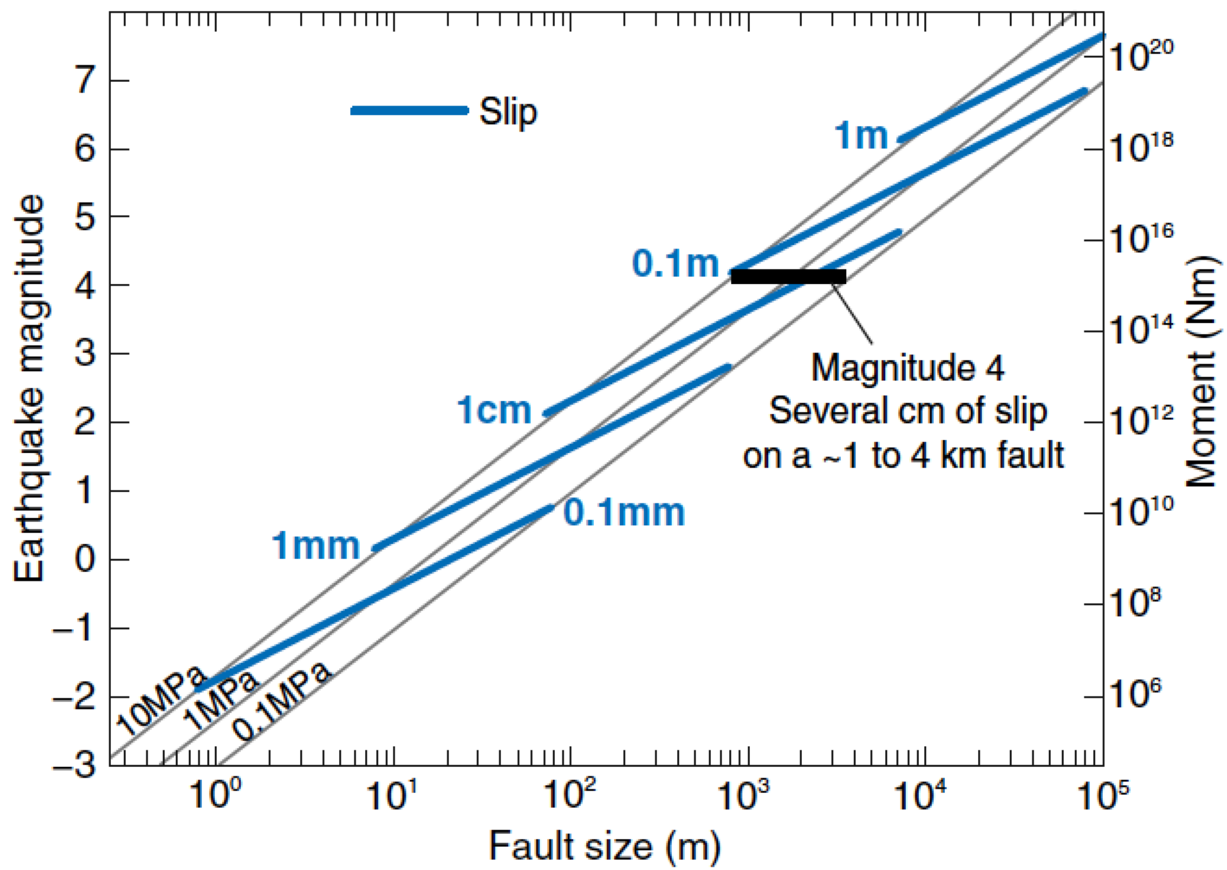
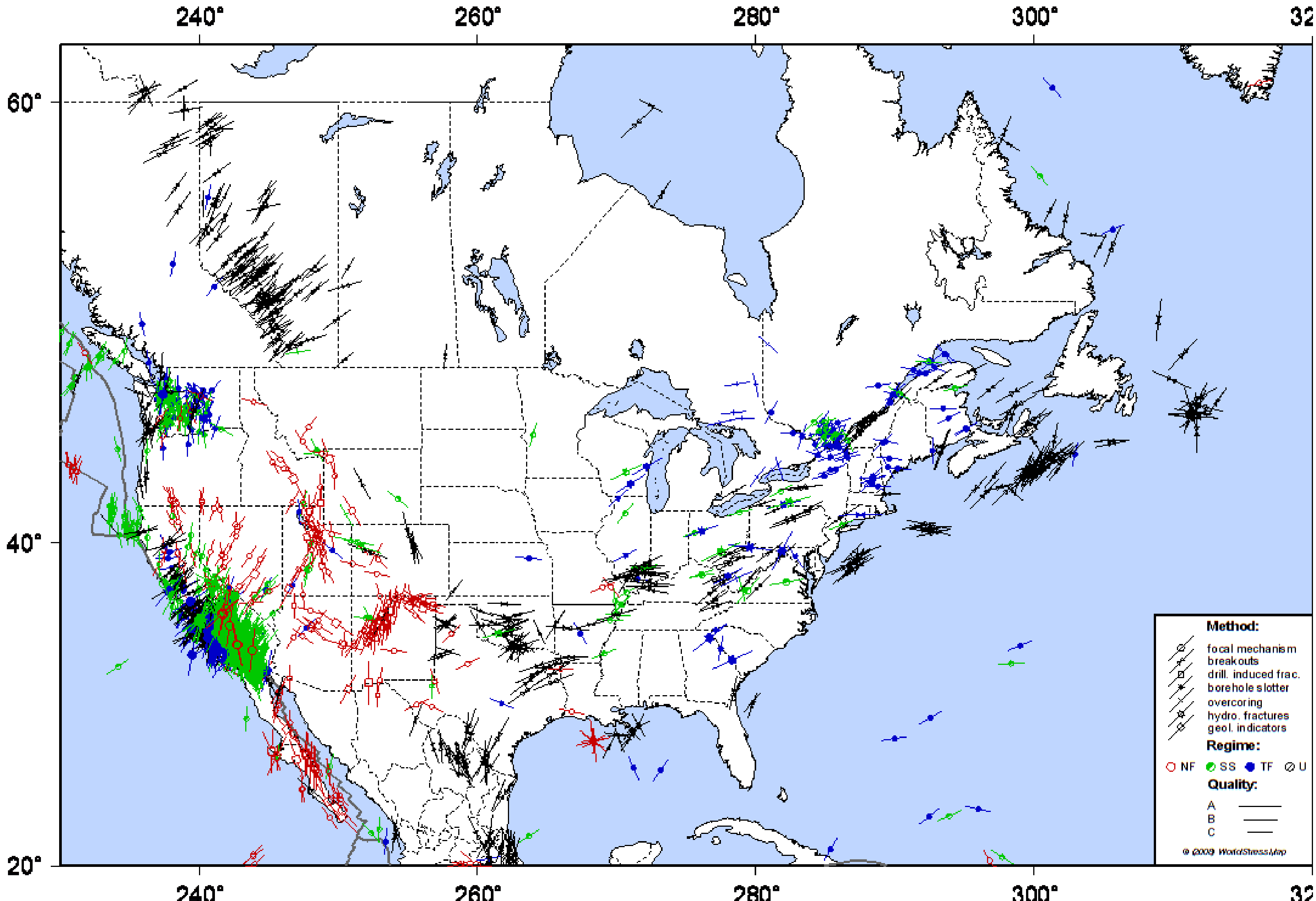


Fig. 2. Relationships among various scaling parameters for earthquakes. The larger the earthquake, the larger the fault and amount of slip, depending on the stress drop in a particular earthquake. Observational data indicate that earthquake stress drops range between 0.1 and 10 MPa.



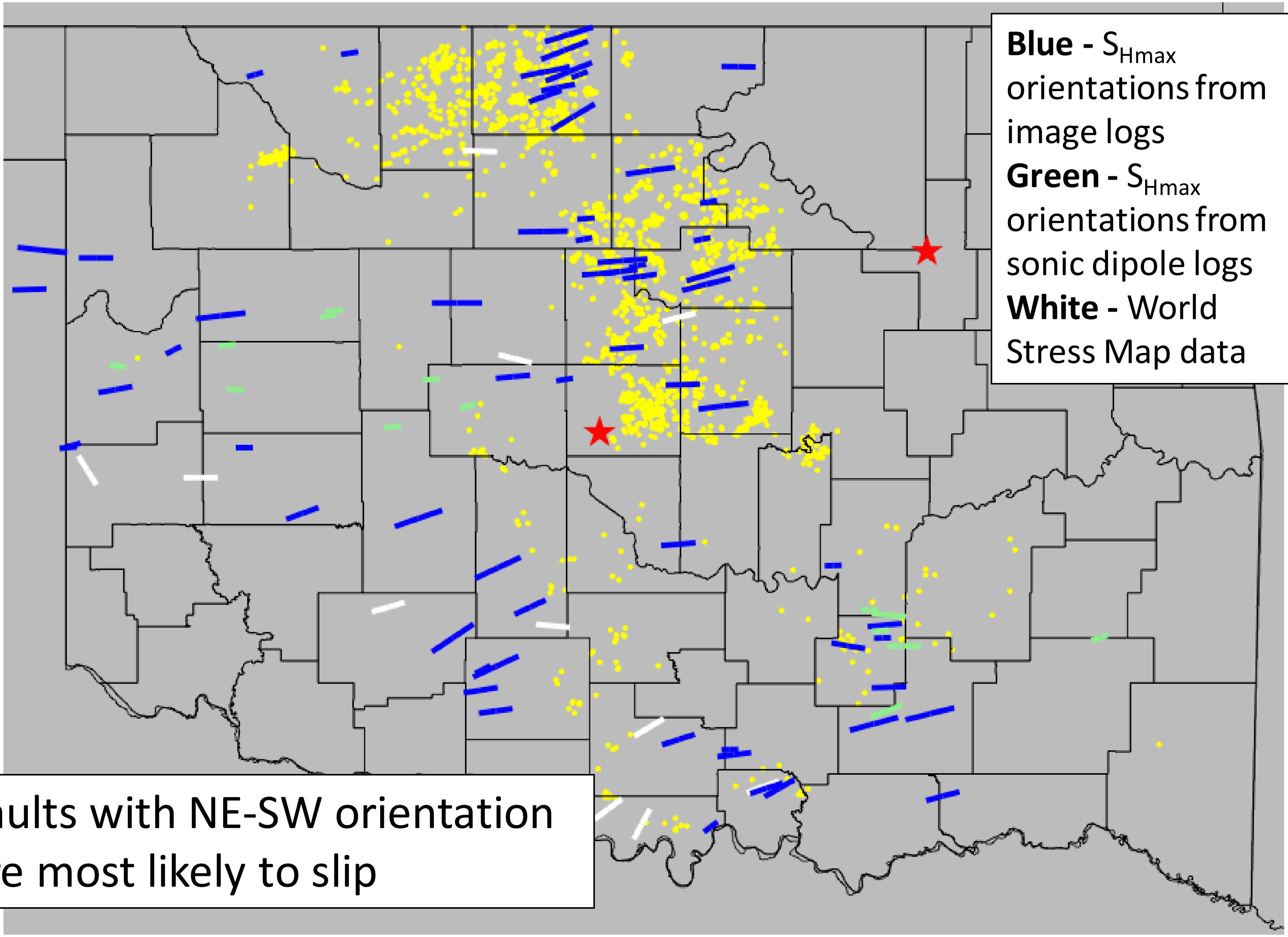
Projection: Mercator

World Stress Map Rel. 2008

Heidelberg Academy of Sciences and Humanities

Geophysical Institute, University of Karlsruhe

From Alt and Zoback, 2014



Faults with NE-SW orientation are most likely to slip