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**
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
- Grid
- Energy Systems Integration
- Transportation

Summit meeting: March 12-13, 2014
Subsurface Engineering: Critical for current & future energy systems

Shale hydrocarbons

CO₂ Storage

Primary Energy Use by Source, 2014
- Natural Gas: 28%
- Petroleum: 35%
- Coal: 18%
- Nuclear: 8%
- Renewables: 10%
- Geothermal: 0.2%

Compressed Air Energy Storage

Nuclear waste 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. anticipiative 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

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**Energy Field Observatories**

**Fit For Purpose Simulation Capabilities**
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
• **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,* S. Ge,* J. W. Godt,² B. A. Belkis,³ J. L. Rubinstein⁴

Weingarten et al., Science, 2015
Earthquakes (red) and Disposal wells (blue) in Oklahoma

Induced Seismicity – the general idea...

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

Figure from Rutquist et al. (2014)
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
Geyser earthquakes are not clustered at the points of injection.
CO₂ storage experiment at Krechba gas field in Algeria: Another way to observe deformation related to subsurface stress distribution – ground surface uplift

CO₂ 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

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- Nanoporous geomaterials – reactivity, flow and mechanics
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Crosscutting themes and approaches

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

Shale (s.l.) has become a critical energy material......
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
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.
<table>
<thead>
<tr>
<th>Wellbore Integrity</th>
<th>Subsurface Stress &amp; Induced Seismicity</th>
<th>Permeability Manipulation</th>
<th>New Subsurface Signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced computation</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Nanoporous geomaterials</td>
<td>X</td>
<td></td>
<td>X</td>
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<tr>
<td>Reactive multiphase flow</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Chemical-mechanical coupling</td>
<td>X</td>
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<td>Architected geomaterials</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Imaging Stress and Geochem. features</td>
<td>X</td>
<td>X</td>
<td>X</td>
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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
<table>
<thead>
<tr>
<th>Discovery Research</th>
<th>Use-inspired Basic Research</th>
<th>Applied Research</th>
<th>Technology Maturation &amp; Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Microscopic basis of macroscopic complexity - scaling</td>
<td>□ Mineral-fluid interface complexity and dynamics</td>
<td>□ Develop and test methods for assessing storage capacity and for monitoring containment of CO₂ storage</td>
<td>□ Develop site selection criteria</td>
</tr>
<tr>
<td>□ Highly reactive subsurface materials and environments</td>
<td>□ Nanoparticulate and colloid chemistry and physics</td>
<td>□ Develop remediation methods to ensure permanent storage</td>
<td>□ Develop storage and operating engineering approaches</td>
</tr>
<tr>
<td>□ Thermodynamics of the solute-to-solid continuum</td>
<td>□ Dynamic imaging of flow and transport</td>
<td>□ Demonstrate procedures for characterizing storage reservoirs and seals</td>
<td>□ Storage demonstrations</td>
</tr>
<tr>
<td>□ Computational geochemistry of complex moving fluids within porous solids</td>
<td>□ Transport properties and <em>in situ</em> characterization of fluid trapping, isolation and immobilization</td>
<td>□ Integrated models for waste performance prediction and confirmation</td>
<td>□ Apply assessment protocols and technologies for the lifecycle of projects</td>
</tr>
<tr>
<td>□ Integrated analysis, modeling and monitoring of geologic systems</td>
<td>□ Fluid-induced rock deformation</td>
<td>□ Radionuclide partitioning in repository environments.</td>
<td>□ Evaluate release of radionuclide inventory from the repository</td>
</tr>
<tr>
<td>□ Simulation of multi-scale systems for ultra-long times</td>
<td>□ Biogeochemistry in extreme subsurface environments</td>
<td>□ Waste form stability and release models.</td>
<td>□ Assess corrosion/alteration of engineered materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>□ Incorporate new conceptual models into uncertainty assessments.</td>
<td>□ Long-term safety/risk assessment for emplacement of energy system by-products.</td>
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Office of Science

FE, RW, EM, EERE
Bedford Canyon Turbidites
(http://blogs.agu.org/mountainbeltway)

Thank You

Marcellus Shale
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.
Faults with NE-SW orientation are most likely to slip.