Engineering Challenges in the Recovery of Heat from Sedimentary Reservoirs

Derek Elsworth (Penn State)

Outcomes from Prior Meetings

SedHeat 2011 (John Holbrook)
Penrose 2013 (John Holbrook)

Some Key Issues in EGS and Sedimentary Geothermal Reservoirs (SGRs)

- Why SedHeat?
  - EGS versus SGRs/SGS
  - SedHeat as alternate route with Shale Gas
- Spectrum of Behaviors EGS to SGR
- Fluid Flow and Heat Transport Modes

Prospects for Applying Innovations from Rapidly Evolving Oil and Gas (2016)

- Reservoir Engineering
- Co-Produced Reservoirs
- Drilling
- Completions
- Subsurface Characterization
- Induced Seismicity

Outcomes from ARMA-AAPG-SedHeat Meeting

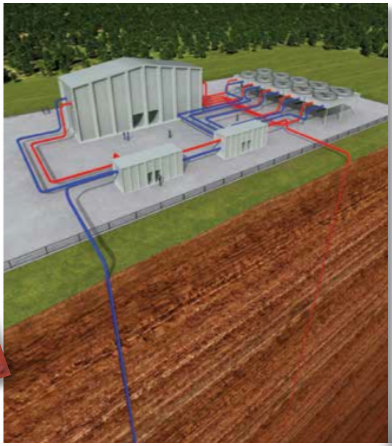
"Key Needs" or "No Problem"

Sedimentary Geothermal Reservoirs (SGRs)

TRACKING AN ENERGY ELEPHANT

SCIENCE AND ENGINEERING CHALLENGES FOR UNLOCKING THE GEOTHERMAL POTENTIAL OF SEDIMENTARY BASINS

NSF-SEES WORKSHOP REPORT



PENROSE CONFERENCE

Predicting and Detecting Natural and Induced Flow Paths for Geothermal Fluids in Deep Sedimentary Basins

October 19 – 23, 2013, Newpark Hotel, Park City Utah

SedHeat was created to provide a central exchange of information and an opportunity to link researchers with common goals for a common purpose. It provides a place to foster training, mentor emerging scholars and a venue to present and exchange ideas. Our purpose is to build and sustain a diverse and interdisciplinary network of researchers who are focused on addressing the basic science, engineering and educational challenges for sustainable geothermal energy development from sedimentary basins.

WHAT WE DO

Our intention is to continually grow as a network, as well as attract new parties interested in the topic of sedimentary-basin geothermal energy.

- > Steering Committee
- > RCN Members
- > Grant Programs
- > Join RCN
- > Workshops & Meetings
- > Travel Grants

RESEARCH COORDINATION NETWORK

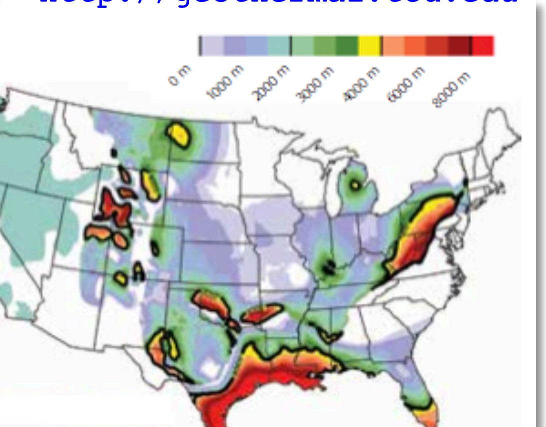
The Research Coordination Network (RCN) provides a central location for members to exchange information, the opportunity to link with researchers of common goals for common purposes, and build a research community for geothermal energy from sedimentary basins.

HOW WE DO IT

SedHeat provides information and opportunities to participate in grant programs, workshops, meetings, conferences, educational and

SedHeat Initiative

http://geothermal.tcu.edu



…ediment thickness in the conterminous … Basin and Range basins … t al., 2006)

ARMA-AAPG-SEDHEAT WORKSHOP

SUCCESSFUL ENGINEERING OF SEDIMENTARY GEOTHERMAL SYSTEMS

Friday June 24th and Saturday June 25th, 2016

50th Rock Mechanics/Geomechanics Symposium

Westin Galleria, Houston, Texas

Derek Elsworth, John Holbrook, Charles Fairhurst, Sid Green: Conveners

armasymposium.org/workshops - Information

armasymposium.org/registration - Registration

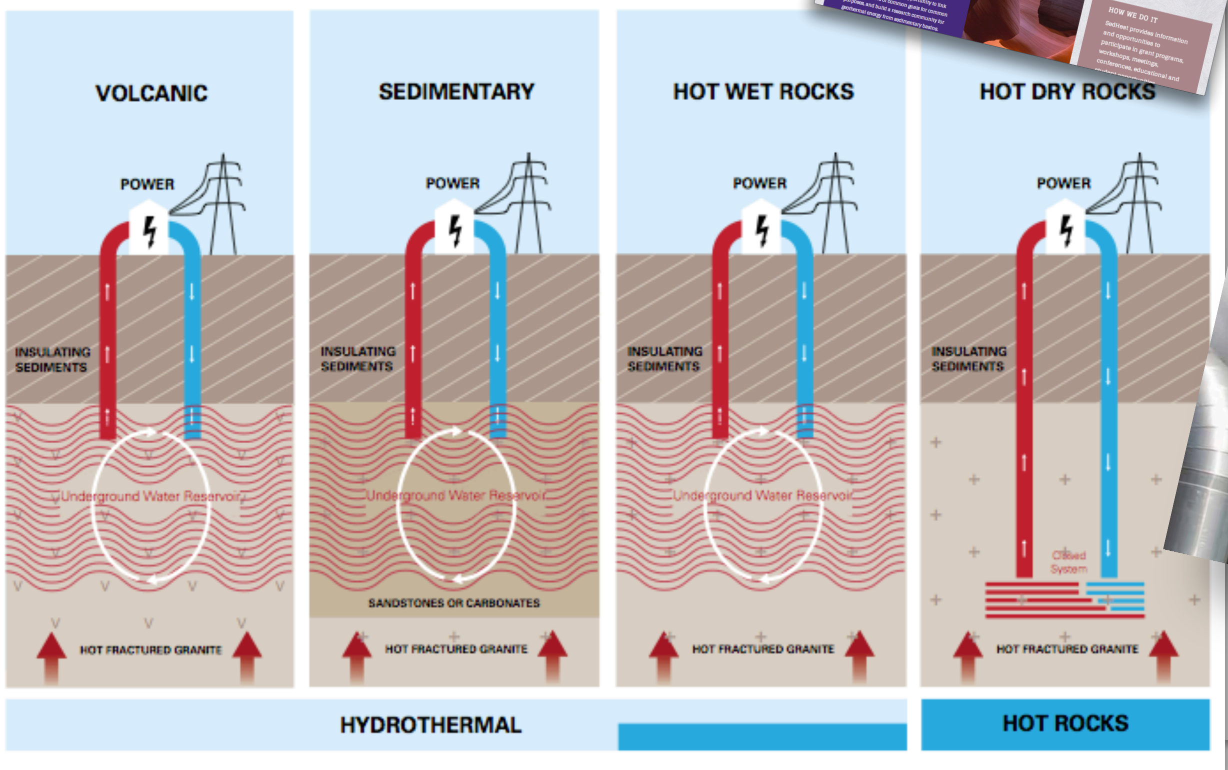
This workshop will explore the impediments to making sedimentary geothermal reservoirs a commercial reality and in particular will examine the potential to leverage new practices and techniques evolving from subsurface engineering in low permeability and environmentally challenging environments – such as for shale gas and for geothermal energy.

Topical Areas

Reservoir Engineering at Large Scale
Geopressured Resources/Co-Produced Reservoirs
Drilling
Completions
Geophysical Characterization
Induced Seismicity
Education/Cyberinfrastructure

For information on available discussion and speaking opportunities, please contact: elsworth@psu.edu

Figure 2: Average temperature at 4.5 km, contermin… …ted States. (Tester, et al., 2006, after Blackwell and Richards, 2004)



Basic Observations of Permeability Evolution and IS

Challenges

- Prospecting (characterization)
- Accessing (drilling)
- Creating reservoir
- Sustaining reservoir
- Environmental issues

Observation

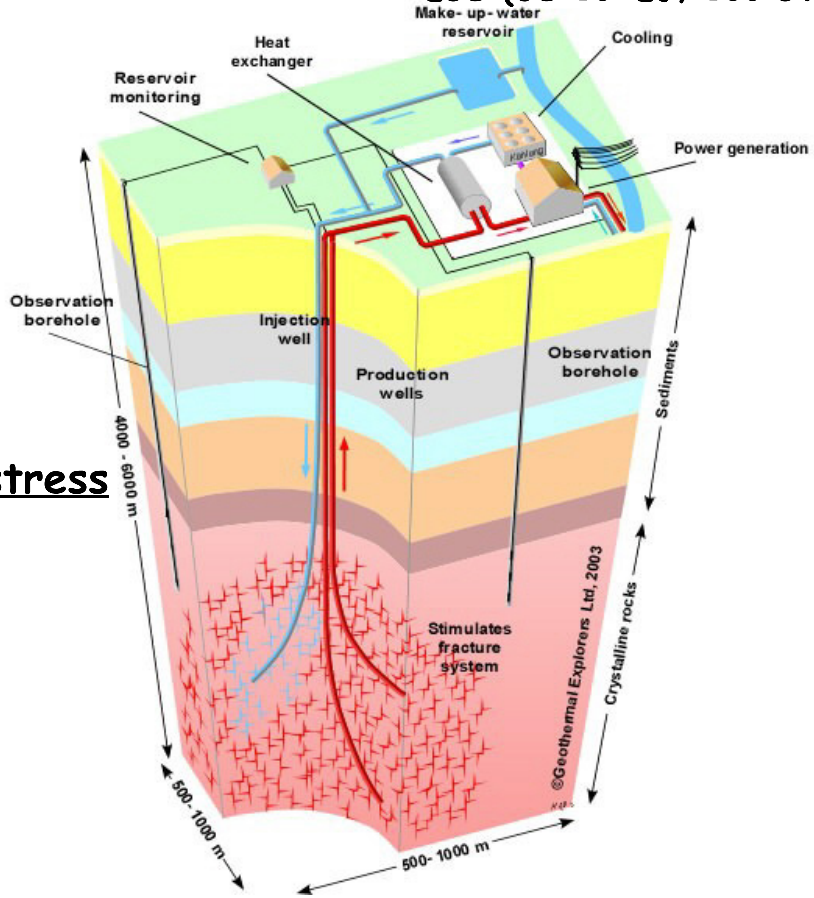
- Stress-sensitive reservoirs
- T H M C all influence via <u>effective stress</u>
- <u>Effective stresses</u> influence
    - Permeability
    - Reactive surface area
    - Induced seismicity

Understanding T H M C is key:

- Size of relative effects of THMC(B)
- Timing of effects
- Migration within reservoir
- Using them to engineer the reservoir

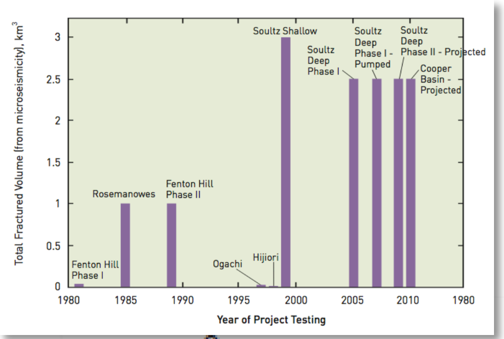
Resource

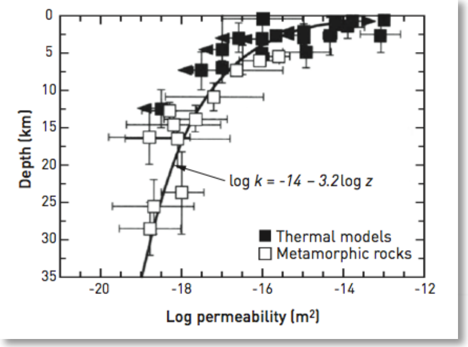
- Hydrothermal (US:10^4 EJ)
- EGS (US:10^7 EJ; 100 GW in 50y)

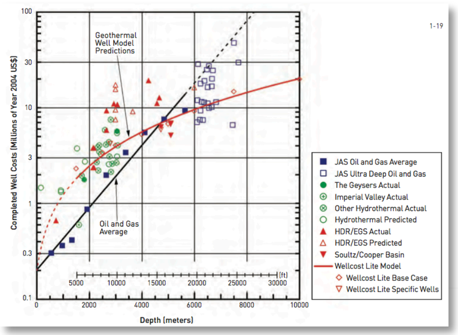


Permeability
Reactive surface area
Induced seismicity

Can EGS ever be Viable?

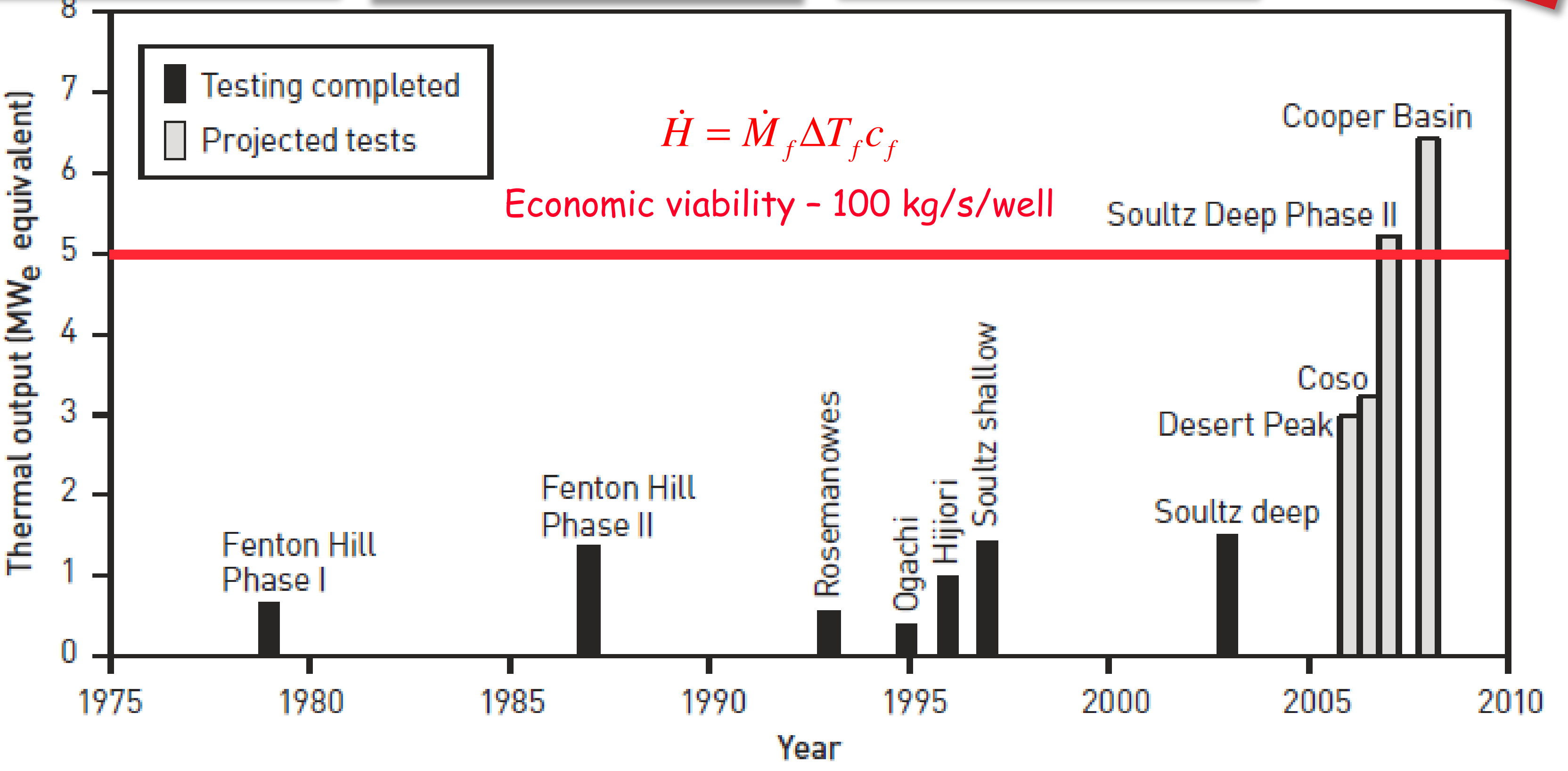







The Future of Geothermal Energy

Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century



$$\dot{H} = \dot{M}_f \Delta T_f c_f$$

Economic viability – 100 kg/s/well

Induced Seismicity

The New York Times

Quake Fears Stall Energy Extraction Project

By JAMES GLANZ
Published: July 13, 2009

Two federal agencies are stopping a contentious California project from fracturing bedrock miles underground and extracting its geothermal energy until a scientific review determines whether the project could produce dangerous earthquakes, spokeswomen for the Energy and Interior Departments said on Monday.

Jim Wilson/The New York Times

The project by AltaRock Energy, a start-up company with offices in Seattle and Sausalito, Calif., had won a grant of $6.25 million from the Energy Department, and officials at the Interior Department had indicated that it was likely to issue permits allowing the company to fracture bedrock on federal land in one of the most seismically active areas of the world, Northern California.

But when contacted last month by The New York Times for an article on the project, several federal officials said that AltaRock had not disclosed that a similar project in Basel, Switzerland, was shut down when it generated earthquakes that shook the city in 2006 and 2007.

Key Questions in SGRs and EGS

Needs $\dot{H} = \dot{M}_f \Delta T_f c_f$

- **Fluid availability**
  - Native or introduced
  - H_2O/CO_2 working fluids?
  - Combined with sequestration?
- **Fluid transmission**
  - Permeability microD to mD?
  - <u>Distributed permeability</u>
- **Thermal efficiency**
  - Large heat transfer area
  - Small conduction length
- **Long-lived**
  - Maintain mD and HT-area
  - Chemistry
- **Environment**
  - Induced seismicity
  - Fugitive fluids
- **Ubiquitous**

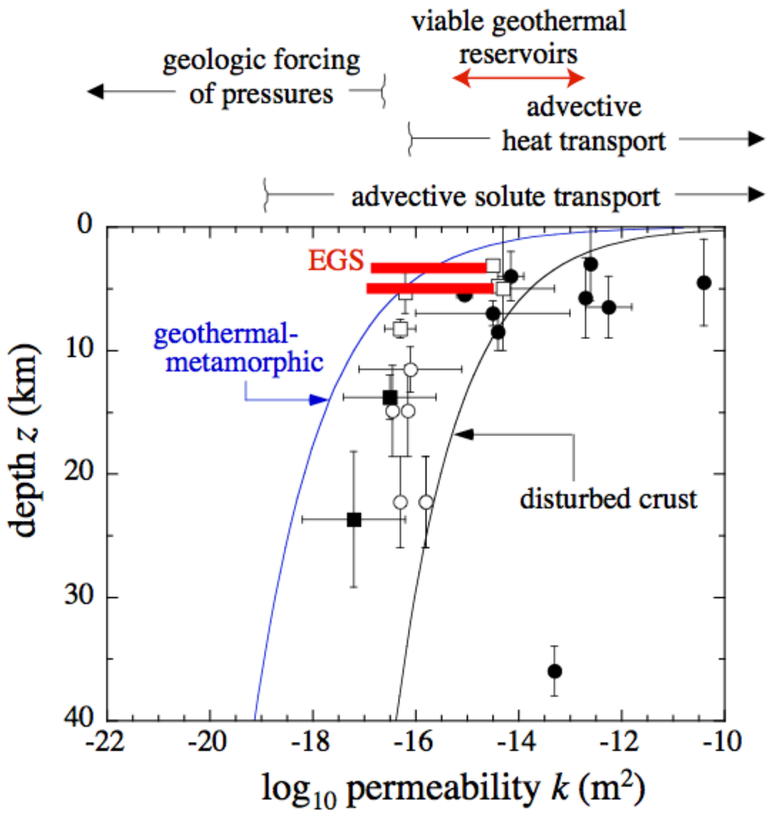
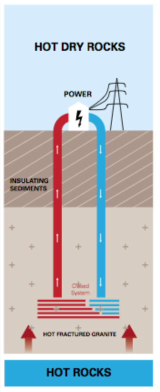


Figure 12: Evidence for relatively high crustal-scale permeabilities showing showing power-law fit to data. Geothermal-metamorphic curve is the best-fit to geothermal-metamorphic data [*Manga and Ingebritsen*, 1999, 2002]. "Disturbed-crust" curve interpolates midpoints in reported ranges in *k* and *z* for a given locality [*Manning and Ingebritsen*, 2010, their Table 1]; error bars depict the full permissible range for a plotted locality and are not Gaussian errors, and the Dobi (Afar) earthquake swarm is not shown on this plot (it is off-scale). Red lines indicate permeabilities before and after EGS reservoir stimulation at Soultz (upper line) and Basel (lower line) from *Evans et al.* [2005] and *Häring et al.* [2008], respectively. Arrows above the graph show the range of permeability in which different processes dominate.

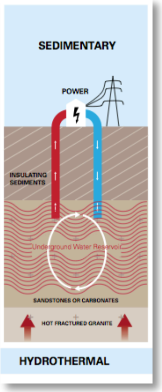
Steve.ai [Ingebritsen and Manning, various, in Manga et al., 2012]

Contrasts Between EGSs & SGRs

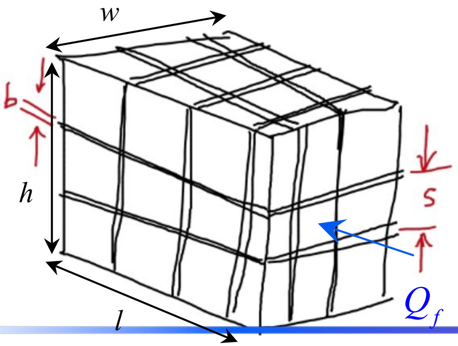
EGS (Order of Mag.)	Property	SGRs (Order of Mag)
Fractured-non-porous	General	Porous-fractured
<<1%,<1%	Porosity, n_0 -> n_{stim}	~10-30%, ~same
microD -> mD	Permeability, k_0 -> k_{stim}	>mD -> >mD
10^6	K_f/k_{matrix}	10^6 ->1
10-100m	Heat transfer length, s	1m -> 1cm
>>100/1. >100/1	*$Heat_{solid}/Heat_{fluid}$	~10/1-2/1, same
?	Chemistry	?
V. Strong	TM Perm. Feedbacks	Less strong
Moderate, late time	TC Perm. Feedbacks	Strong?



$$*\frac{\text{Heat in solid}}{\text{Heat in fluid}}=\frac{\cancel{V}(1-n)\rho_R c_R \Delta T}{\cancel{V}(n)\rho_W c_W \Delta T}=\frac{(1-n)}{n}\,\frac{\rho_R c_R}{\rho_W c_W}$$



Thermal Drawdown EGS -vs- SGRs



$$\dot{H}_{solid} \sim A\lambda_R \frac{dT}{dx} \sim \frac{V\lambda_R \Delta T}{s^2}$$

$$\dot{H}_{fluid} \sim Q_f \rho_W c_W \Delta T$$

$$\frac{\dot{H}_f}{\dot{H}_s} \sim \frac{\rho_W c_W}{\lambda_R}\frac{Q_f s^2}{V} = Q_D$$

$EGS:$

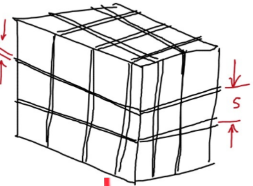
$\dot{H}_f \to \infty$

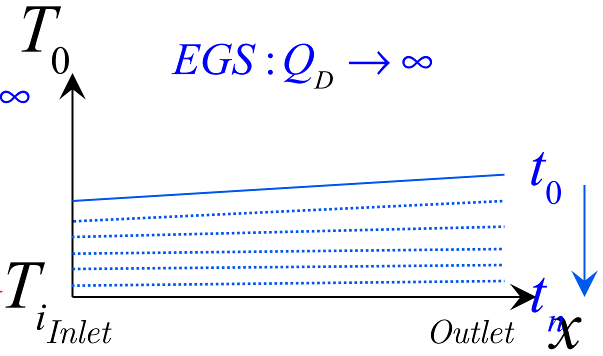
$\dot{H}_f / \dot{H}_s \to \infty$

$Q_D \to \infty$

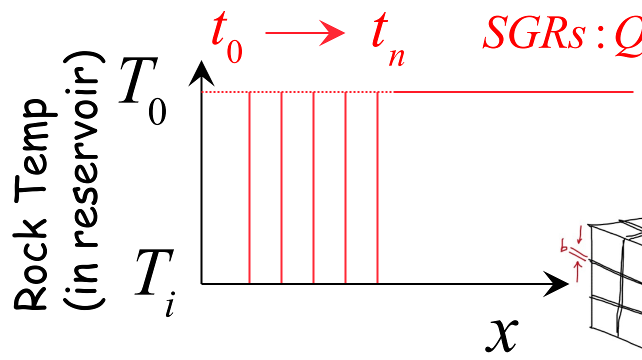
In-Reservoir Water Temperature Distributions:

$EGS: Q_D \to \infty$





$SGRs: Q_D \to 0$

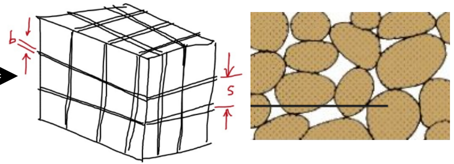


$SGRs:$

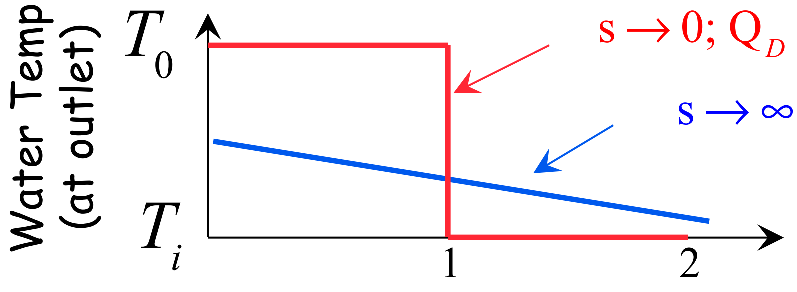
$\dot{H}_s \to 0$

$\dot{H}_f / \dot{H}_s \to 0$

$Q_D \to 0$



Thermal Output:



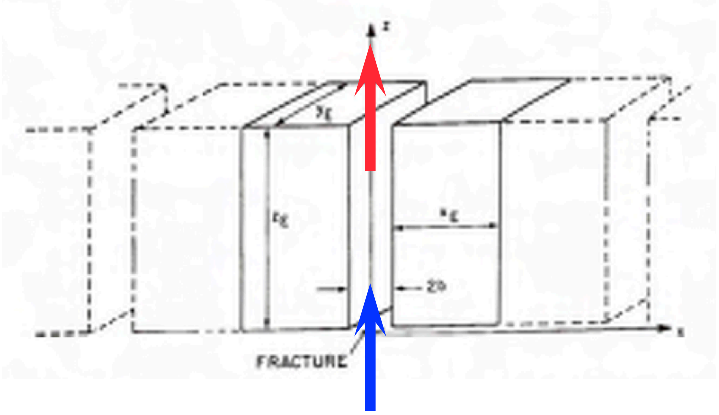
s → 0; $Q_D \to 0$; Thermal-front present

s → ∞; $Q_D \to \infty$; Thermal front absent

$$t_D = \frac{\rho_W c_W}{\rho_R c_R}\frac{Q_f t}{V}$$

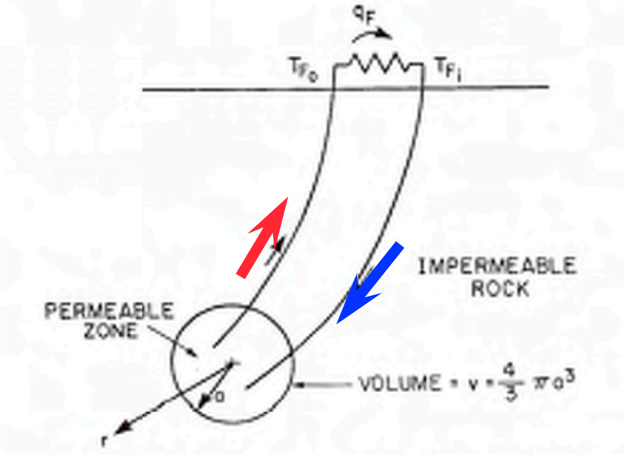
Thermal Recovery at Field Scale

Parallel Flow Model



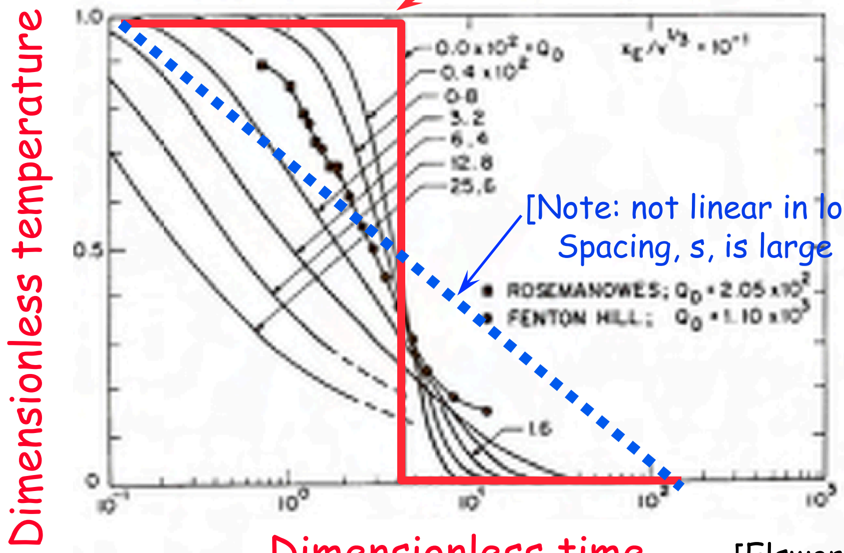
[Gringarten and Witherspoon, Geothermics,1974]

Spherical Reservoir Model



[Elsworth, JGR, 1989]

Spacing, s, is small



Dimensionless temperature

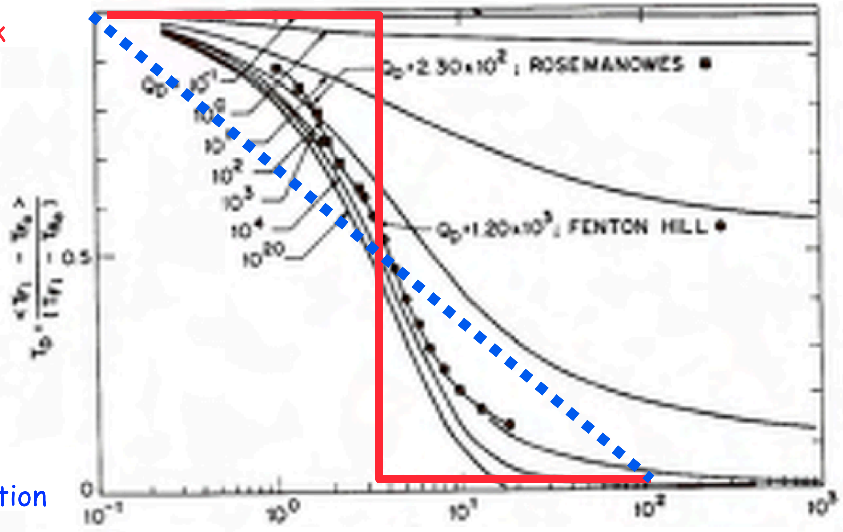
[Note: not linear in log-time]

Spacing, s, is large

T_{rock}

$T_{injection}$

Dimensionless time



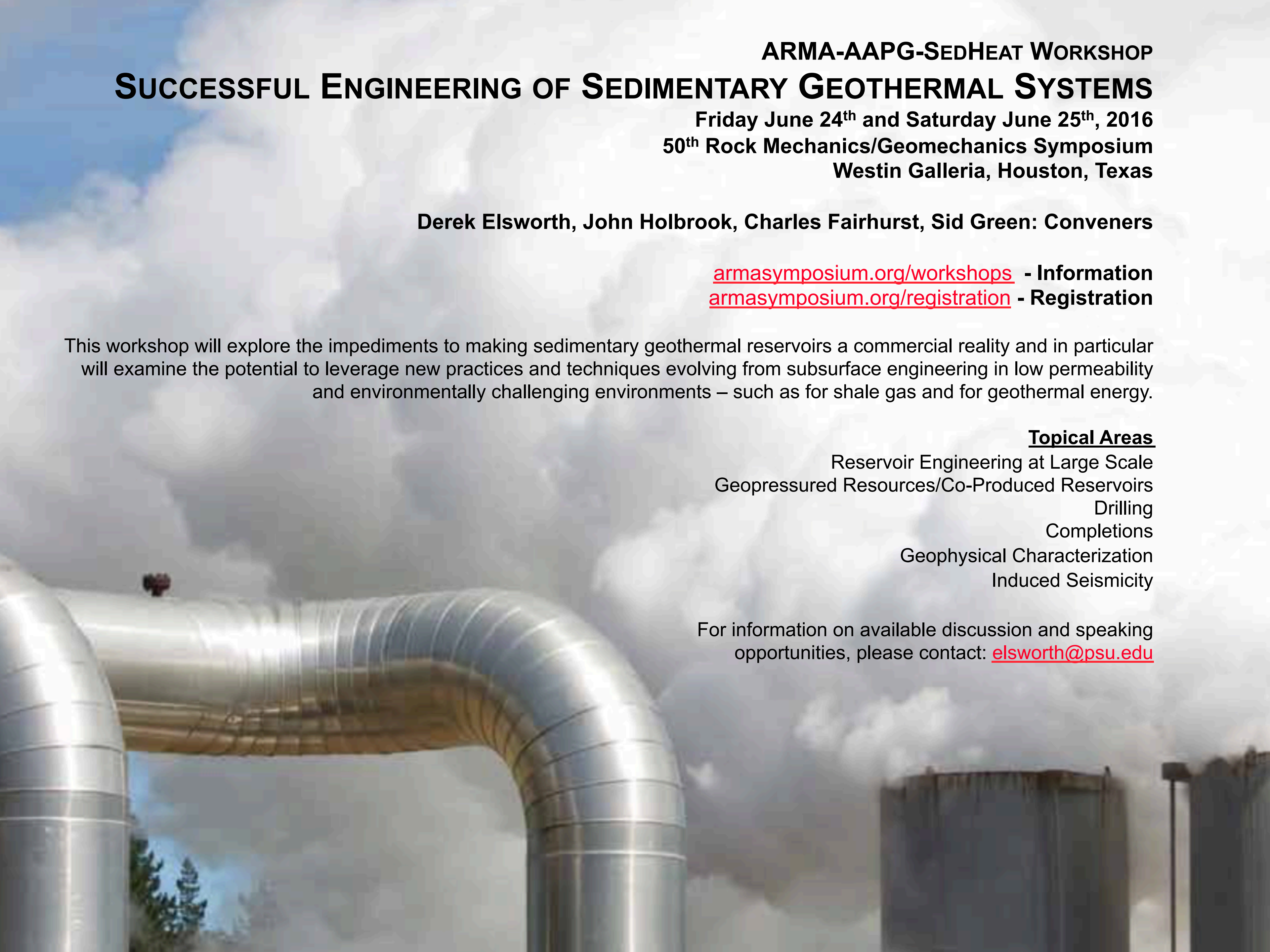
[Elsworth, JVGR, 1990]

Dimensionless time

Key Questions in EGS and SGRs

Needs $\dot{H} = \dot{M}_f \Delta T_f c_f$

- **Fluid availability**
  - Native or introduced – fluid/geochemical compatibility
  - H_2O/CO_2 working fluids? – arid envts.
- **Fluid transmission**
  - Permeability microD to milliD? – high enough?
  - Distributed permeability
    - Characterizing location and magnitude
    - Defining mechanisms of perm evolution (chem/mech/thermal)
    - Well configurations for sweep efficiency and isolating short-circuits
- **Thermal efficiency**
  - Large heat transfer area – better for SGRs than EGS?
  - Small conduction length – better for SGRs than EGS?
- **Long-lived**
  - Maintain mD and HT-area – better understanding diagenetic effects?
  - Chemistry - complex
- **Environment**
  - Induced seismicity - Event size (max)/timing/processes (THMCB)
  - Fugitive fluids – Fluid loss on production and environment – seal integrity
- **Ubiquitous**



ARMA-AAPG-SEDHEAT WORKSHOP

SUCCESSFUL ENGINEERING OF SEDIMENTARY GEOTHERMAL SYSTEMS

Friday June 24th and Saturday June 25th, 2016
50th Rock Mechanics/Geomechanics Symposium
Westin Galleria, Houston, Texas

Derek Elsworth, John Holbrook, Charles Fairhurst, Sid Green: Conveners

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This workshop will explore the impediments to making sedimentary geothermal reservoirs a commercial reality and in particular will examine the potential to leverage new practices and techniques evolving from subsurface engineering in low permeability and environmentally challenging environments – such as for shale gas and for geothermal energy.

Topical Areas

Reservoir Engineering at Large Scale
Geopressured Resources/Co-Produced Reservoirs
Drilling
Completions
Geophysical Characterization
Induced Seismicity

For information on available discussion and speaking opportunities, please contact: elsworth@psu.edu

Derek Elsworth (Penn State), John Holbrook (TCU), Charles Fairhurst (UMN), Sid Green (Utah)

WHAT DO WE HOPE TO ACHIEVE HERE?

What are the Key Issues in Developing the Resource Base of Sedimentary Geothermal Reservoirs (SGRs)?

What are the Prospects for Applying Innovations from Rapidly Evolving Oil and Gas Engineering?

Reservoir Engineering
Co-Produced Reservoirs
Drilling
Completions
Subsurface Characterization
Induced Seismicity

SUMMARIZED NEEDS

Define "Key Needs" as closing slide and re-visit in discussion

ARMA-AAPG-SEDHEAT WORKSHOP

SUCCESSFUL ENGINEERING OF SEDIMENTARY GEOTHERMAL SYSTEMS

50th Rock Mechanics/Geomechanics Symposium, Houston, Texas 2016
Conveners: Derek Elsworth, John Holbrook, Charles Fairhurst, Sid Green

FRIDAY AM – Derek Elsworth

8:00 – 9:50 Introduction and Setting-the-Stage

Welcome, Overview and Goals of the Meeting – The Conveners

The SedHeat Initiative – John Holbrook (TCU)

Newberry EGS Demonstration; Results and Future Plans – Mike Swyer (AltaRock)

10:10 – 12:10 Reservoir Engineering at Large Scale [1]

Cornell Geothermal District Heating Trade-offs: Hot Sed Aquifers or Basement EGS? – Teresa Jordan (Cornell)

CO_2 Plume Geothermal – Jimmy Randolph (UMN)/Jeff Bielicki (OSU)

N_2 Plume Geothermal – Tom Buscheck (LLNL)

FRIDAY PM – John Holbrook

1:30 – 3:30 Reservoir Engineering at Large Scale [2]

Influence of Heterogeneity on EGS performance – Tom Doe (Golder)

Reservoir Geomechanics for SedHeat – Peter Connolly (Chevron)

The Radiator-Enhanced Geothermal System: Emulating a Natural Hydrothermal System – Markus Hilpert (JHU)

3:50 – 5:50 Co-Produced Reservoirs

The UND-DOE Low Temperature Geothermal Power Plant – Will Gosnold (UND)

A Sedimentary Enhanced Geothermal Reservoir: Lyons Sandstone, Wattenberg Field, CO – Luis Zerpa (CSM)

50 years of CO_2 EOR experience benefits CO_2 storage – Larry Lake (UT)

ARMA-AAPG-SEDHEAT WORKSHOP
SUCCESSFUL ENGINEERING OF SEDIMENTARY GEOTHERMAL SYSTEMS

SATURDAY AM – Sid Green
8:00 – 9:50 Drilling
Drain Holes and Mud Motors for Geothermal Applications – Bill Maurer (Maurer Engineering)
Drilling Challenges in Geothermal Reservoirs – Doug Blankenship (Sandia)
Directional Drilling: Historical Developments, Current Technology, Future Challenges – Emmanuel Detournay (UMN)

10:10 – 12:10 Completions
Long-term Cold Water Injectivity at Raft River and Implications for Fracture Evolution – Mitch Plummer (INL)
New Hydraulic-Natural Fracture Interaction Mechanisms Unique to 3D Hydraulic Fracturing – Pengcheng Fu (LLNL)
Hydraulic Fracturing – Ernie Brown (Schlumberger)
ARMA Fracturing Workshop Summary - John McLennan (UU)

SATURDAY PM – Charles Fairhurst
1:30 – 3:30 Geophysical Characterization of Completions
Fracture Network Engineering: Optimizing Production using Geomechanical Sensitivity Analyses – Will Pettitt (Itasca)
Microseismic Geomechanical Interpretation of HFStimulation of Unconventional Reservoirs – Shawn Maxwell (IMaGE)
Induced Seismicity: Fluid Migration and Earthquake Nucleation in Oklahoma - Katie Keranen (Cornell)

3:50 – 5:50 Induced Seismicity
Hydromechanical and Active Seismic Monitoring to Characterize Stimulated Fracture Systems – Yves Guglielmi (LBNL)
Monitoring of Rock Fracturing Induced by Fluid Injection in the Laboratory – Sergey Stanchits (Schlumberger)
Simulation and forecasting of induced seismicity and its collective properties – David Dempsey (Auckland)

5:50 – 6:00 Consensus, Challenges and Needs – The Conveners

Closure and Adjournment

Implications for Energy Independence, Energy Security and for Climate Change?

APRIL 11, 2011

Libya's Civil War

A GRAVE SCANDAL AT ARLINGTON

People Power for Palestine
BY JOE KLEIN

BATTER UP!
YOUR GUIDE TO THE 2011 BASEBALL SEASON

The last great work of David Foster Wallace
BY LEV GROSSMAN

TIME

ENVIRONMENT SPECIAL

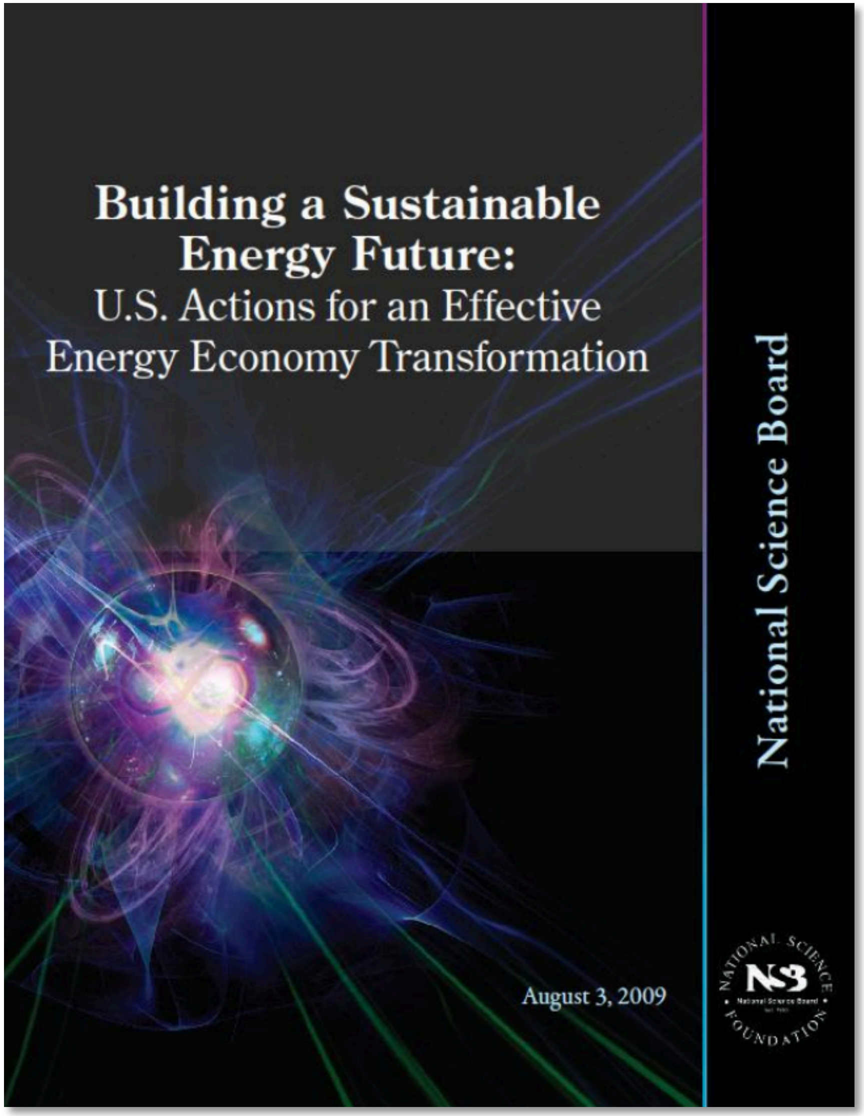
THIS ROCK COULD POWER THE WORLD

WHY SHALE CAN SOLVE THE ENERGY CRISIS
BY BRYAN WALSH

A century's worth is buried in our backyards ...

... but drilling for it threatens our land

www.time.com



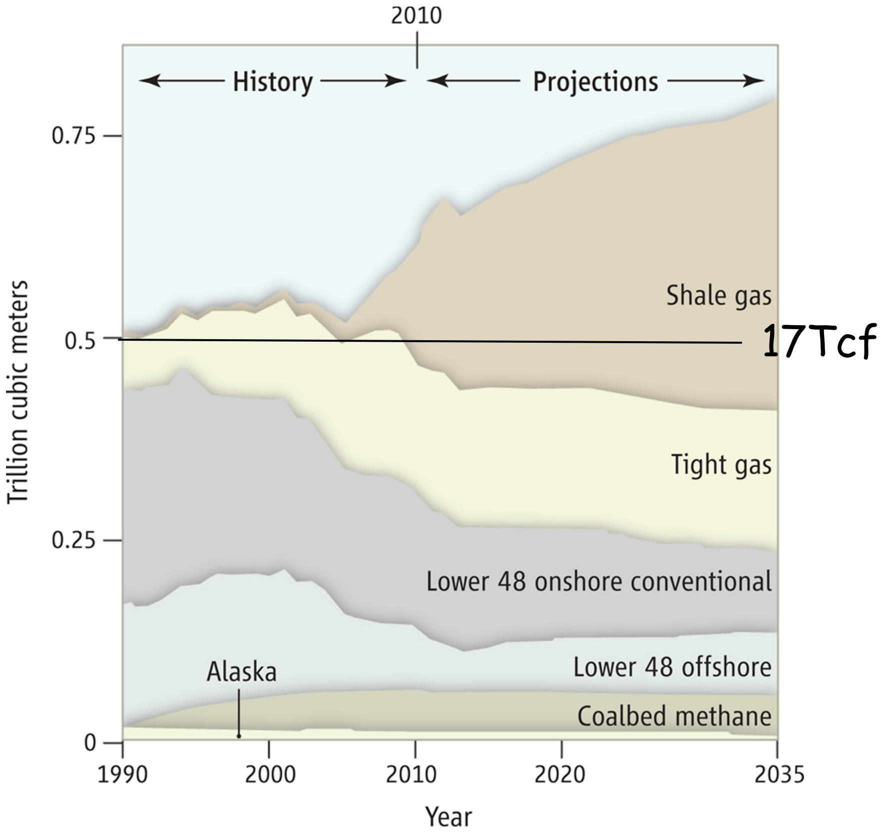
Building a Sustainable Energy Future:
U.S. Actions for an Effective Energy Economy Transformation

August 3, 2009

National Science Board

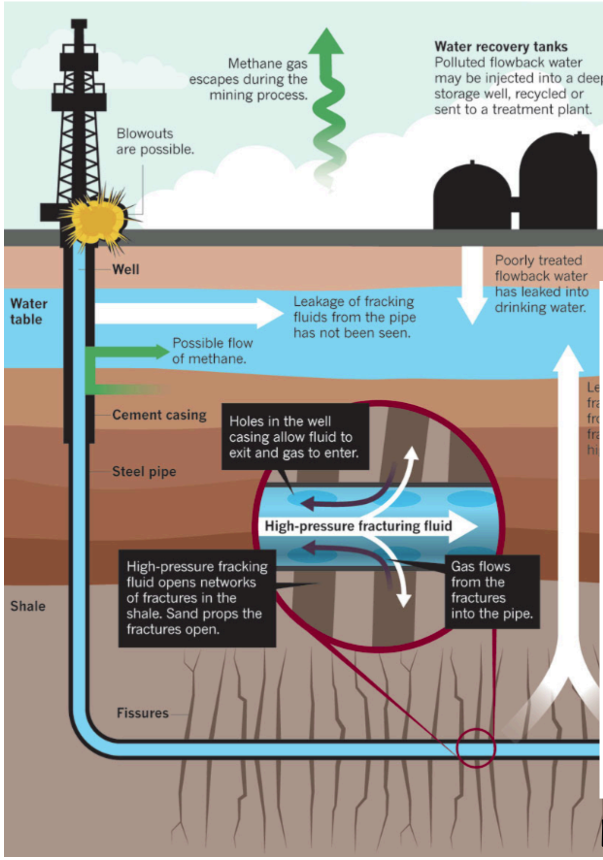
Projected Growth and Opportunities

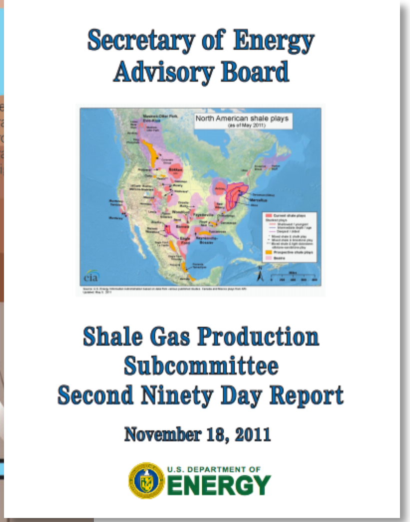
Natural Gas Utilization



[Science, Oct 18, 2012]

Upstream





Secretary of Energy
Advisory Board

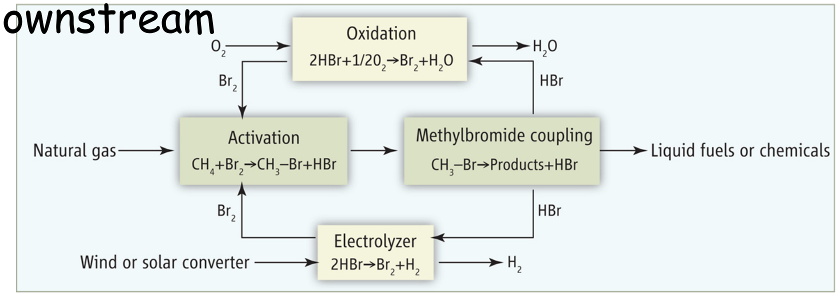
Shale Gas Production
Subcommittee
Second Ninety Day Report

November 18, 2011

U.S. DEPARTMENT OF ENERGY

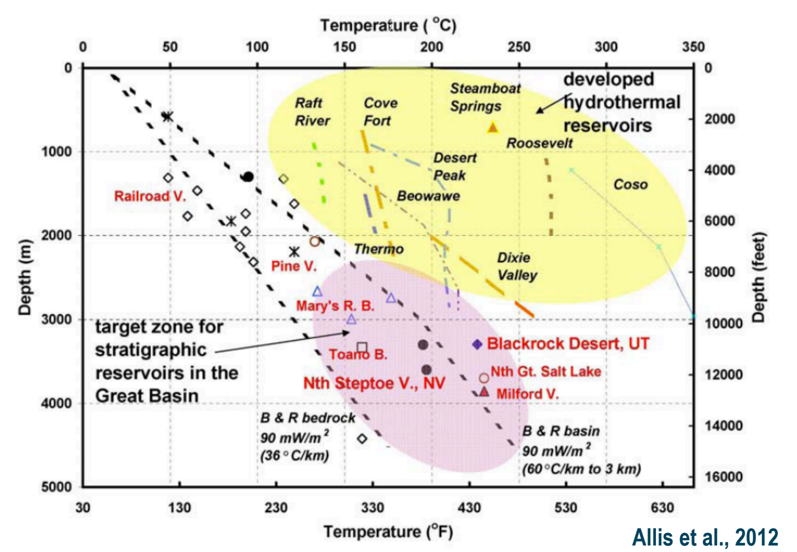
[Nature, 2011]

Downstream

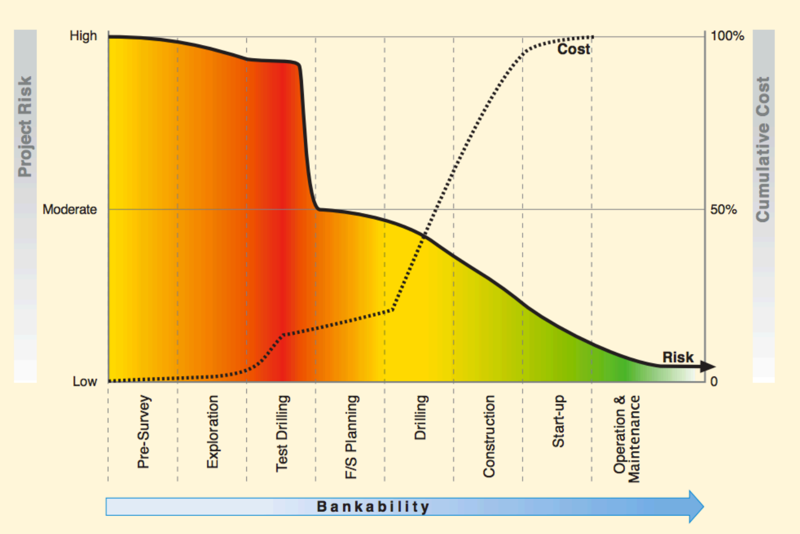


Key Issues for Sedimentary Hosted Geothermal Systems

- Establish the necessary boundary conditions
  - Sufficient temperature
  - Adequate perm, either current or induced
  - Threshold flow rate
- Define the engineering challenge



Allis et al., 2012



ESMAP, 2012 Geothermal handbook: Planning and Financing Power Generation

•Direct use as well as power applications

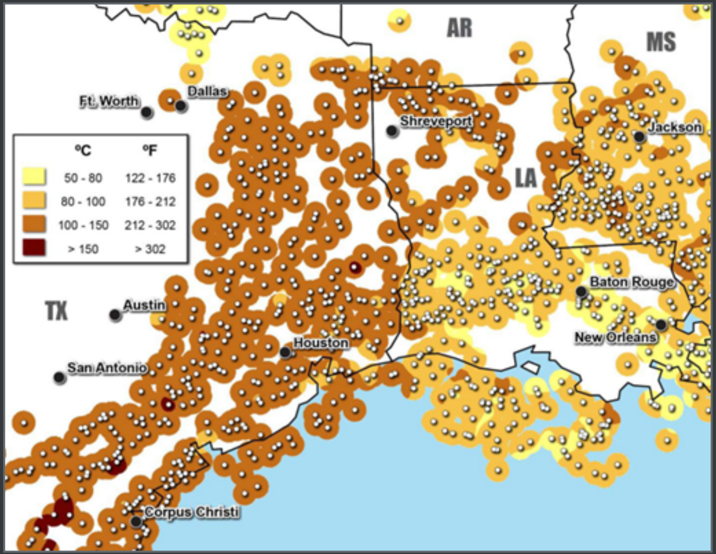
•Timelines/value of money and total costs are critical

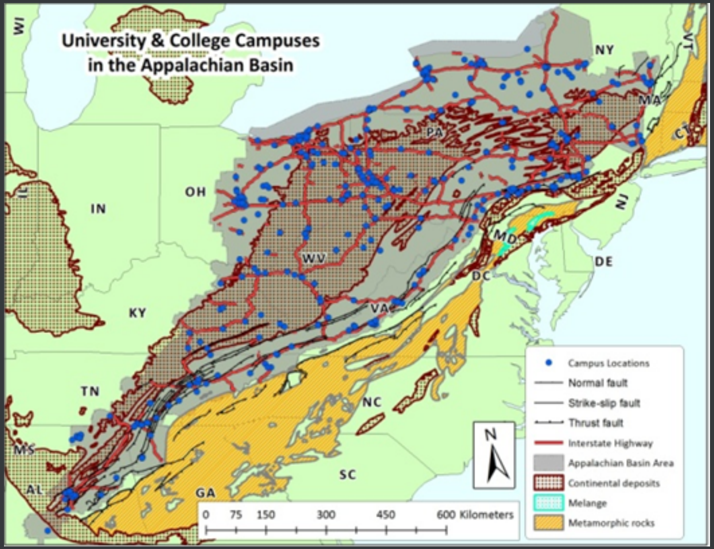
[Penrose, 2013, Dan King, GTP]

What's Next for Low Temp?

[Penrose, 2013, Dan King, GTP]

Materials Extraction, Direct-Use, Hybrid Systems





- Execute on **Co-production** initiative
- **Strategic Materials** - Resource assessment and feasibility
- Large-scale **Direct Use**: where does it make technical and commercial sense?
- R&D on innovative **Energy Conversion**

Induced Seismicity

NEWSFOCUS

Ohio rumblings. Wastewater injected at this site in Youngstown triggered jolting earthquakes that prompted injection-well shutdowns and strong new regulations.

SEISMOLOGY

Learning How to NOT Make Your Own Earthquakes

As fluid injections into Earth's crust trigger quakes across the United States, researchers are scrambling to learn how to avoid making more

First off, fracking for shale gas is not touching off the earthquakes that have been shaking previously calm regions from New Mexico to Texas, Ohio, and Arkansas. But all manner of other energy-related fluid injection—including deep disposal of fracking's wastewater,

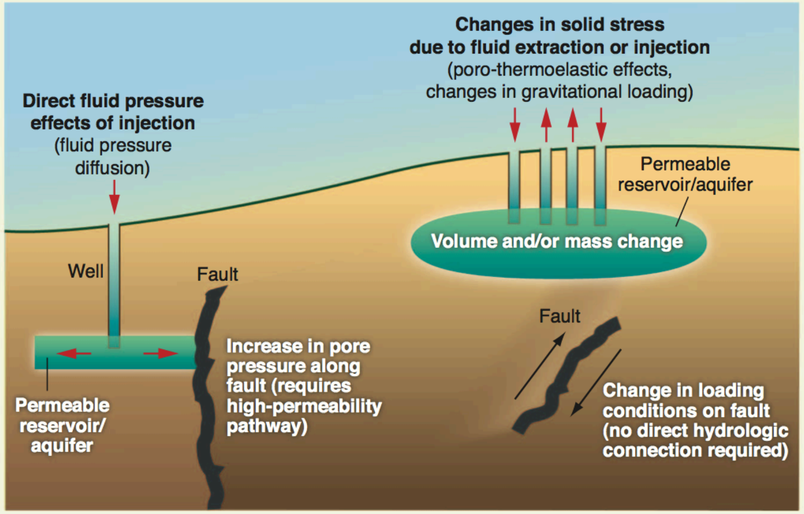
seismicity, they are beginning to see a way ahead: learn as you go. Thorough preinjection studies followed by close monitoring of cautiously increasing injection offer to lower, although never eliminate, the risk of triggering intolerable earthquakes.

Arkansas. In the current March/April issue of *Seismological Research Letters*, the University of Memphis seismologist recounts his learn-as-you-go experience with injection-triggered quakes strong enough to seriously shake up the locals.

Fracking for natural gas, formally known as hydraulic fracturing, had come to Arkansas around 2009. Not that a seismologist in Memphis would have noticed. Injecting water into gas-bearing shale at high pressures does break the rock to free the gas—that's the point, after all. But the resulting tiny quakes rarely get above magnitude 0 (the logarithmic scale includes negative numbers), never mind to the magnitude-3 quakes that people might feel.

But shale gas drillers need to dispose of the millions of liters of water laden with natural brines and added chemicals that flow back up after a shale gas well has been fracked (*Science*, 25 June 2010, p. 1624). Injecting fracking wastewater into deep rock is a common solution, so starting in April 2009, 1- to 3-kilometer-deep disposal wells were sunk in the vicinity of Guy (population 706) and Greenbrier (population 4706), Arkansas.

That's when Horton and Scott Ausbrooks of the Arkansas Geological Survey took note of a curious cluster of earthquakes near Greenbrier. The Guy-Greenbrier area had had only one quake of magnitude 2.5 or greater in 2007 and two in 2008. But there were

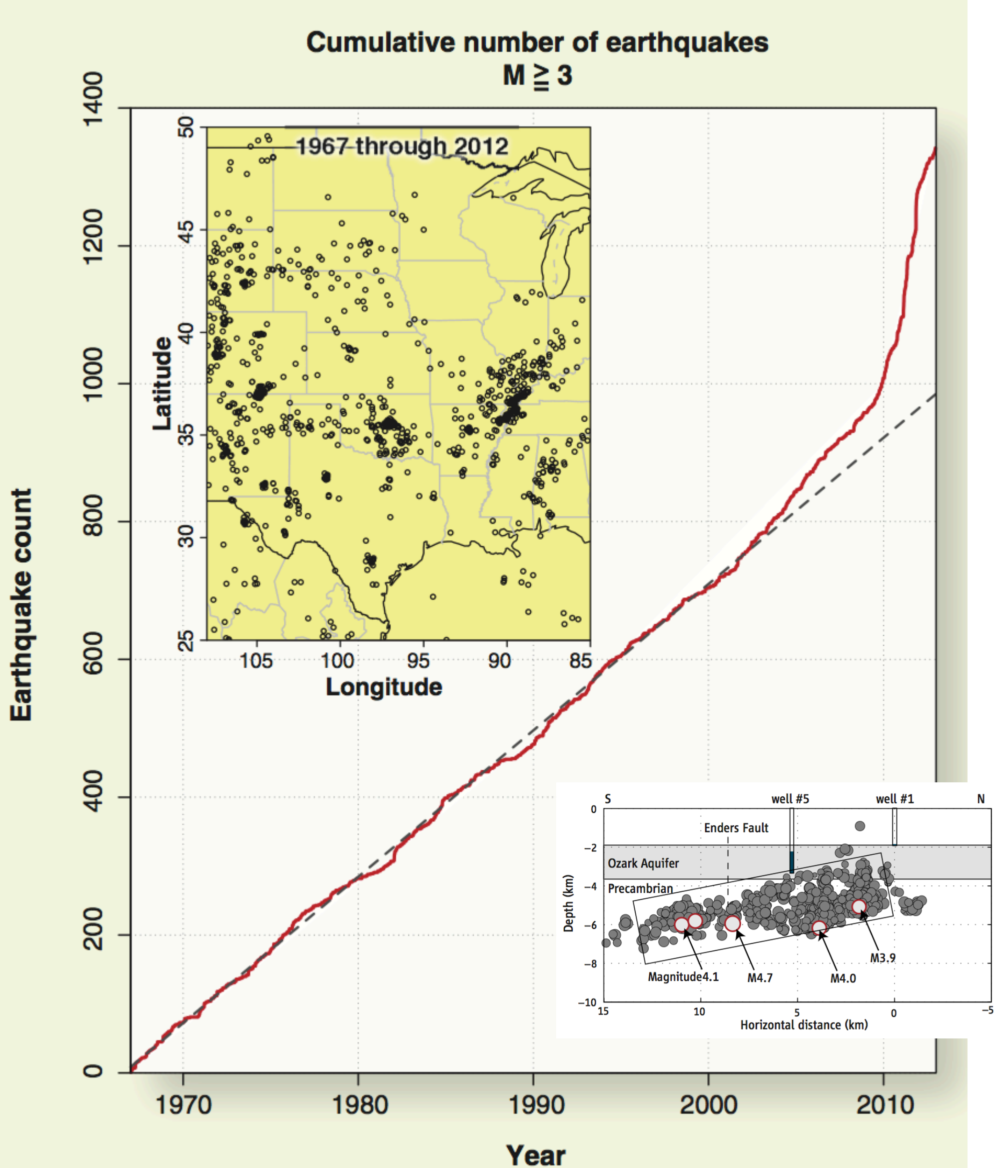


Changes in solid stress due to fluid extraction or injection
(poro-thermoelastic effects, changes in gravitational loading)

Direct fluid pressure effects of injection
(fluid pressure diffusion)

Increase in pore pressure along fault (requires high-permeability pathway)

Change in loading conditions on fault (no direct hydrologic connection required)

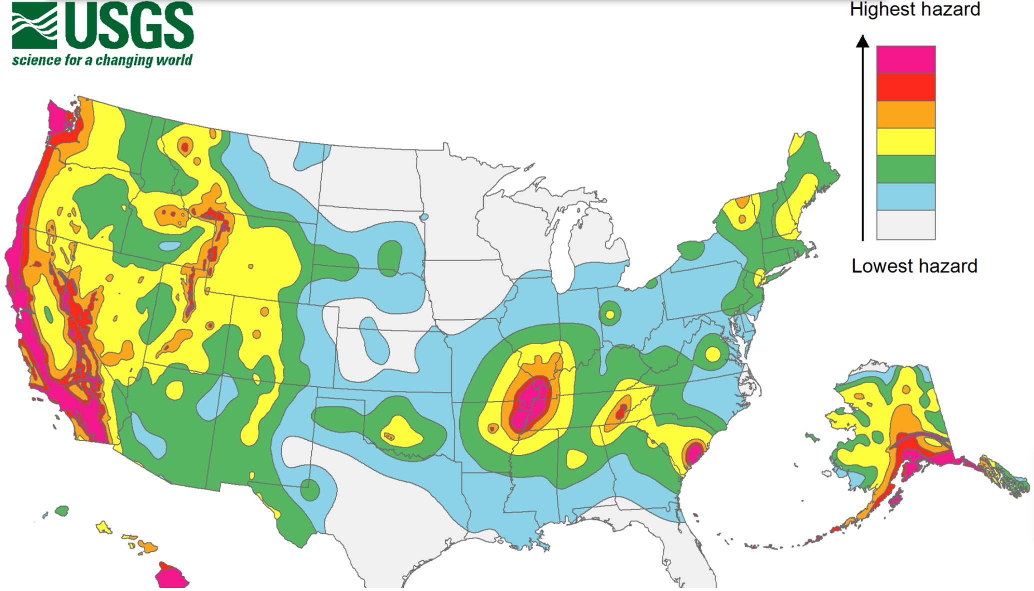


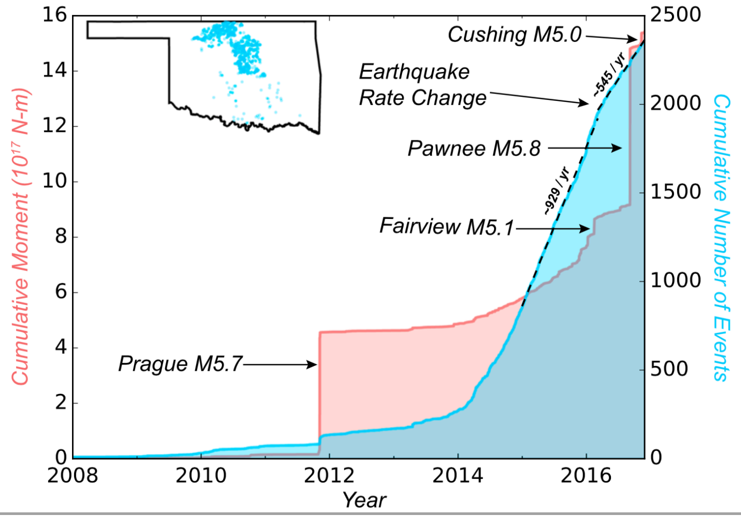
Cumulative number of earthquakes
M ≧ 3

[Ellsworth, Science, 2013]

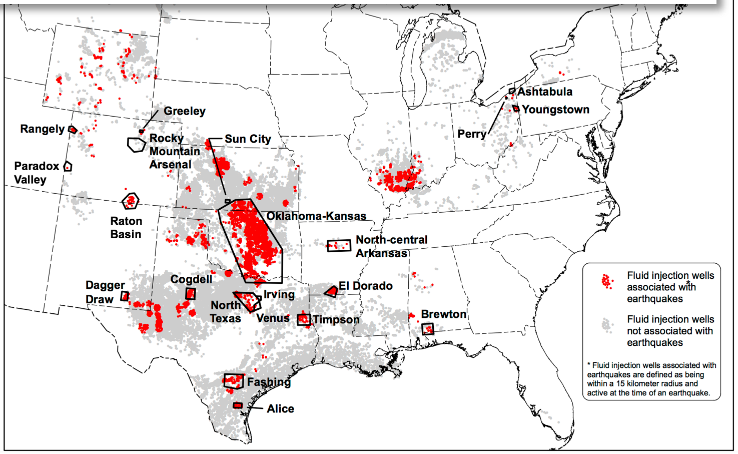
Induced Seismicity

US Seismic Hazard

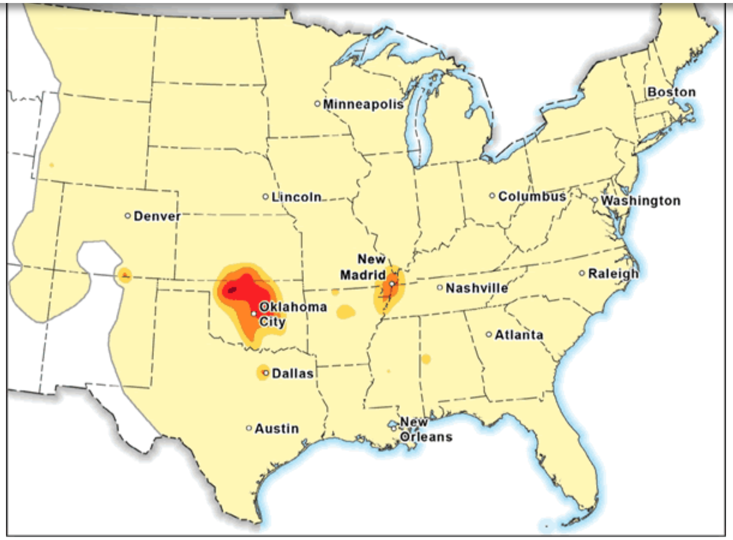




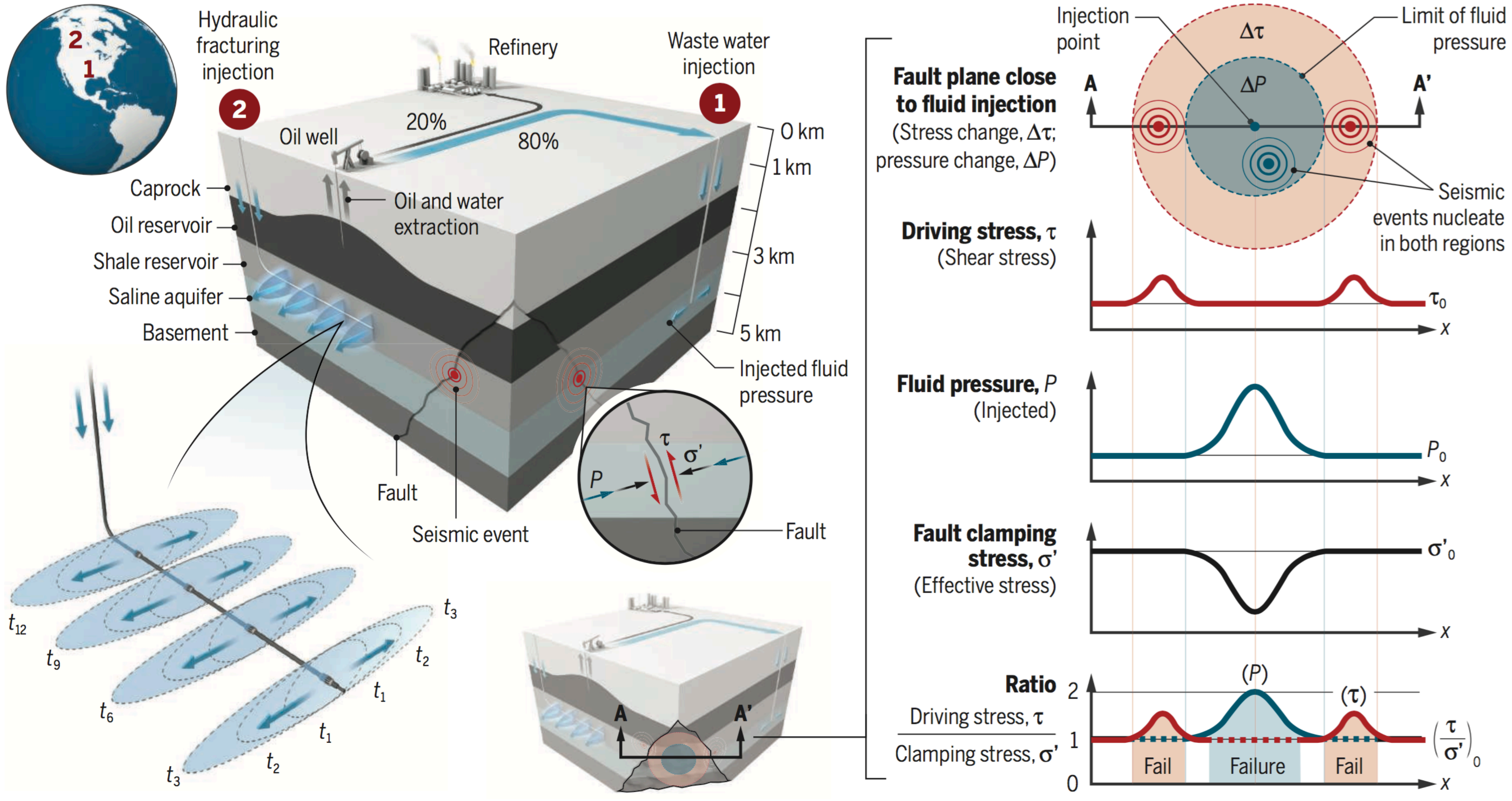
Seismic/Aseismic Fields



Mid-west Seismic Hazard

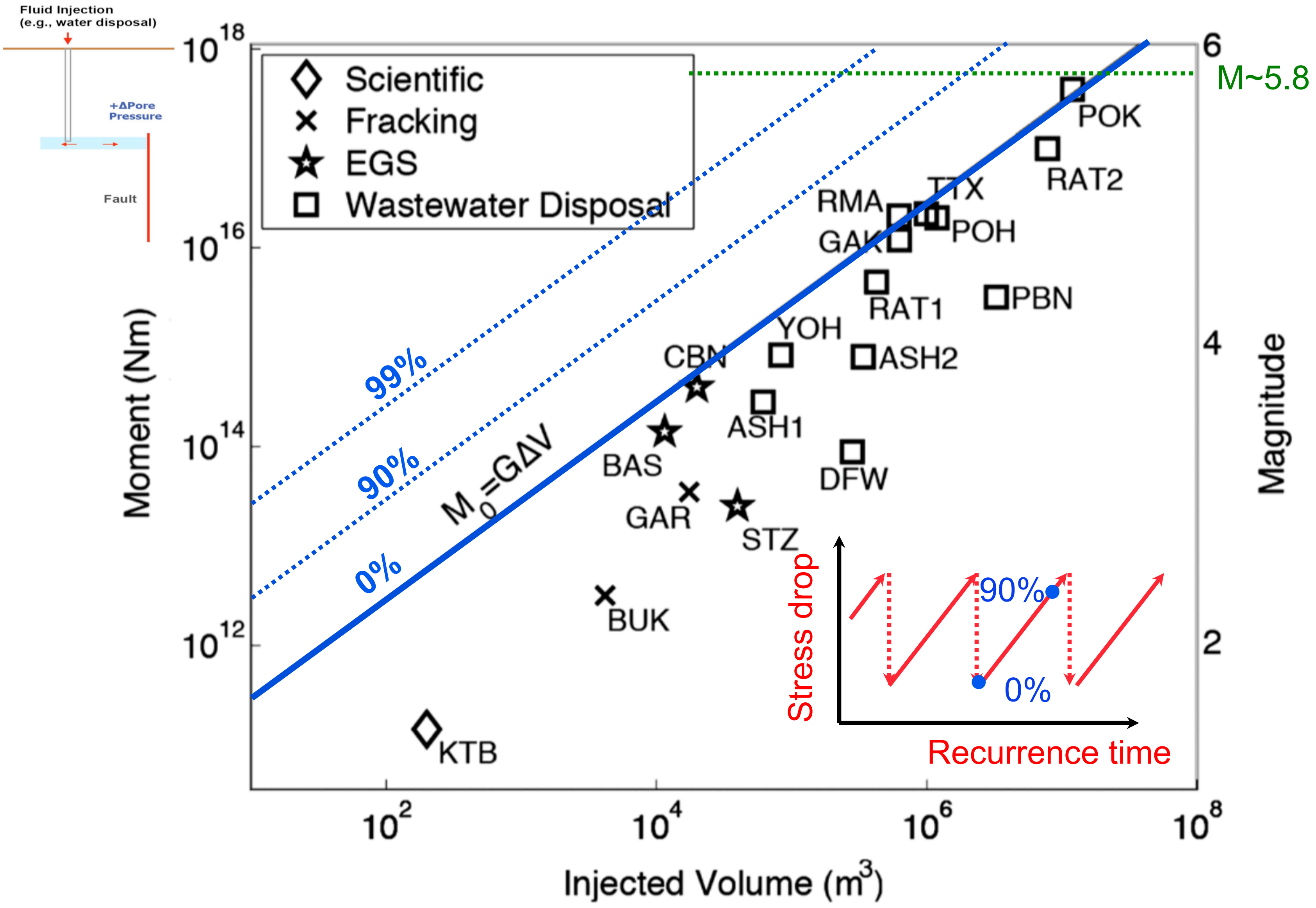


Induced Seismicity



[Elsworth et al., Science, 2016]

Maximum Anticipated Moment Magnitude – M or M_dot? M_{Gross} or M_{Net}? Triggered –vs- Induced?



After [McGarr, JGR, 2014]

Summary of 2016 “Engineering Challenges” Meeting (DE)

2. Possibility of using various fluids $H_2O/N_2/CO_2$

$$\dot{H} = \dot{M}_f \Delta T_f c_f$$

1. Sedimentary aquifers can be quite hot – ND – 98C (Will Gosnold) – Cherry pick

3. Wells can be prolific

50 kg/s for ND

Horizontal wells – length-in-zone

$$\dot{H} = \dot{M}_f \Delta T_f$$

Sedimentary Reservoirs – Porous/less fracture-dominated - Helpful

Environment: Induced Seismicity – conjectured small effects

dV_{net} is small – therefore dp is small?

dT_{net} is small – therefore dEpsilon is small?

These outcomes suggest that SedHeat should be straightforward?

Summary of 2016 “Engineering Challenges” Meeting (SJG)

Use of Shale Gas Technology
- Horizontal drilling
- Massive hydraulic fracturing

Different Mental Pictures of the Reservoir
- EGS-like reservoir – low perm and all secondary perm
- High-permeability initial reservoir

Important Role of Fluids
- Proppants
- Rock-fluid interactions, and fluid chemical/phase reactions
- Precipitation of solids, plugging of fractures

Feasibility Study Quite Straightforward

Induced Seismicity
- Science/Causality/Mitigation
- Public perception

Cost of Failed Projects versus ROI/Success/Value of Resource

So Why No/Sparing Adoption?

Value of resource?: 25c/BBL – ROI small in comparison to hydrocarbons with much larger energy density

Risk/Cost of failure: One unsuccessful well – geothermal versus hydrocarbon well

i.e. The "George Mitchell" Story….

Necessary "Step-Changes"?

$\dot{H} = \dot{M}_f \Delta T_f c_f$ and Environment

Systems (c_f):	CO_2/N_2 combinations – scale of 1 GW and 10c/kWh
Depth/Temp(dT):	Reduce drilling costs to depth (>60% of cost is drilling) Reduce tripping and casing or increase ROP Very high enthalpy wells (>600C)
Flow/Sweep(M):	Horizontal drilling – seems necessary Completions Cheaper methods for smart completions (<$0.5M/system)
Environment:	Gross volumes of injection are large - but net volumes are small? Chemical limits over the long-term?

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