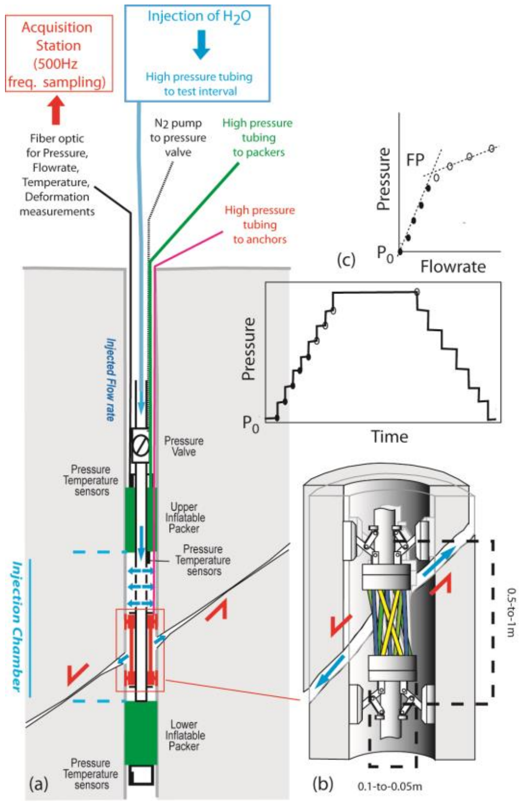

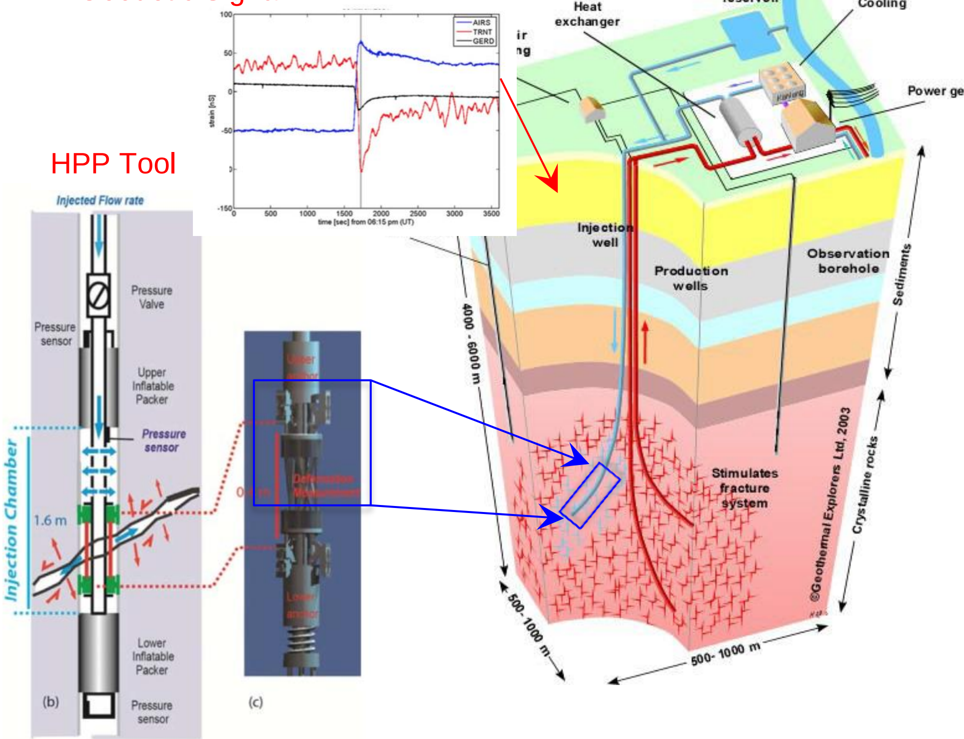

Surface and Subsurface Geodesy Combined with Active Borehole Experimentation for the Advanced Characterization of EGS Reservoirs

Project Officer: William Vandermeer

Total Project Funding: \$195k + \$020k = \$215k

May 13, 2015

Derek Elsworth

Co-PIs: Yves Guglielmi, Aix-Marseille

Glen Mattioli, UT Arlington/UNAVCO

Pennsylvania State University

HRC: Tools

Relevance/Impact of Research [Challenges]

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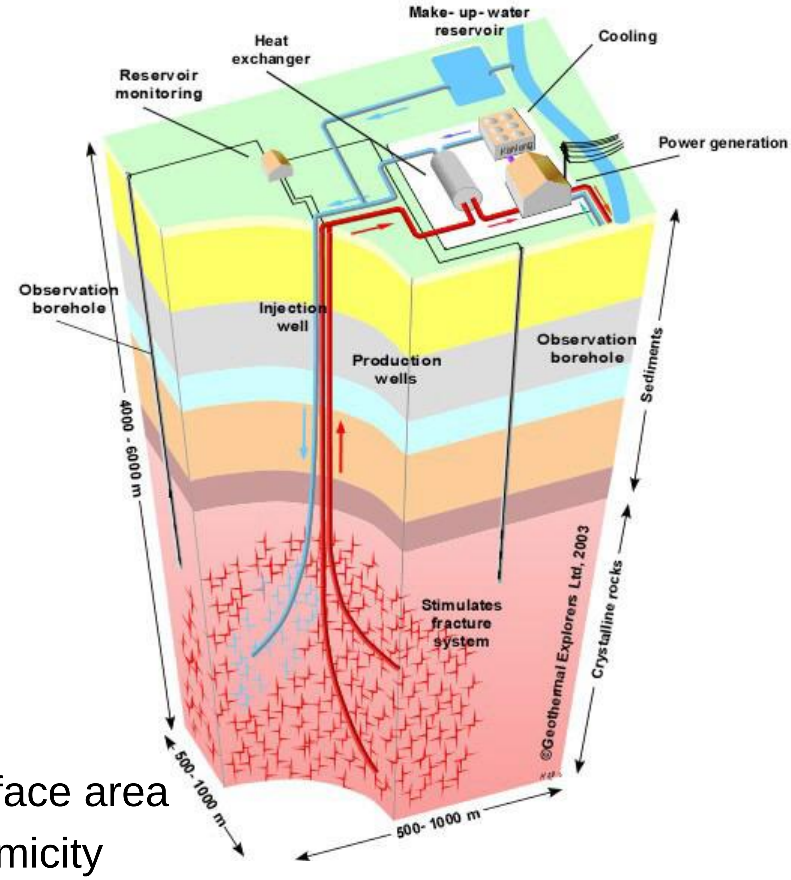
Challenges
- Prospecting (characterization)
- Accessing (drilling)
- *Creating reservoir*
- *Sustaining reservoir*
- *Environmental issues (e.g. seismicity)*

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

Understanding T H M C is key:
- Size of relative effects of THMC
- Timing of effects
- Migration within reservoir
- Using them to engineer the reservoir

{ Permeability
Reactive surface area
Induced seismicity

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



Relevance/Impact of Research

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Needs: $\dot{H} = \dot{M}_f \mathrm{D} T_f c_f$

- Fluid availability
  - Native or introduced
  - $H_2 0/CO_2$ working fluids?
- Fluid transmission
  - Permeability microD to mD?
  - Distributed permeability
- Thermal efficiency
  - Large heat transfer area
  - Small conduction length
- Long-lived
  - Maintain mD and HT-area
  - Chemistry
- Environment
  - Induced seismicity
  - Fugitive fluids
- Ubiquitous

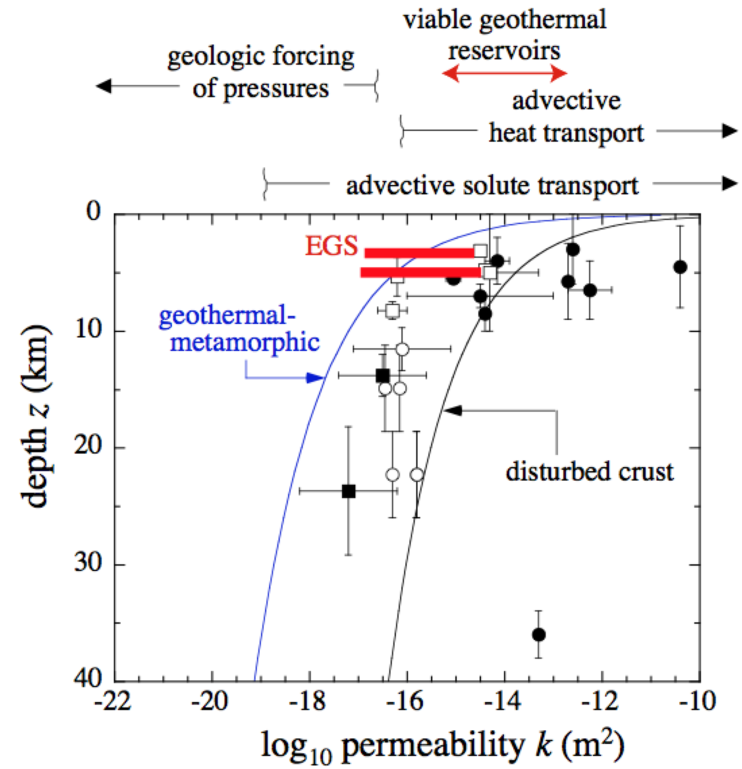

Figure 12: Evidence for relatively high crustal-scale permeabilities showing showing power-law fit to data. Geothermal-metamorphic curve is the best-fit to geothermal-metamorphic data [*Manga and Ingebritsen*, 1999, 2002]. "Disturbed-crust" curve interpolates midpoints in reported ranges in *k* and *z* 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]

Relevance/Impact of Research

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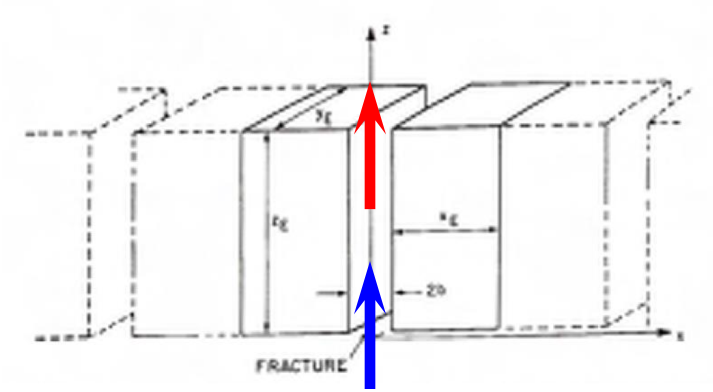
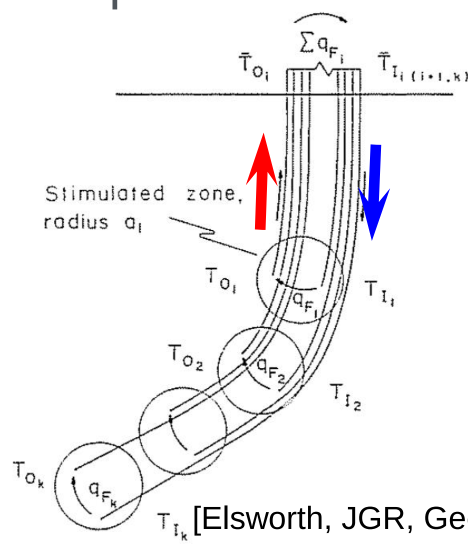
Parallel Flow Model

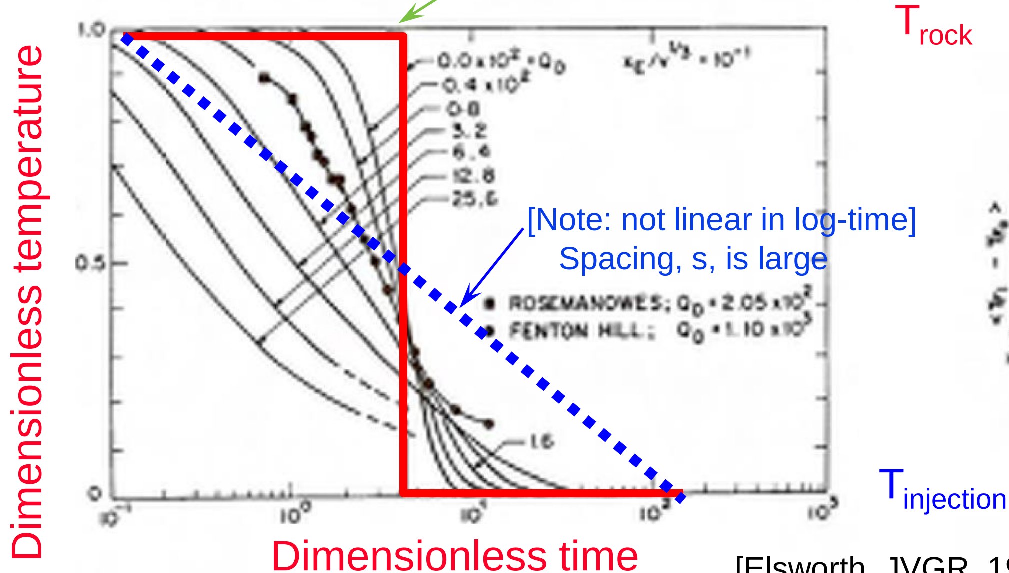


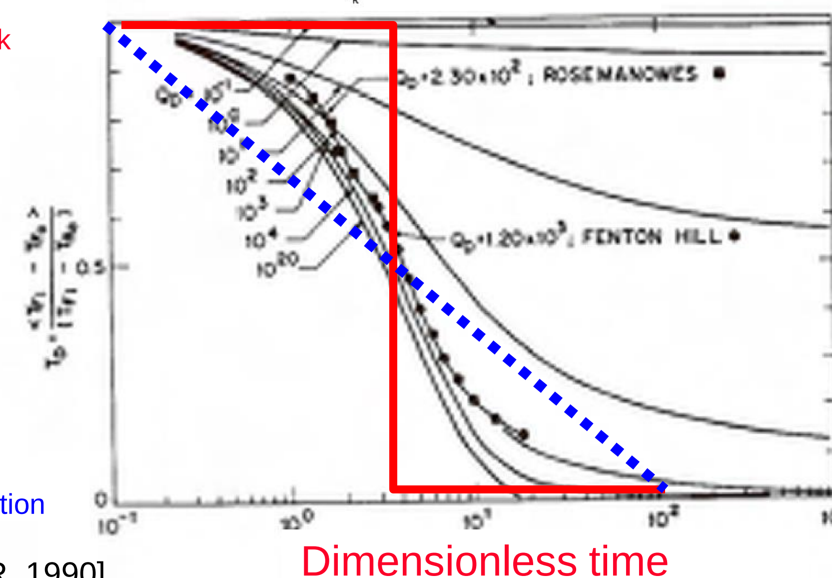
[Gringarten and Witherspoon, Geothermics,1974]

Multiple Zone Spherical Reservoir Model



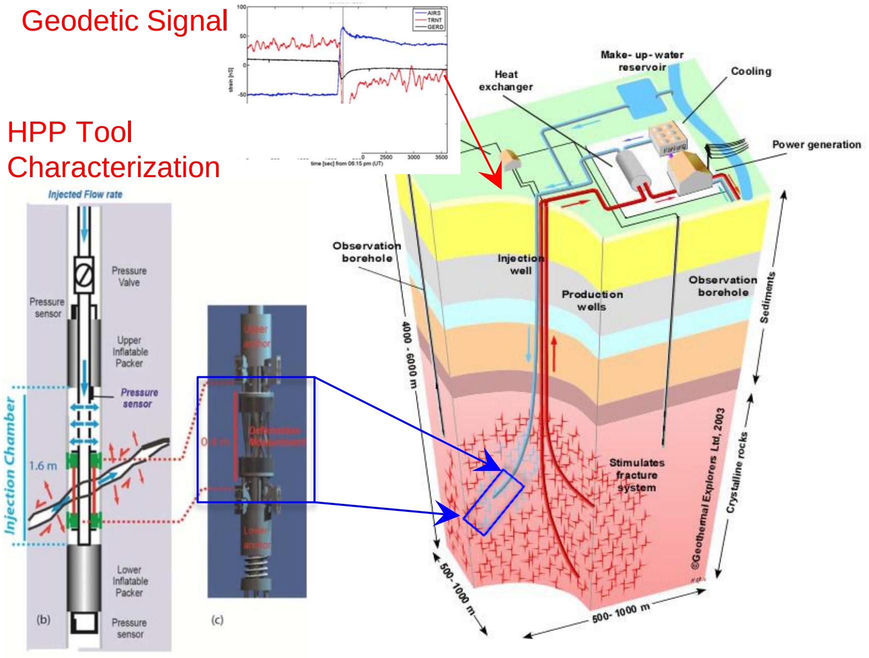
[Elsworth, JGR, Geothermics 1989]





[Elsworth, JVGR, 1990]

Scientific/Technical Approach



Summary: Extend the HPP borehole tool to measure reservoir characteristics at 300C and 100 MPa and constrain reservoir evolution through real-time borehole and surface geodesy.

Impact: Enable real-time measurement and management of reservoir evolution.

Key Idea: Constraining reservoir flow paths through borehole tool characterization and subsurface and surface geodesy.

Objective: We will explore the utility of combining active downhole experimentation with borehole and surface geodesy to determine both the characteristics and evolving state of EGS reservoirs both prior to stimulation and during production.

Approach: In this work we propose to:

- **Task 1:** Determine the feasibility of utilizing the hydraulic pulse protocol (HPP) borehole tool at temperatures to ~300C and at rock stresses to ~100 MPa to measure key reservoir characteristics related to fluid transmission, heat transfer and the propensity for induced seismicity – and zonal control.
- **Task 2:** Determine the feasibility of extending the HPP tool to measure thermo-mechanical and chemo-mechanical characteristics of fractures, *in situ*, to project the evolution of flow, heat transfer and seismicity in time and to do this at both high temperature and stress.
- **Task 3:** Determine the improvement in resolution of flow paths within the reservoir that are afforded by continuous measurements of borehole strain along uncased portions of reservoir-penetrating borehole(s). And,
- **Task 4:** Examine the potential for combining multi-modal surface geodesy (deformation, strain, tilt and seismics) with parameters recovered from the HPP borehole tool (*e.g.* fracture permeability, deformability and stress), and continuously measured fluid injection and recovery rates to image flow structure of EGS reservoirs, *in vivo*.

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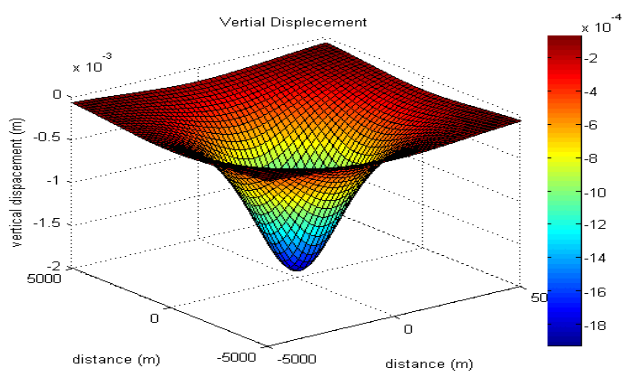
Reservoir Monitoring by Surface Geodesy

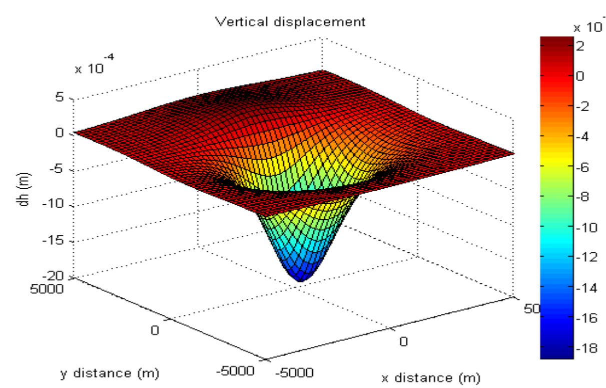
- Useful in defining active processes in reservoir evolution (flow and temperatures via thermal strains)
- We can monitor (modalities and causes)
  - Volume change
    1) Thermal contraction - heat energy transfer from rock to fluid
    2) Volume increase due to pressurization
  - Shear slip (Fault reactivation) : evolution of major flow path / monitoring induced seismicity

Volume change (Mogi Solution)

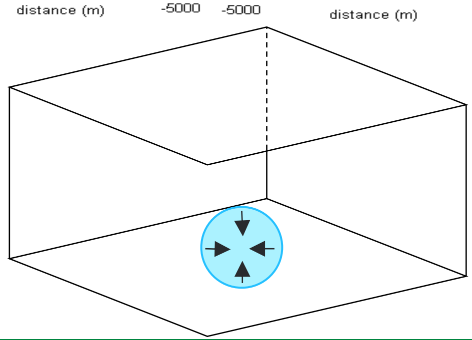
Slip deformation (Okada Solution)

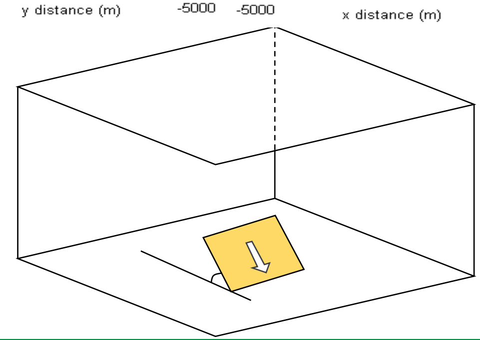
Vertical displacement on surface





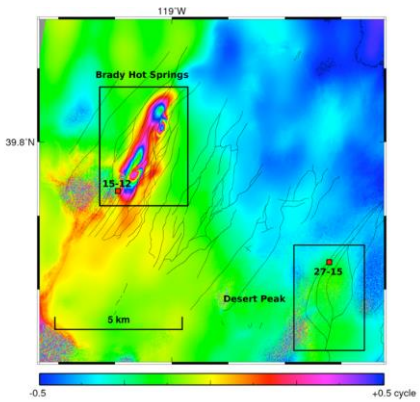
Subsurface deformation



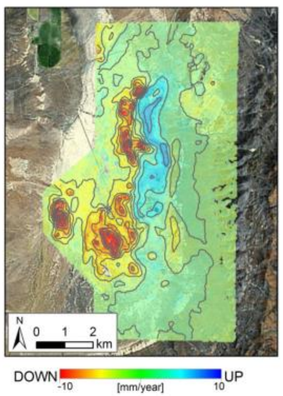


Correlations of observed surface deformation with source

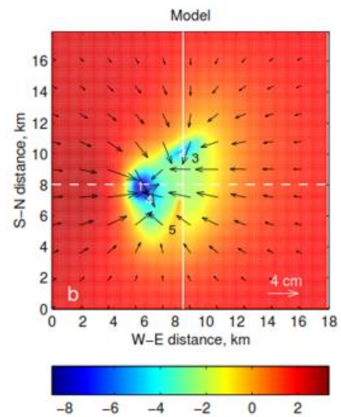
Surface displacement measured by InSAR



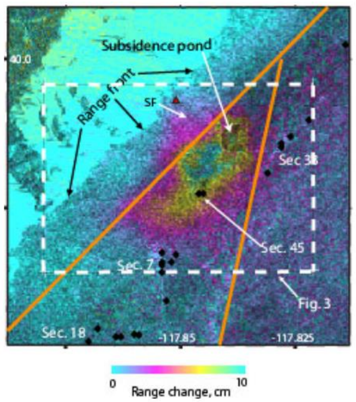
Brady and Desert peak [Ali, 2014]



San Emidio [Falorini, 2011]

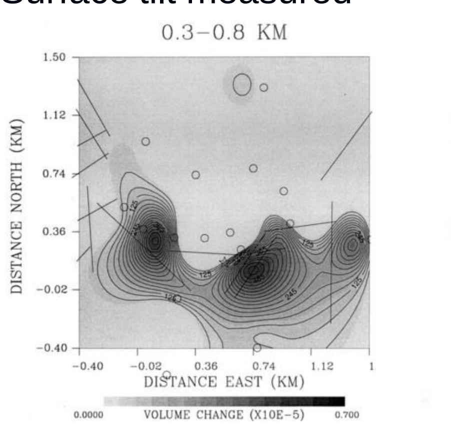


Coso [Fialko, 2000]

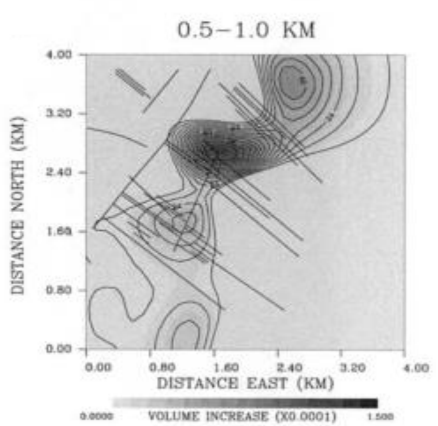


Dixie Valley [Foxall, 2003]

Surface tilt measured



Inverted subsurface volume change in Hijiori, Japan [Vasco, 2001]



Inverted subsurface volume change in Okuaizu, Japan [Vasco, 2001]

Measured deformations are larger than the source volumes reasonably expected from volumetric sources alone.

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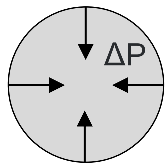
Deformation of Constrained Reservoir

Reservoir (fractured)

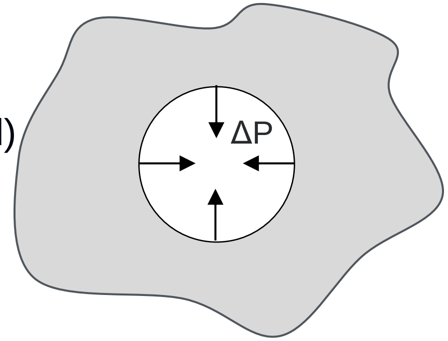


Elastic modulus for fractured rock

$$\frac{1}{E_{res}} = \frac{1}{E} + \frac{1}{k_n S}$$

$$\frac{\Delta V}{V} = \frac{1}{K_{res}} \Delta P = \frac{3(1-2\nu)}{E_{res}} \Delta P$$

Host rock (un-fractured)



$$\frac{\Delta V}{V} = \frac{3}{4G_{host}} \Delta P = \frac{3(1+\nu)}{2E_{host}} \Delta P$$

Volume modulus for reservoir + surrounding rock is $K_{res} + \frac{4G_{host}}{3}$

Volumetric strain from thermal contraction becomes:

$$\frac{\Delta V}{V} = \frac{\Delta P}{K_{res} + \frac{4G_{host}}{3}} = \frac{\alpha_v \Delta T}{1 + \frac{4G_{host}}{3K_{res}}} = \frac{1}{1 + \frac{2(1-2\nu)}{(1+\nu)} \frac{E_{host}}{E_{res}}} \alpha_v \Delta T$$

$$\Delta P = K_{res} \alpha_v \Delta T$$

Constrained volumetric strain ratio (ν=0.25 assumed)

E_{res}/E_{host}	Deformation Ratio	Mode
1.00	0.56	1. Fully coupled
0.50	0.38	2. Soft inclusion
0.10	0.11	Very Soft
0.01	0.01	Extremely Soft

Reservoir and host rock decouples when

$$\frac{\Delta P}{K_{res} + \frac{4G_{host}}{3}} = \frac{3\sigma}{4G_{host}} \quad \Rightarrow \quad \Delta P = K_{res}\alpha_v \Delta T = \left(\frac{3K_{res}}{4G_{host}} + 1\right)\sigma = \left(\frac{E_{res}}{E_{host}} \frac{(1+\nu)}{2(1-2\nu)} + 1\right)\sigma$$

(σ is far field stress)

3. Detaching inclusion

Subsurface Volume Change from Thermal Contraction

- $$\frac{\Delta V}{V} = \frac{1}{1+\frac{2(1-2\nu)}{(1+\nu)}\frac{E_{host}}{E_{res}}}\alpha_v \Delta T \sim 0.56\alpha_v \Delta T$$ (for v=0.25 and E_{host}=E_{res})

- Equating heat energy loss in rock and heat energy gain in fluid, we can recover rate of thermal volume change

$$\alpha_v \Delta T_r = \alpha_v \frac{\rho_f c_f}{\rho_r c_r} Q_f \Delta T_f$$

[ρ_f: fluid density, c_f: fluid specific heat, ρ_r: rock density, c_r: rock specific heat, Q_f: flow rate, ΔT_f: fluid temperature change between injection and production]

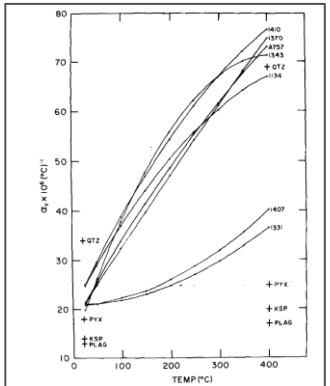


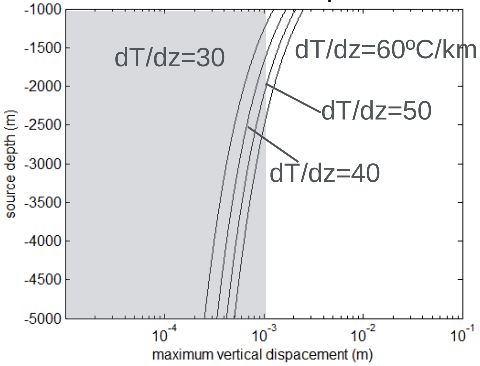
Fig. 1. Volume coefficient of thermal expansion versus temperature. The numbers at the right side of the graph are the sample numbers. The mineral data are from Skinner [11].

themal expansion [Cooper, 1977]

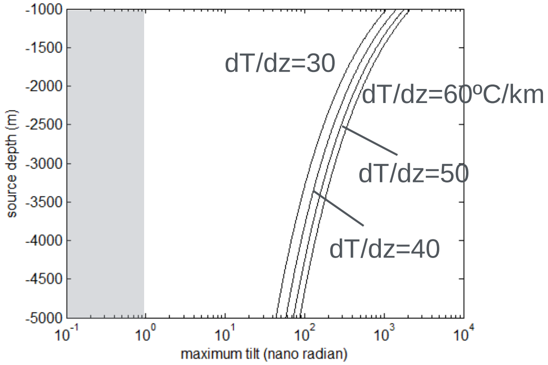
Surface Deformation (Mogi Solution)

- Maximum surface deformations from thermal contraction
  - 1 year operation with flowrate Q_f=0.1m^3/s
  - ΔT_f is calculated from various geothermal gradients
  - Other assumptions : $(\rho_f c_f)/(\rho_r c_r)$=2, α=5x10^{-5}/K, v=0.25 and E_{host}=E_{res}
  - Results (gray area : un-resolvable with current tool)

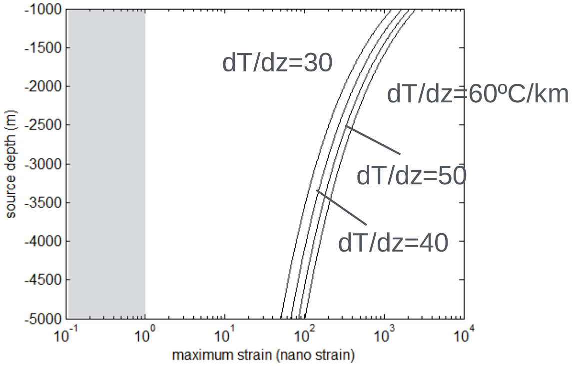
Maximum vertical displacement



Maximum tilt



Maximum radial strain

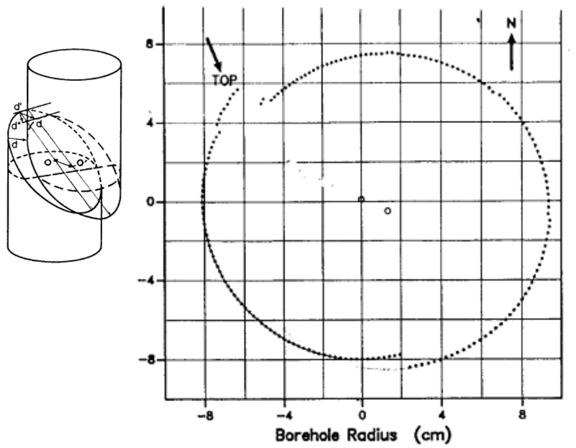


→ Tilt and strains are generally detectable (>1 nano radian, >1 nano strain) while vertical displacement is not (<1mm)

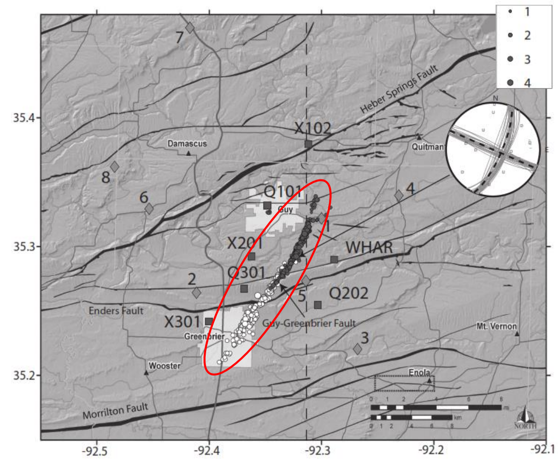
Accomplishments, Results and Progress
Tasks 4 & 3: Surface and Borehole Geodesy

Subsurface Shear Deformation

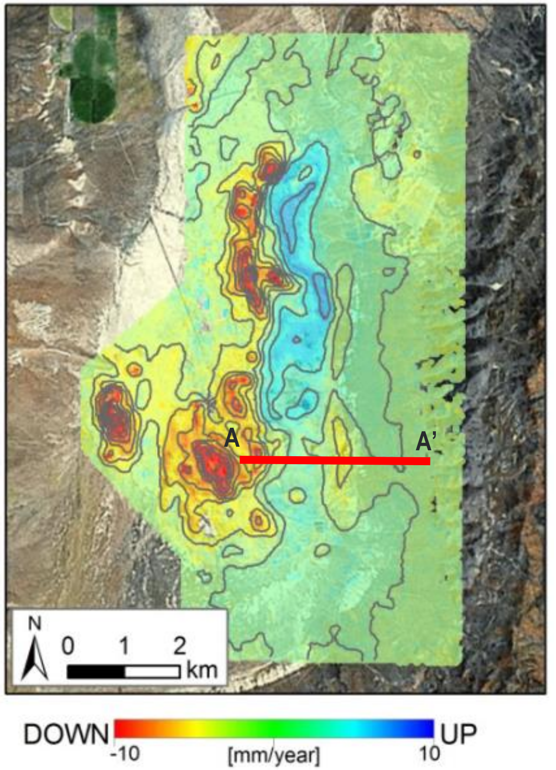
- Single MEQs are generally too small to create significant surface deformation
- Multiple seismic event + aseismic slip accumulation in a fault zone would induce considerable slip offset
    - Borehole diameter at Soultz project indicated over 4cm aseismic slip
    - Seismicity trend sometimes implies multiple event accumulation in single fault plane
    - Asymmetric surface deformation can be observed (may induced by high angle dipping slip)
    - Tiltmeter response in Hijiori and Okuaizu in Japan was excessively large to be explained by subsurface volume change
    - Aspect of surface deformation look closely related to pre-existing fault zones



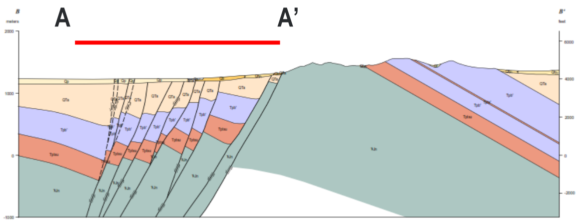
Slip measurement by borehole diameter at Soultz. Maximum calculated slip : 4.7cm [Cornet, 1997]



MEQ trends (gray and white circle) induced by Arkansas Disposal Well [Horton, 2012]



Vertical displacement in San Emidio Geothermal Field [Falorini, 2011]



West – East cross section [Rhodes, 2011]

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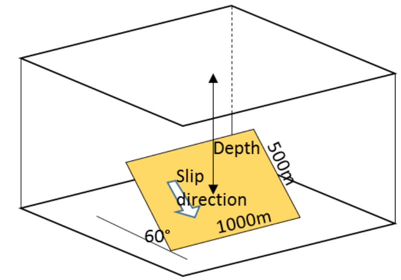
Shear-Slip Induced Surface Deformation

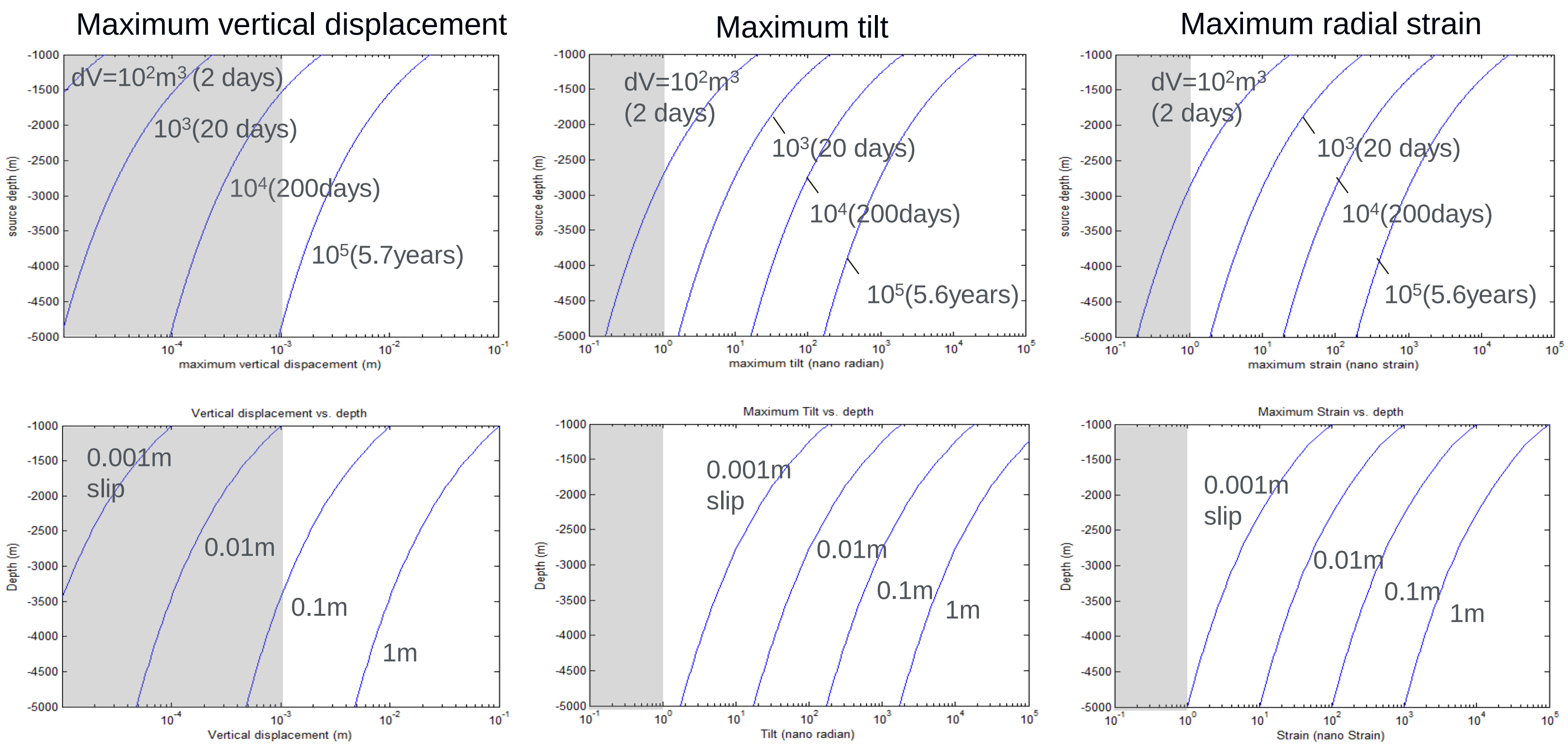
- More detailed deconvolution of subsurface deformation can be achieved by tilt and strain
- Advantage of surface geodetic instrument : High resolution (+ Dense sampling interval that records short term behavior)



Fault geometry assumption for slip

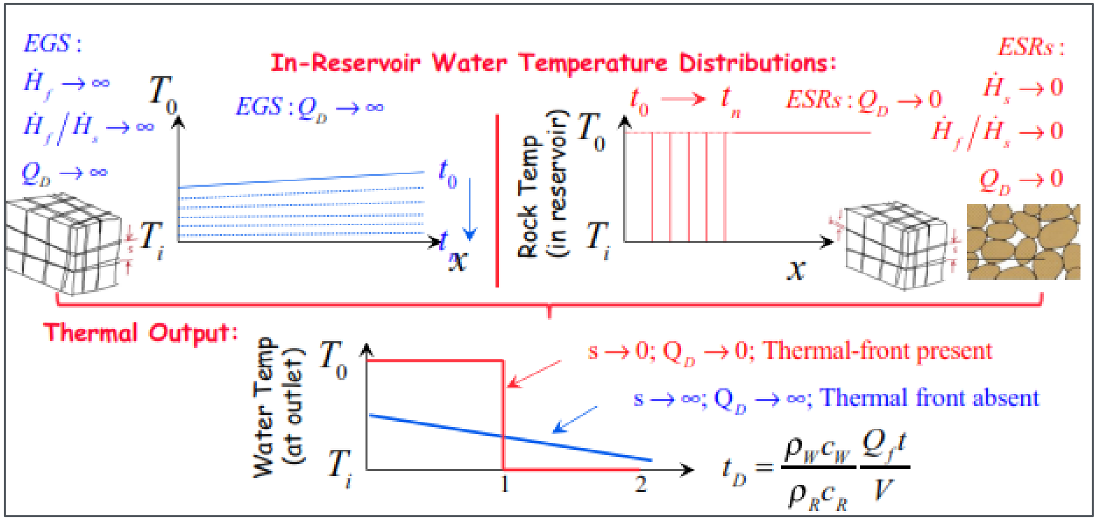
Volume Change
():equivalent period for Heat production
·Q_f=0.1m³/s
·ΔT=100ºC
·$(\rho_f c_f)/(\rho_r c_r)$=2
· α=5x10⁻⁵/K
· ν=0.25
· $E_{host}=E_{res}$

Slip



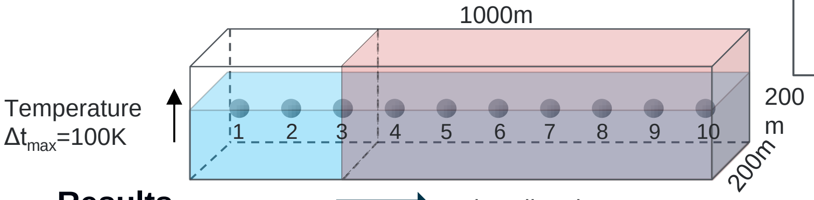
* Gray area represents unresolvable resolution with current tool (~0.001m, ~1nano-radian, ~1nano-strain)

Spatial Resolution of Volume Change (Thermal front present vs. absent)

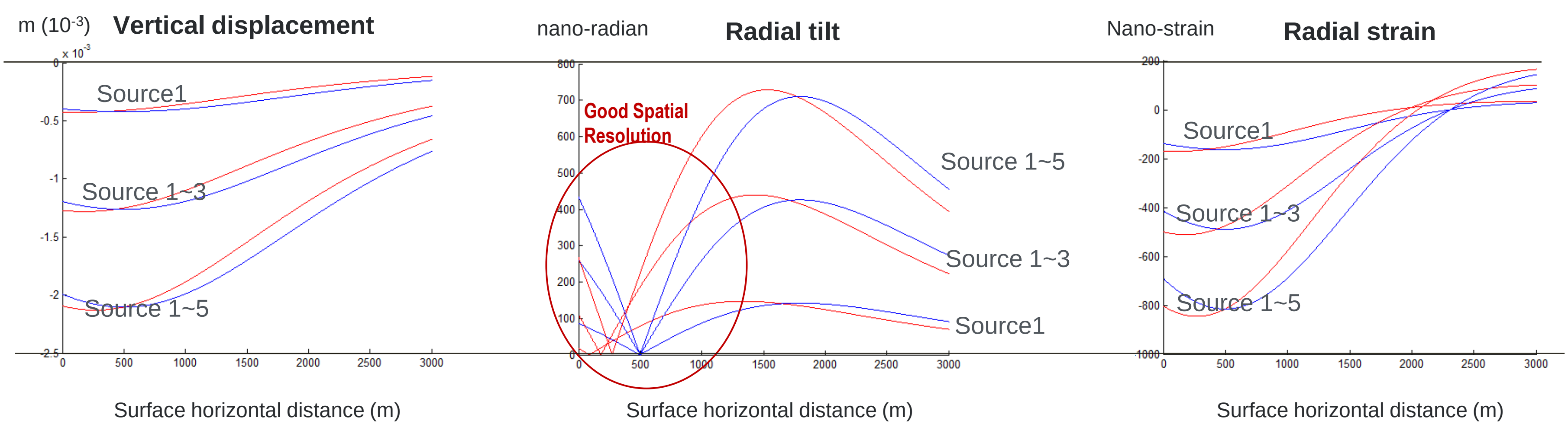


Model Description

1000m x 200m x 200m reservoir in10 sections
Red: Thermal front in reservoir
Blue: Uniform thermal drawdown
Equivalent thermal output and superposed Mogi
Depth: 2500m, v=0.25, $E_{host}=E_{res}$ and $\alpha_v=5\times10^{-5}$



Results



Accomplishments, Results and Progress
Task 1: Hot-HPP Tool Feasibility

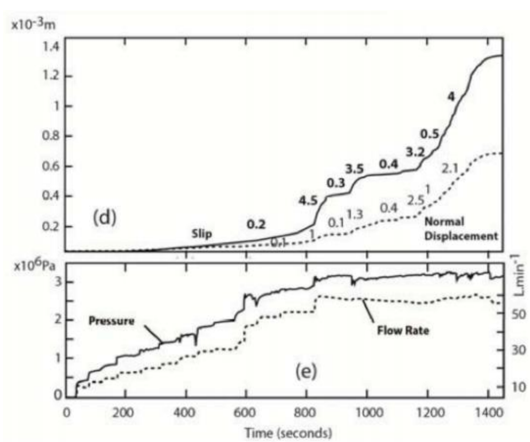
Borehole Deformation Sensor (HPP, Hydraulic Pulse Protocol)

Tool description

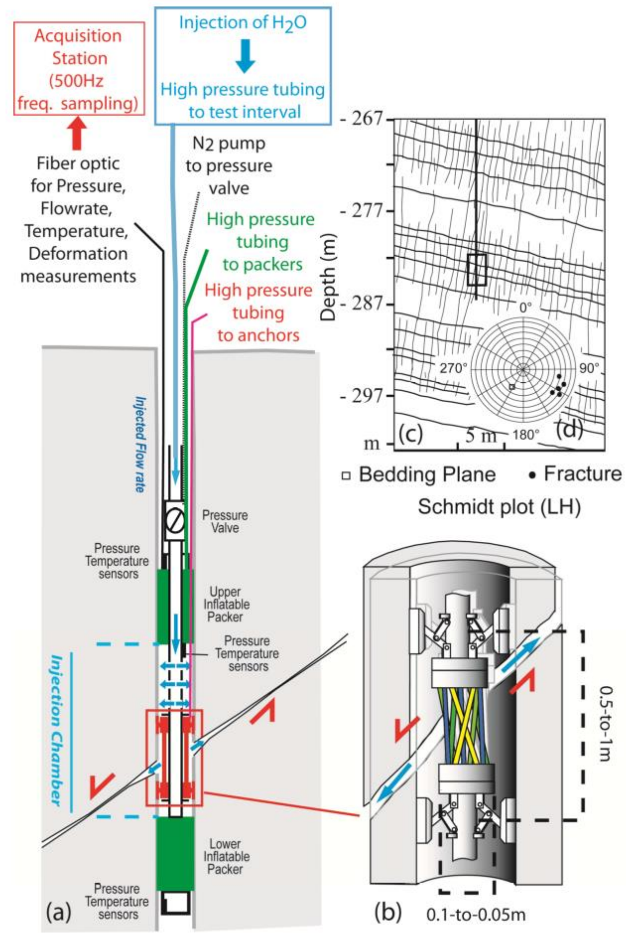
- Packs-off zone available for inflow testing
- Measures concurrent deformations during step tests
- Resolution to micrometer in normal and shear mode
- Monitoring and DAQ at surface (ambient temp)
- Current capabilities (15 MPa and +100C)

Tool Needs

- Elevate endurance to 100 MPa and 300C
- Develop protocols for:
  - Initial state (stress, temp, perm)
  - Evolving fracture rheology, stability, permeability
- Define how these (and other) key characteristics of the reservoir will evolve with action of stress, temperature and chemistry



Step Pressurization and Displacement Response



Schematic representation of HPP tool

Future Directions

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Schedule of Tasks and Milestones	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
						Year 1						
*Milestones M1 at end of Quarter 1 Q1, etc.			Q1			Q2			Q3			Y1
Task 0 Cost and resource allocation for GDR/NGDS	x											
Task 1: Necessary modifications to HPP Borehole Tool for 300C and 100 MPa												
1.1 Define current tool capabilities												
1.2 Scope specifications of sensors for 300C and 100 MPa			M1*									
1.3 Define additional sensors for Task 2												
1.4 Complete scoping design for revised tool												
Task 2: Develop Protocols for Extended Parameters to be Recovered from the HPP Tool												
2.1 Existing protocols for stress and permeability												
2.2 Protocols for friction and slip stability parameters (a-b)												
2.3 Protocols for strain partitioning between fractures and matrix (inversion)												
2.4 Protocols for permeability evolution with thermal stress									M3			
2.5 Protocols for permeability evolution with chemical potential												
Task 3: Determine Constraint of Reservoir Flow Evolution from Borehole Geodesy												
3.1 Develop models for plug-flow and uniform temperature reservoir strains												
3.2 Determine borehole strain ranges for reservoir drawdown												
3.3 Develop coupled model to determine borehole strain magnitudes						M2						
Task 4: Determine Constraint of Reservoir Flow Evolution from Surface Geodesy												
4.1 Determine surface displacement/strain/tilt ranges for reservoir drawdown						Go/Ngo						
4.2 Develop coupled model for coinversion of surface-measured data												
4.3 Extend model to flow evaluation									M3			
4.4 Coinvert model for permeability evolution using synthetic data												
4.5 Use multiple data sets to improve inversions for reservoir permeability and state												
Group meetings						x						x

Summary Slide – Key Points

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- **Surface Geodesy (Task 4)**
  - Surface strains and tilt resolvable from volumetric/shear deformations but surface displacement of lower resolution
  - Surface strains and tilt have good spatial resolution to describe permeability evolution progress in reservoir
  - Constrained deformation + reservoir decoupling reduces signal and limits maximum deformation - but sufficiently large to describe the reservoir behavior
  - Fault reactivation → detectable slip which would act as a major flow path (by seismic and aseismic slip stacking in a fault zone)
  - Slip causal mechanisms distinguished by:
    - Timing : Contractile volume change continuous and gradual while shear slip would be relatively episodic and rapid, and,
    - Shape : Surface deformation from subsurface slip is generally more asymmetric and intense.
- **Sub-Surface Geodesy (Task 3)**
  - Downhole measurements circumvent some of these resolution issues
  - Requires instrumentation or tool to accomplish this
  - Tasks 4 & 3 essentially complete
- **Hot HPP Tool Feasibility (Task 1)**
  - Evaluation to begin Q2
  - Some principal issues
    - Limits on fiber optics (temperature and clouding)
    - Limits on packers and work-arounds

Additional Information

Selected Publications (2014 & 2015) [www.ems.psu.edu/~elsworth/publications/pubs.htm]

1. Im, K.J., Elsworth, D., Guglielmi, Y., Mattioli, G. (2015) Geodetic constraints on the evolution of flow and transport behavior of EGS reservoirs. Proc. 49th US Symposium on Rock
2. Fang, Y., Elsworth, D., Cladouhos, T. (2015) Mapping permeability tensors in fractured reservoirs using MEQ data. Proc. 49th US Symposium on Rock Mechanics and Geomechanics. San Francisco. June 29-July 1.
3. Gan, Q., Elsworth, D. (2015) A continuum model for coupled stress, fluid flow and heat transfer in discrete fracture networks. Proc. 49th US Symposium on Rock Mechanics and Geomechanics. San Francisco. June 29-July 1.
4. Elsworth, D., Gan, Q., Fang, Y., Pogacnik, J., Taron, J., Izadi, G., Guglielmi, Y., Im, K.J., Ishibashi, T. (2015) Control of permeability and seismicity – keys to the successful development of EGS reservoirs. Proc. 10th Anniversary Int. Symp. of the Center of Environmental Science and Disaster Mitigation for Advanced Research, Muroran, Japan, March 13-14.
5. Im, K.J., Elsworth, D., Fang, Y. (2015) Asymptotic analysis of thermal stimulation of geothermal reservoirs. Proc. 40th Workshop on Geothermal Reservoir Engineering, Stanford, California Jan 26-28. SGP-TR-204.
6. Fang, Y., Elsworth, D., Cladouhos, T. (2015) Estimating in-situ permeability of stimulated EGS reservoirs using MEQ moment magnitude: an analysis of Newberry MEQ data. Proc. 40th Workshop on Geothermal Reservoir Engineering, Stanford, California Jan 26-28. SGP-TR-204.
7. Gan, Q. and Elsworth, D. (2015) Fault reactivation due to thermal drawdown in enhanced geothermal reservoirs. Proc. 40th Workshop on Geothermal Reservoir Engineering, Stanford, California Jan 26-28. SGP-TR-204.

Invited Presentations

2015: Int. Symp. Envt. Sci. and Disaster Management, Muroran, Japan

2014: AGU; ETH Zurich