



Detection and Characterization of Natural and Induced Fractures for the Development of Enhanced Geothermal Systems

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GO18190

– **Timeline**

- 10/1/2008-9/30/2011
- Up to date, ~50% of project completed

– **Budget**

- Total project funding: \$1,279,969
 - DOE share: \$1,019,769; Awardee share: \$260,000
- Funding received in FY09 (10/1/08 to 9/30/09)
 - DOE share: \$229,204; Awardee share \$76,694 (25.07%)
- Funding for FY10 (10/1/09 to 9/30/10)
 - DOE share: \$484,832; Awardee share: \$105,200

– **Barriers**

- **Site characterization:** Development of advanced geophysical methods for determining EGS reservoir properties and resource assessment.
- **Reservoir validation:** Detection and imaging of natural and induced fractures for successful EGS development

– **Partners:** ENEL/North America and New England Research, Inc.

Project Objectives

- Combine geophysical methods for reservoir and fracture characterization with rock physics measurements made under in-situ conditions (up to 350⁰ C) for development of geothermal systems
- Apply the model to the Cove Fort-Sulphurdale geothermal field in Utah
- Generalize reservoir characterization model for application to other EGS sites

- **Determination of Reservoir Geometry and Properties using:**
 - *Seismic Velocity Tomography*
 - *Seismic Attenuation Tomography*
 - *Magnetotelluric Imaging*
 - *Reservoir Geoproperties from Combined Geophysical Datasets*
- **Fracture Detection and Characterization**
 - *Use Microearthquakes for Fracture Detection, Mapping*
 - *Fracture Imaging Using Generalized Radon Transform*
 - *Characterization of In-situ Stress and Fracture Properties for Reservoir Modeling and Simulation*
- **Laboratory Measurements on Cores at Reservoir Conditions**
- **Joint Interpretation of Laboratory and Field Data for a Detailed Model of the Prospect (Cove Fort)**

1. Collected geological and geophysical data (heat flow, gravity, seismic, and MT) for the geothermal site
2. Generated the subsurface tomographic images for the geothermal site (V_p , V_s , resistivity)
3. Designed apparatus for high temperature/high pressure petrophysical measurements
4. Developed advanced methods for fracture and microseismic event characterization using full waveforms
5. Planned the local seismic network to be installed in 2010

These results helped better characterize the subsurface structure, shape, geophysical properties and temperature of the “body” suitable for EGS and for further development of Cove Fort.

1. Collected Geological and Geophysical Data

Heat Flow Data

Data: SMU

High heat flow and
negative Bouguer gravity
anomaly around the site

Gravity Data

Data: UT El Paso

Legend

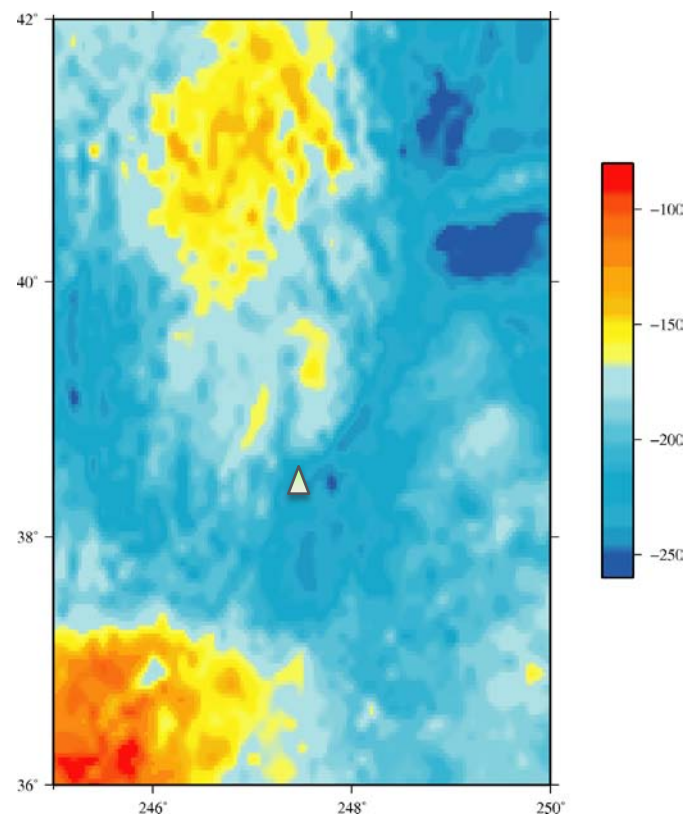
- Cove Fort
- Well Locations

Heat Flow

milliwatts/m²

Filled Contours

- 1 - 59
- 59 - 74
- 74 - 94
- 94 - 142
- 142 - 263
- 263 and above



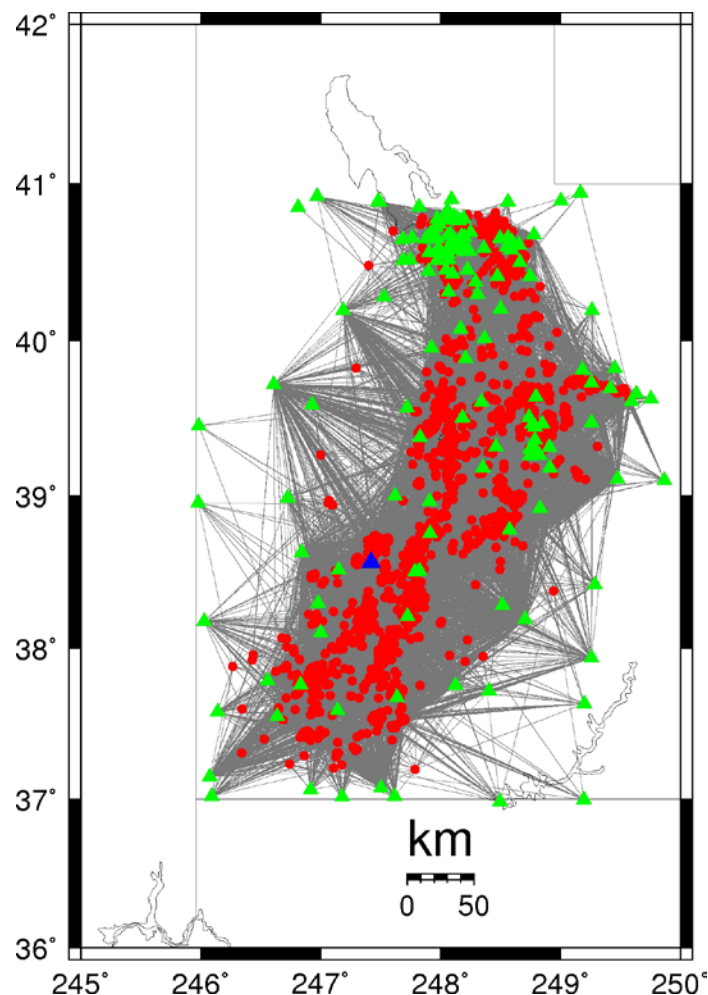
1. Collected Geological and Geophysical Data (cont'd)

Seismic Data

Seismic raypaths used for tomography

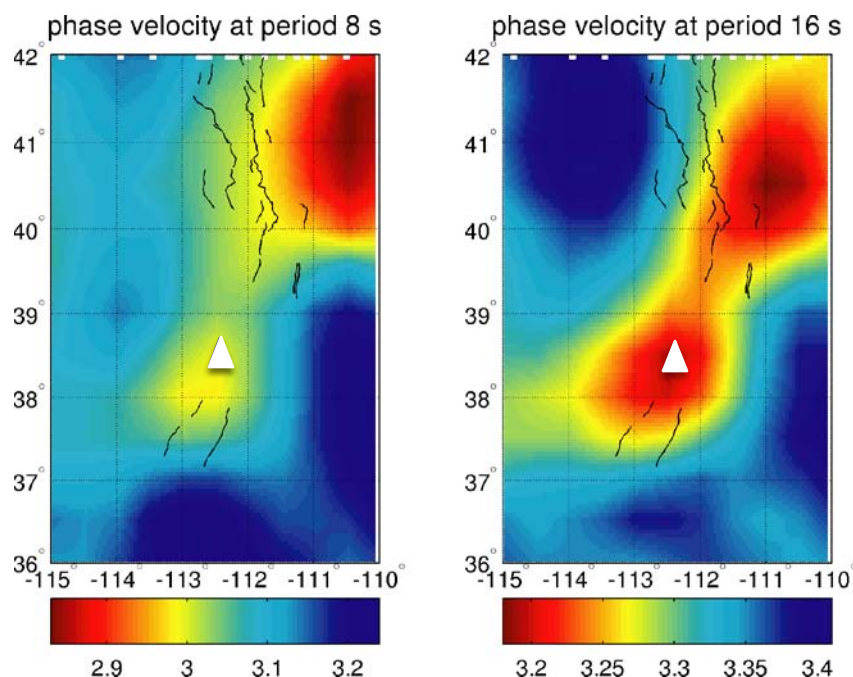
-  Events
-  Stations
-  Cove Fort

(data from Univ. of Utah and IRIS)

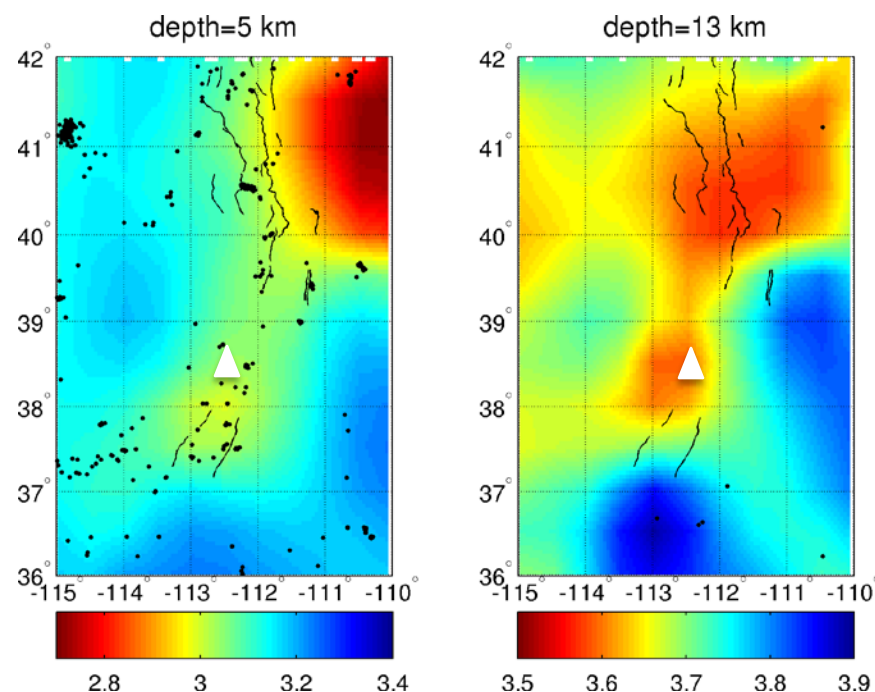


2. Generated subsurface tomographic images

Seismic surface wave phase velocity maps (from Univ. of Colorado)



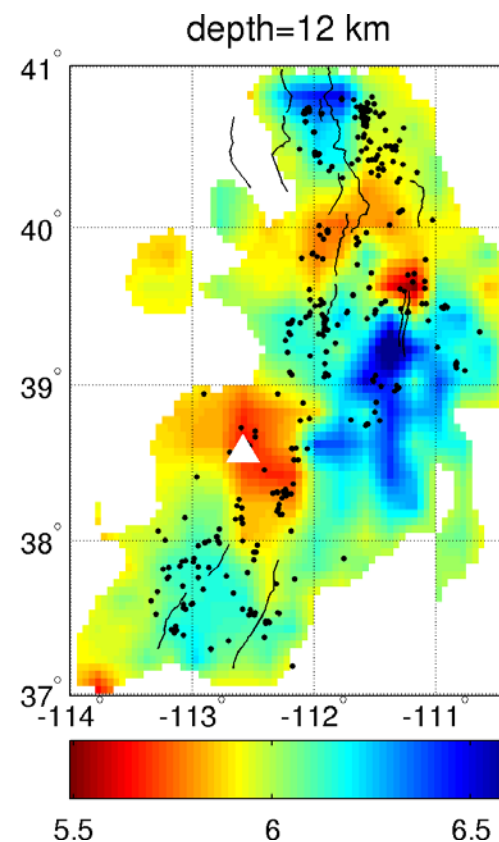
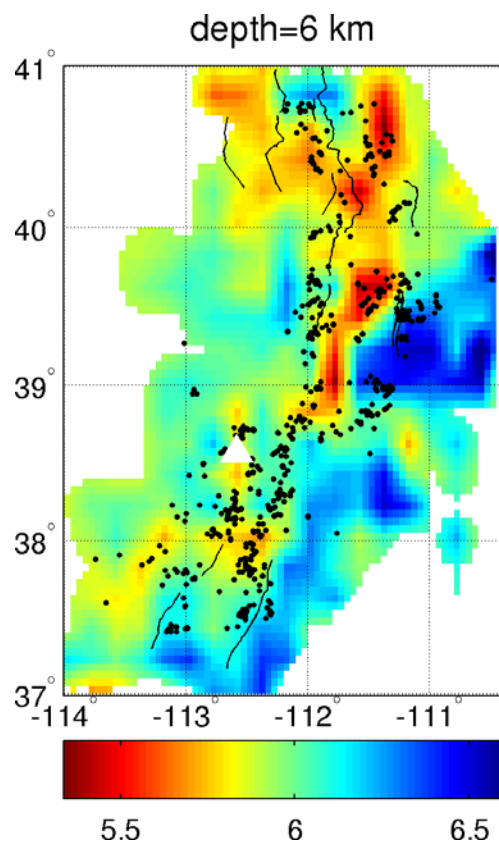
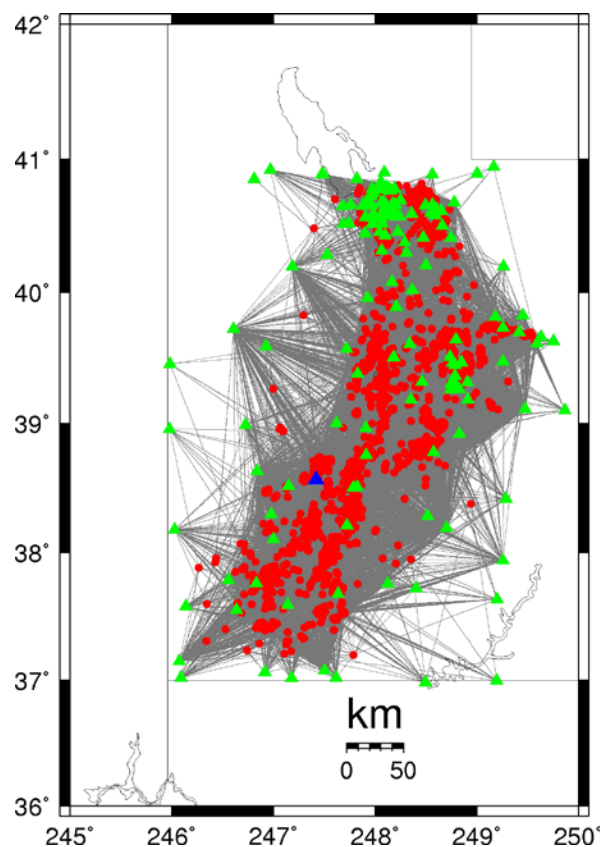
Shear velocities from surface wave inversion



Low velocity anomalies are present beneath the Cove Fort geothermal site.

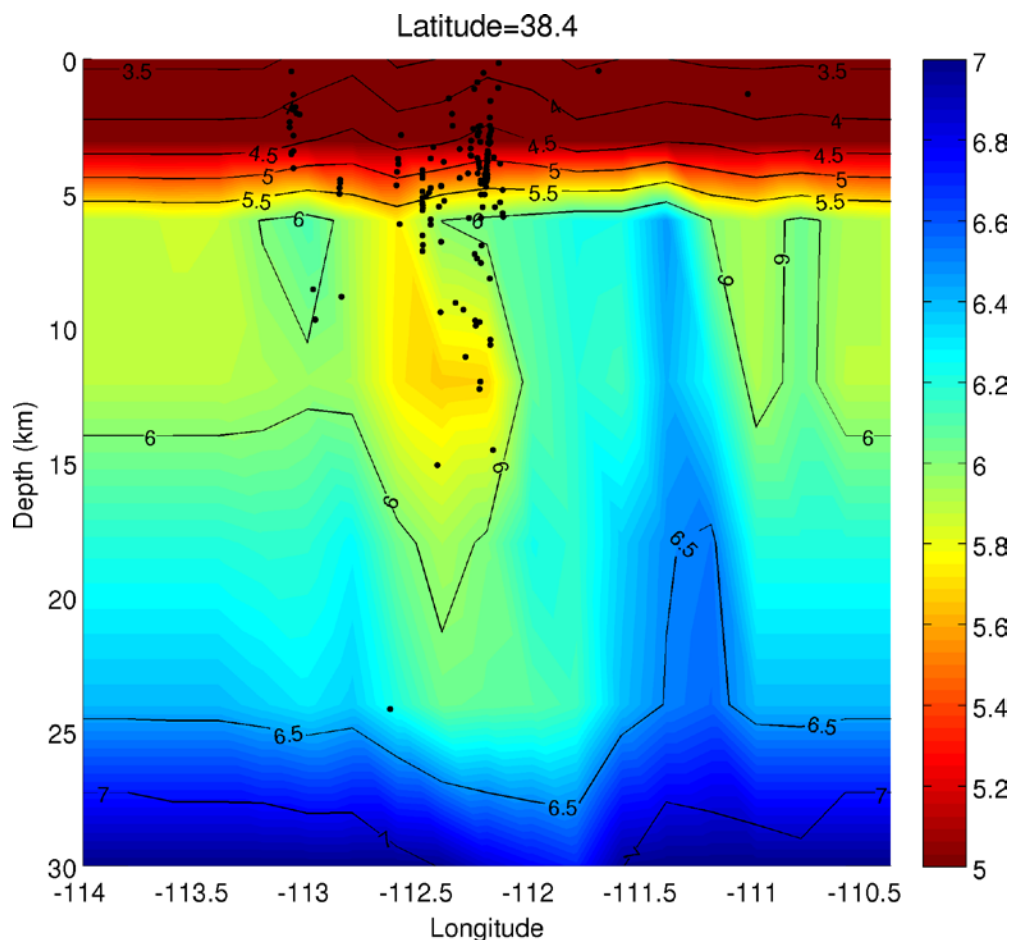
2. Generated subsurface tomographic images (cont'd)

Vp (body wave) model from double-difference seismic tomography



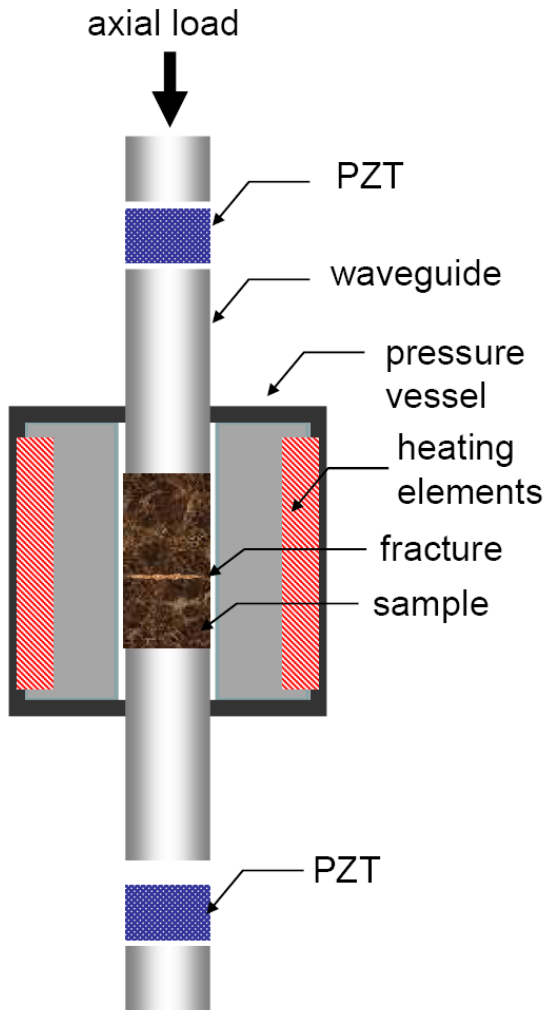
2. Generated subsurface tomographic images (cont'd)

Cross Section of Vp velocities under Cove Fort



At depths between ~5 to ~15 km beneath Cove Fort, there exists a low velocity anomaly, indicating high temperature

3. Developed apparatus for high P,T petrophysical measurements



$$T_{\max} = 350^{\circ} \text{ C}$$

Lateral stress from
confining liquid/gas

$$\sigma_{\text{axial}} = P_{\text{confining}}$$

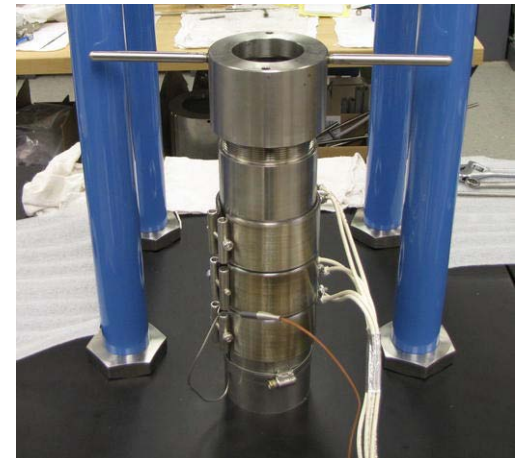
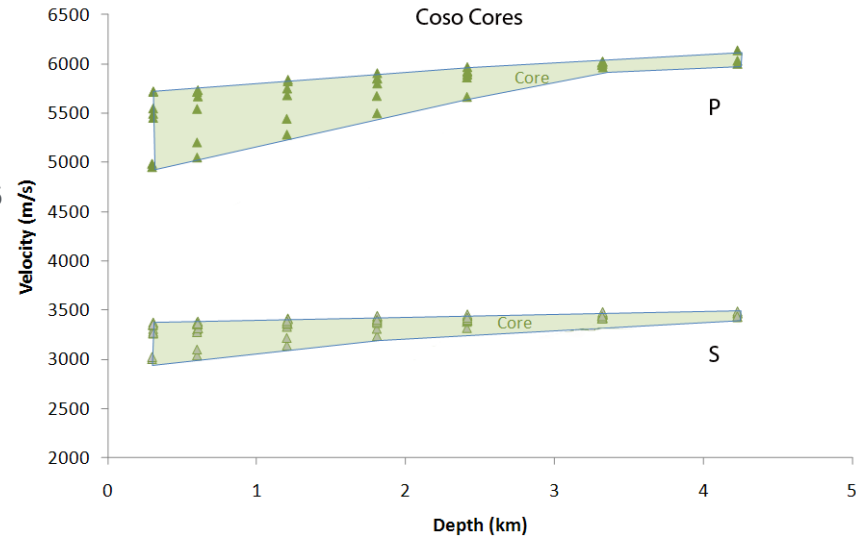
Configuration:

Velocity

Fracture Conductivity

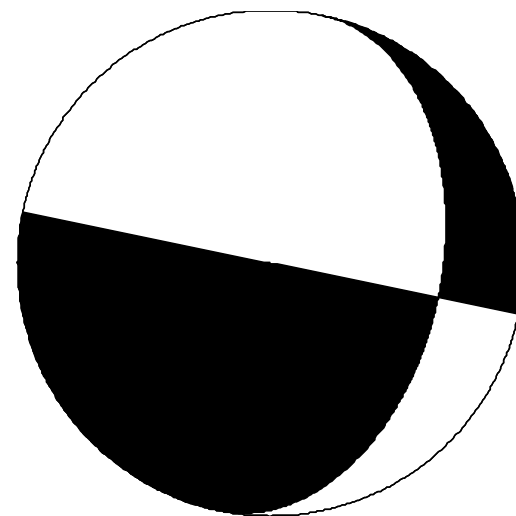
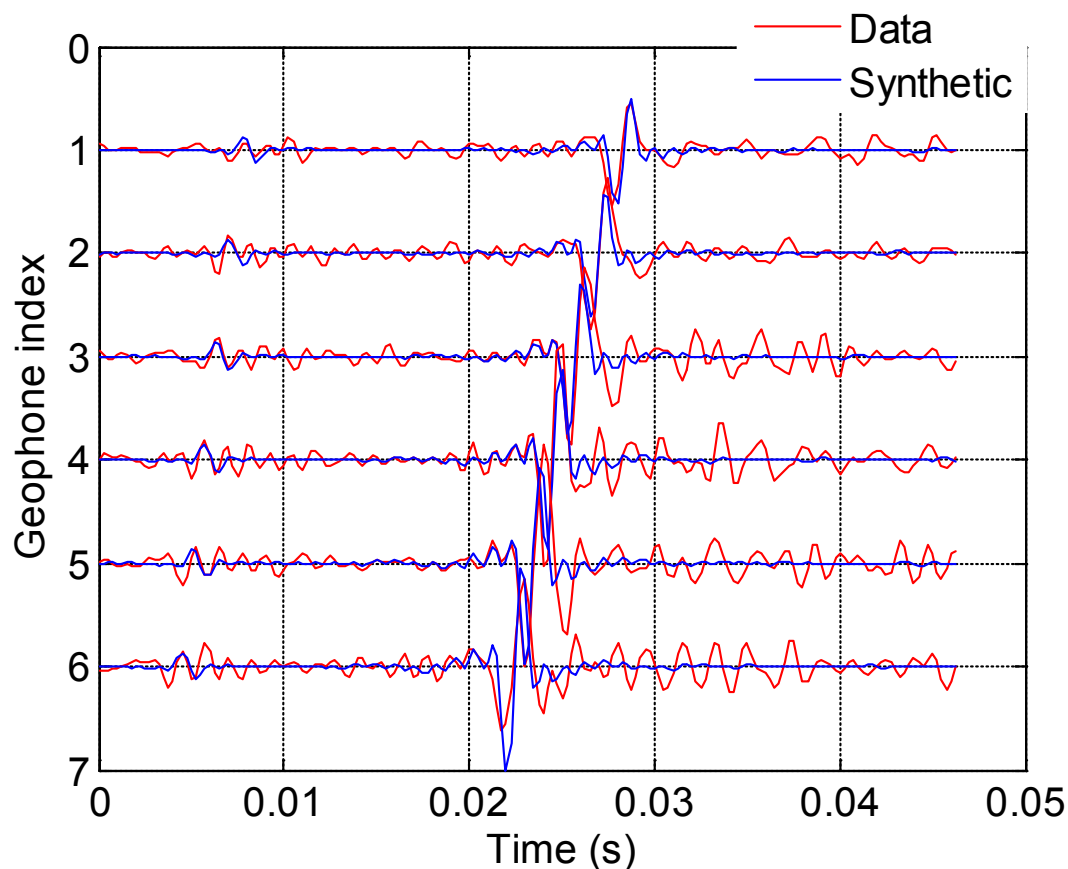
Fracture healing

Fracture stiffness



4. Developed methods for microseismic source mechanisms and fracture characterization

Determine stress regime and fracturing mechanism from microseismic waveform analysis

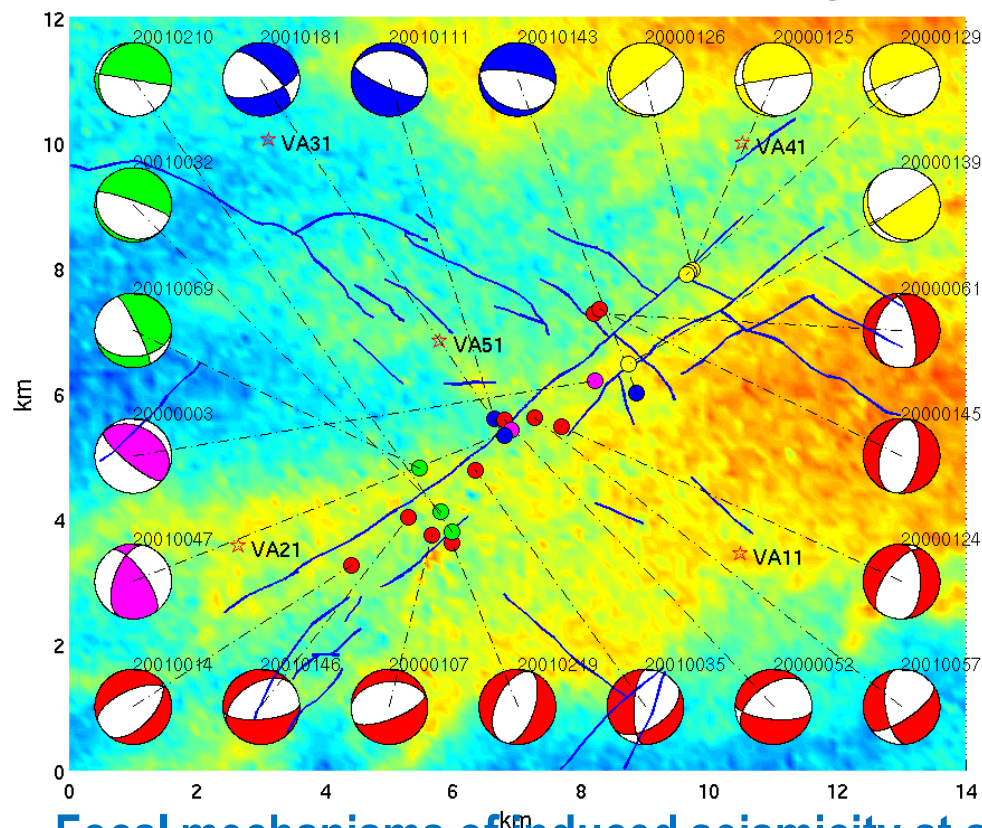


Moment magnitude: -2.9
Stress drop: 52 Kpa
Isotropic component: -26%
Deviatoric component: 74%
(Strike, dip, rake) = (102, 90, 61) Degrees

Song et al. (2010)

4. Developed methods for microseismic source mechanisms and fracture characterization (cont'd)

Locate and determine focal mechanisms of induced seismicity using high frequency full waveforms



Focal mechanisms of induced seismicity at an oil field using a 5-station network

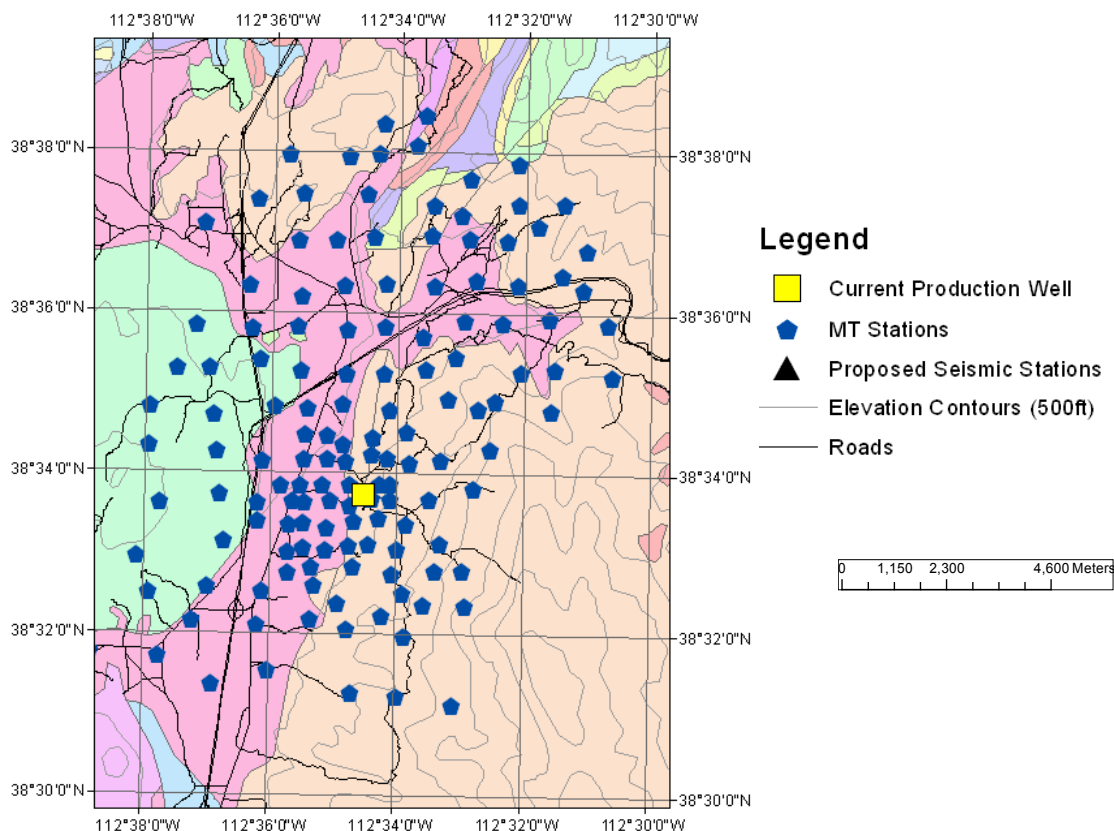
A new method is developed to match high frequency waveforms to determine focal mechanisms of small earthquakes in the case of a sparse station network.

Focal mechanisms give the information on stress regime.

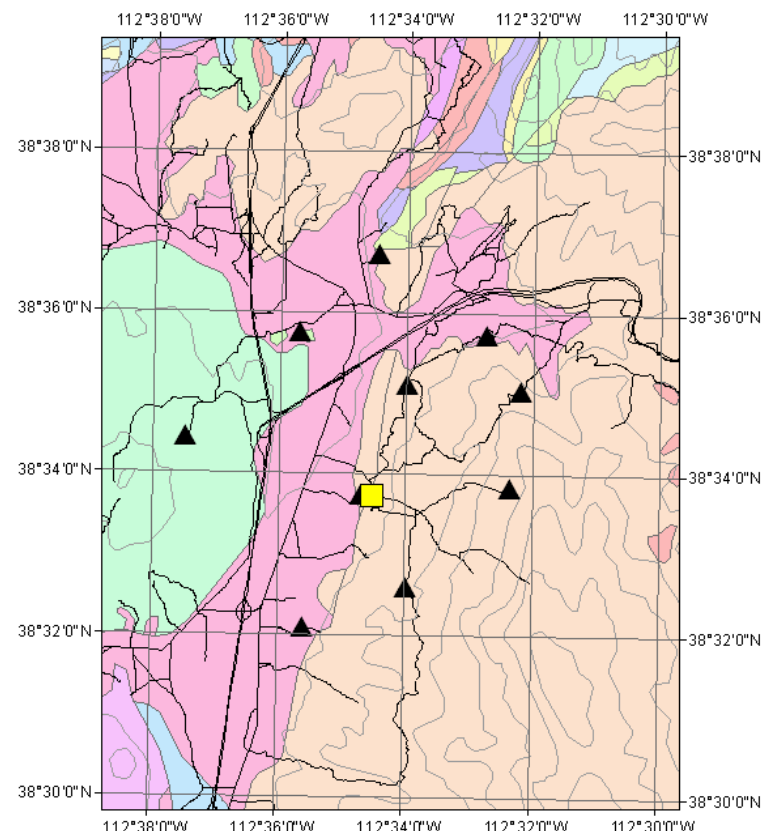
Li et al. (2010), submitted to GJI.

5. Planned local seismic network deployment

MT Network



Seismic Network



- MIT (Cambridge, MA) leading coordination efforts between partners ENEL/NA (Reno, NV and Cove Fort, UT) and NER (White River Junction, VT).
- Communication between MIT, ENEL and NER
 - Regularly scheduled meetings between all partners
 - Special meetings for key field activities
 - Email and phone contact
- Collection of materials for quarterly and annual reports

Tasks		Year 1				Year 2				Year 3			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
I. 3D structure & bulk properties	Gather seismic data	→											
	Generate database		→										
	Seismic Tomography		→										
	Attenuation Anisotropy					→							
	Design and deploy seismic network					→							
II. Fracture detection and imaging	EQ location, microseismic monitoring					→							
	Fracture imaging						→						
III. Joint Inversion & synthesis	Joint Inversion									→			
	Synthesis of Data									→			
	Other sites									→			
IV. Lab Measurements				→									
Annual and Quarterly Reports		Q	Q	Q	A	Q	Q	Q	A	Q	Q	Q	A
Annual Meetings					X				X				X

- Install new seismic stations at Cove Fort for high-density network (Summer 2010)
- Analyze microearthquake data for fracture mapping
 - High-resolution seismic velocity /attenuation tomography
 - Focal mechanisms and in-situ stress regime
 - Fault/fracture imaging
 - Anisotropy and preferred fracture orientation
- Detailed geologic model for surface to 10km depth from joint gravity, seismic and MT inversion
- Petrophysical measurements of core samples
- Synthesize geophysical model and laboratory measurements for defining the resource base at Cove Fort
- Generalize model for application to other potential EGS reservoirs

- Generated tomographic images of the structure under Cove Fort, delineated a “hot body” and regions for potential expansion of the geothermal field
- Developed methods for fracture mapping and characterization using microseismic events
- Designed and manufactured laboratory system for testing reservoir cores under in-situ conditions up to 350⁰C
- With the addition of new microseismic data, we will perform a joint inversion of seismic, gravity, EM and petrophysical laboratory data to generate a high resolution model of the reservoir, its resource potential and targets for expansion.
- The analysis methods developed for Cove Fort are applicable to other sites

Supplemental Slides

- ## Papers

- Zhang, H., P. Wang, R. D. van der Hilst, M. N. Toksoz, C. Thurber, and L. Zhu (2009), Three dimensional passive seismic waveform imaging around the SAFOD site, California, using the generalized Radon transform, *Geophys. Res. Lett.*, 36, L23308, doi:10.1029/2009GL040372.
- Li, J., H. Zhang, H.S. Kuleli, and M.N. Toksoz (2010), Focal Mechanism Determination Using High Frequency Waveform Matching and Its Application to Small Magnitude Induced Earthquakes, submitted to *Geophy. J. Int.*
- Song, F. J. Li, M. N Toksöz, N. R. Warpinski (2010), Downhole Microseismic Monitoring of Hydraulic Fracturing: A Full-waveform Approach For Moment Tensor Inversion And Stress Estimation, submitted to *Int. Journal of Rock Mechanics and Mining Sciences*.

- ## Abstracts

- Zhang, H., M. Maceira, M. N. Toksoz, R. Burlacu, C. Rowe, and Y. Yang (2009), Joint geophysical imaging of the Utah area using seismic body waves, surface waves and gravity data, *Eos Trans, AGU, Fall Meet. Suppl.*, Abstract.
- Zhang, H., M. Maceira, T. Benson, and M.N. Toksoz (2010), Three-Dimensional Joint Geophysical Imaging Using an Advanced Multivariate Inversion Technique: the Method and its Application to the Utah area, United States, *Geophysical Research Abstracts Vol. 12*, EGU2010-5553.
- Toksoz, M.N., H. Zhang, T. Benson, and A. Rael (2010), Geothermal resources exploration and assessment around the Cove Fort-Sulphurdale geothermal field in Utah by multiple geophysical imaging, GRC annual meeting, October 24-27, 2010, Sacramento, CA