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Towards the Understanding of Induced Seismicity in Enhanced Geothermal Systems

Project Officer: Lauren Boyd

Total Project Funding: $1,455,251

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Presenter: Prof. Douglas Dreger (UC Berkeley)

The Problem of Seismicity in EGS Operations

- EGS operations rely on small-scale seismicity to delineate fracture extent, fracture type and pathways for water
- EGS operations need to understand physical connections between reservoir operations and large-sale seismicity
- EGS operations need to avoid large-sale seismicity in places where population would be affected

Questions to be asked:

- Are large-scale (M>3) events of tectonic or geothermal origin?
- If large-scale (M>3) events are of geothermal origin are they triggered or induced?

Improve Understanding of Physics Between Reservoir Operations and Seismicity

- Develop a combination of techniques to evaluate the relationship between EGS operations and the induced stress changes throughout the reservoir and the surrounding country rock
- Investigate relationship between geothermal activities and large-size induced seismicity (M>3)
- Predict maximum magnitude of induced future earthquakes and associated ground motion
- Although The Geysers is not a EGS system, the large database offers the means to develop and test the proposed technology to be applied to future EGS systems to manage and mitigate risk

Approach Integrates Four Techniques to Address Objective of Project

- 4-D Double Difference Tomography for Joint Hypocenter Locations, Vp/Vs-Ratio,Vp & Vs Velocity Structure (Array Information Technology, PI Dr. Roland Gritto)
- Full Waveform Moment Tensor Analysis of Events M>3 (UC Berkeley, Co-PI Prof. Douglas Dreger)
- Geomechanical-Numerical Modeling of Water Injection and Steam Production to Model Stress Evolution in the Reservoir (Helmholtz Centre Potsdam, GFZ, Co-PI Dr. Oliver Heidbach)
- Estimation of Seismic Hazard and Calculation of Potential Ground Motion (Lawrence Berkeley National Laboratory, Co-PI Dr. Lawrence Hutchings)

Data: triggered 3-component data from 34 LBNL short-period stations; continuous broadband data from the BDSN; steam production and water injection data from publicly available wells; available fault data throughout reservoir; regional tectonic stress; GPS deformation information

Seismic Imaging

- Generated database with several 100,000s of events and several 1,000,000s of P- and S-wave travel time picks
- Performed simultaneous double-difference inversion for earthquake hypocenters and 3-D P- and S-wave velocity structure (tomoFDD, Zhang and Thurber 2003)
- Performed 3-D imaging for data from 2005-2011
- Presented example for 2011 seismic data with ~32,000 events, rms < 0.2 s and minimum of 8 travel-time phase observations
- Inversion code had to be re-written using dynamic memory allocation to accommodate large number of earthquakes and provide manageable memory requirements and computation times

Scientific Approach: Seismic Imaging

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1.0-1.1 3-D Joint Inversion with Complete Dataset	Completed 3-D seismic imaging of reservoir for each year 2005-2011	4^{th} Qtr. 2012
Task 1.2 4-D Joint Inversion for Temporal Changes in Reservoir	Currently analyzing temporal changes from 2005-2011	2^{nd} Qtr. 2013
Task 5.0 Temporal Changes of Physical Parameters in the Reservoir	Currently investigating spatial correlation between elastic parameters and seismicity	4^{th} Qtr. 2013
Task 7.0 Spatial and Temporal Correlation Between Earthquakes (M>3), Changes in Reservoir Parameters and Numerical Fluid Injection Results	Correlation analyses will be performed when results of seismic imaging, moment tensor analysis and numerical modeling will be completed	1^{st} Qtr. 2014

Scientific Approach: Seismic Imaging

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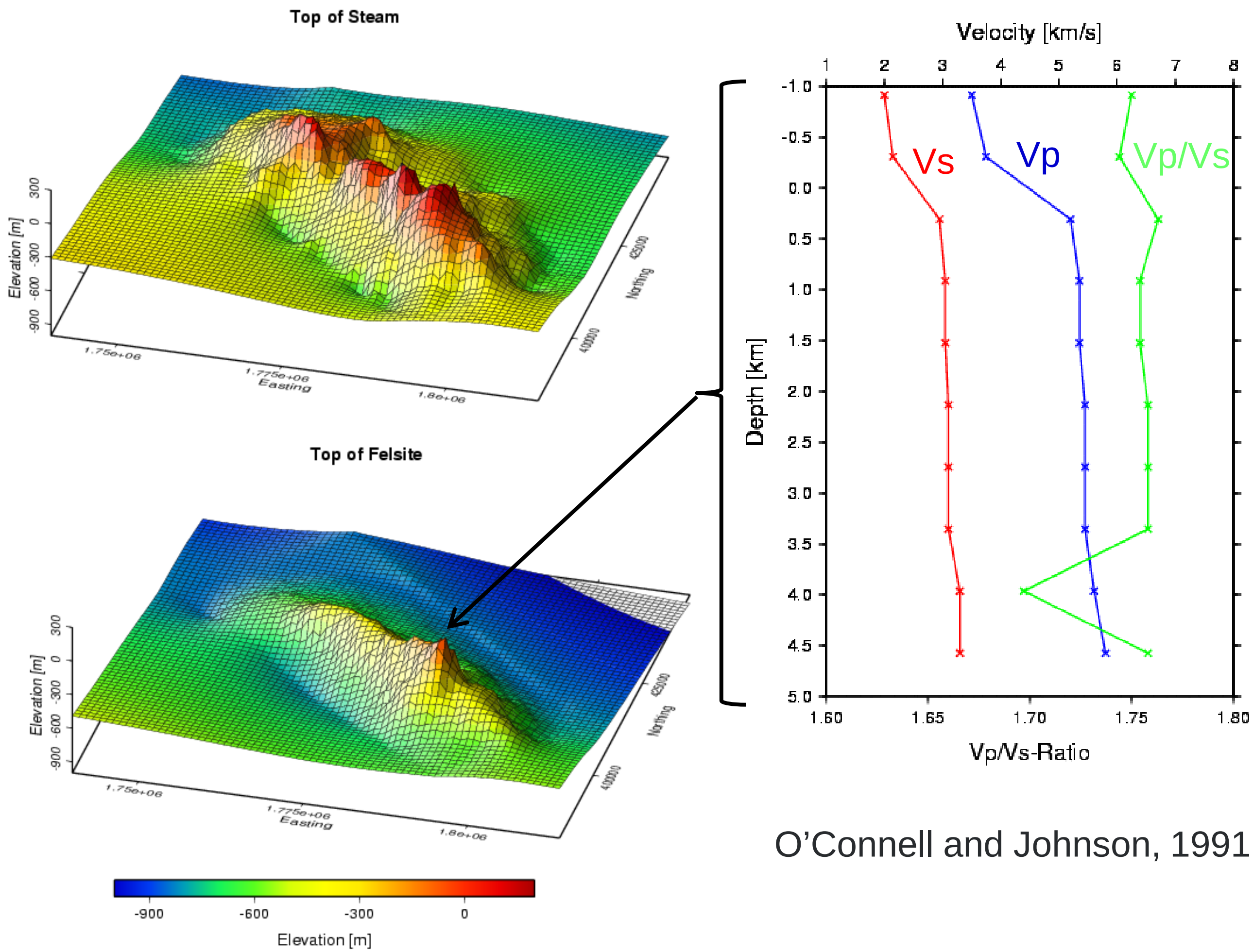
Starting Velocity Model

- Starting velocity model is built on reservoir model and seismic field measurements
- Three layer starting velocity model with topography and gradients in each layer
- Top layer: mélange (conglomerate of graywacke, greenstone and serpentenite)
- Reservoir: metagraywacke (metamorphosed reservoir rock and hornfels)
- Basement: felsite (granitic pluton underlying and partly intruding the reservoir)



O'Connell and Johnson, 1991

Scientific Approach: Seismic Imaging

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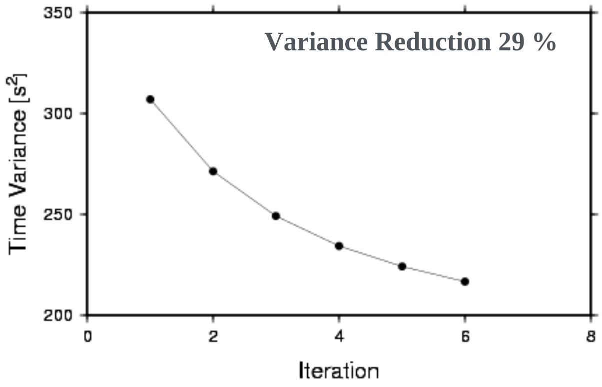
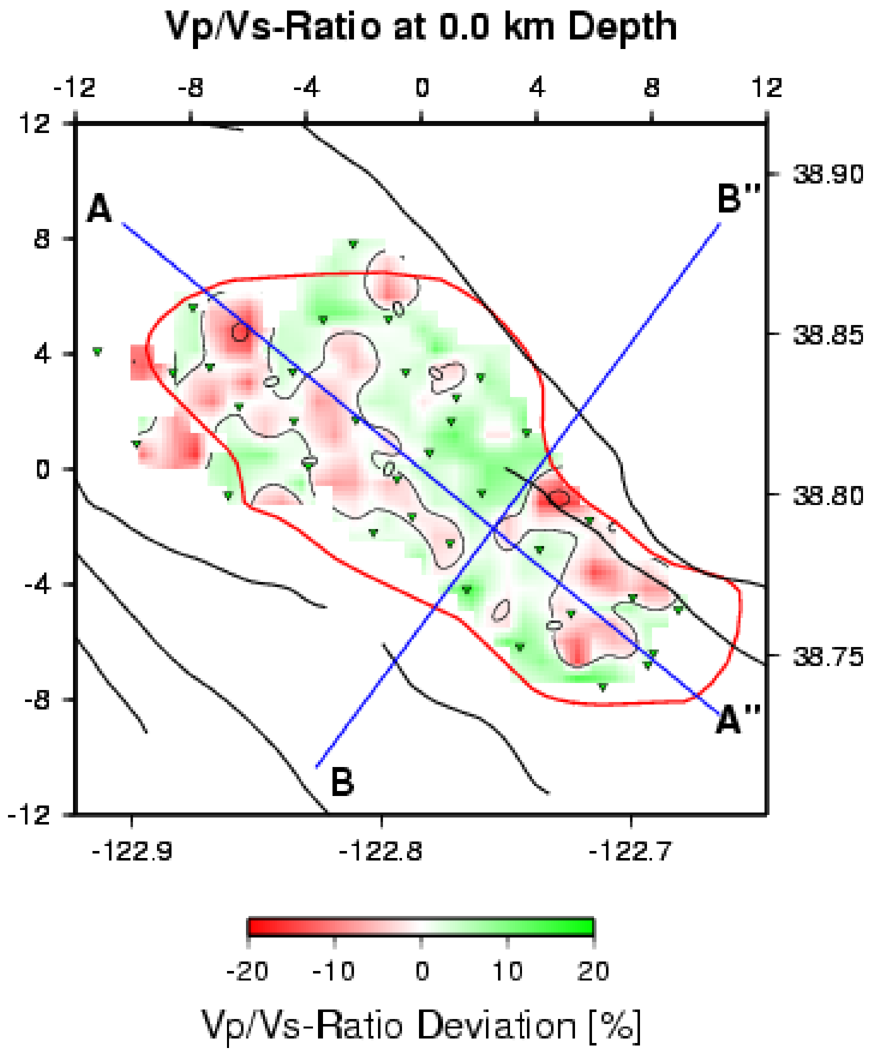
Vp/Vs-Ratio Estimates





- Little Vp/Vs deviation in upper reservoir
- Low Vp/Vs anomaly is developing in central and lower reservoir
- Vp/Vs anomaly diminishes with depth

Scientific Approach: Seismic Imaging

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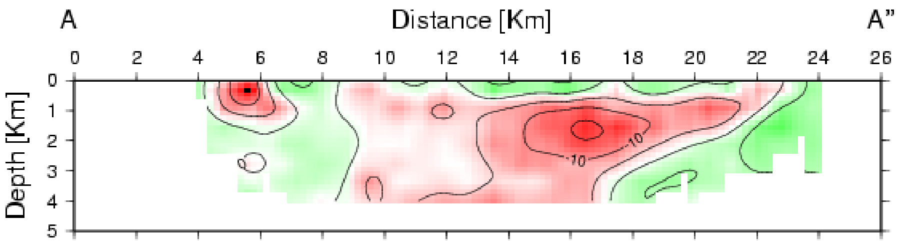
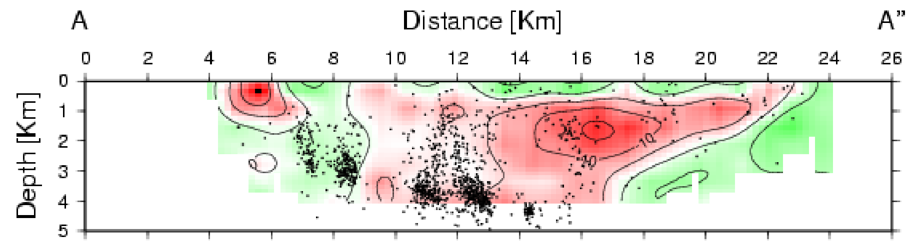
Correlation of Vp/Vs-Ratio to Seismicity

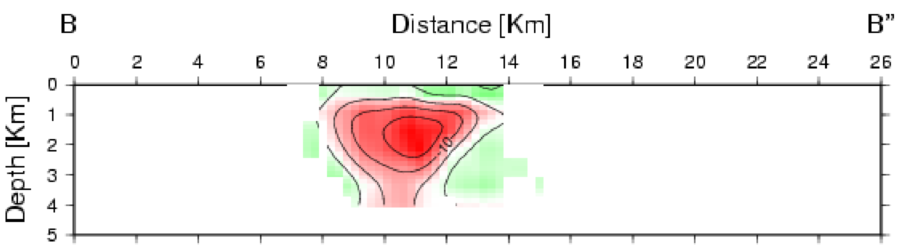
Vp/Vs-Ratio NW-SE Profile



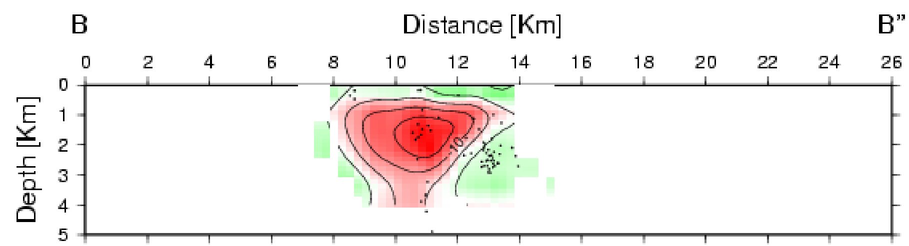
Vp/Vs-Ratio NW-SE Profile

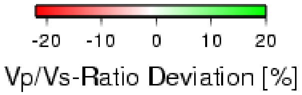


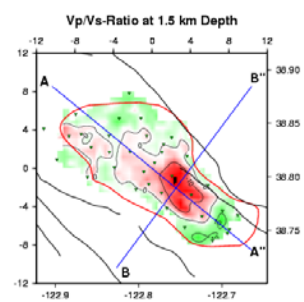
Vp/Vs-Ratio SW-NE Profile

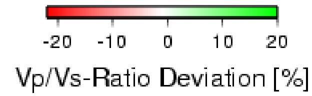


Vp/Vs-Ratio SW-NE Profile









Seismic Imaging Results

- High Vp/Vs spatially correlated to seismicity (indicative of presence of water)
- Vp/Vs-ratio appears to be uncorrelated to Vp (supplemental slides)
- Vp/Vs-ratio appears to be anti-correlated to Vs (supplemental slides)
- Traditional poroelastic theory does not appear to be applicable at The Geysers (supplemental slides)
- Theory of stiffening shear modulus with drying rock appears plausible at The Geysers (supplemental slides)
- Consequently low Vp/Vs-anomalies may be mapping hot regions (i.e., steam)

Future Directions: Seismic Imaging

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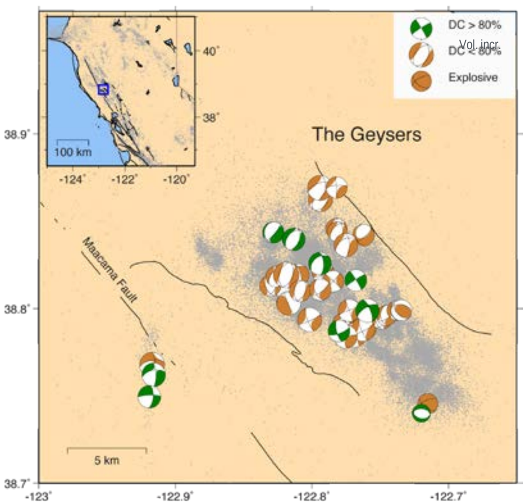
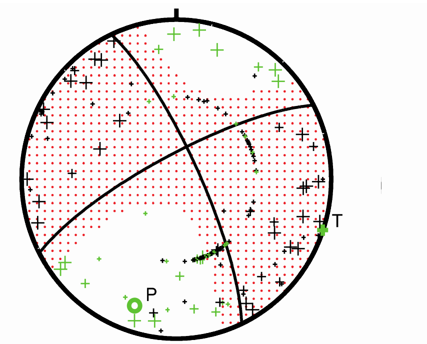
Milestone or Go/No-Go	Status & Expected Completion Date
Task 1.0-1.1 Did seismic imaging with single datasets yield reasonable results?	Yes. Completed 4th Qtr. 2012
Task 1.2 Does seismic imaging of temporal changes in reservoir provide reasonable results?	Currently under way. If yes, proceed. If no, reevaluate division of datasets in time and space. Completion expected 3rd Qtr. 2013
Task 5.0 Can observed variations in velocity be explained by parameters under consideration	If yes, proceed. If no, consider other parameters and/or adjust theories. Completion expected 4th Qtr. 2013
Task 7.0 Do locations of large magnitude events and regions with changes in reservoir properties correlate spatially and temporally?	If yes, proceed. If no, reevaluate locations for large magnitude events and regions with changes in reservoir properties. Completion expected 1st Qtr. 2014

Scientific Approach: Seismic Moment Tensor Analysis

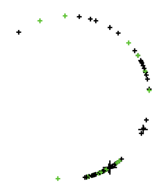
- Seismic moment tensor and finite-source inverse methods, and empirical Green's functions deconvolutions methods to are used to characterize the source parameters and scaling of earthquakes occurring at the Geysers.
- Utilize proven methods developed by the co-PI and students (Dreger, 1996; Dreger et al., 2000; Minson and Dreger, 2008; Ford et al., 2009, 2010, 2012).





Waveform MT constrained by first motions

Full Moment Tensor



Deviatoric Moment Tensor

- A key issue in our study is assessing the significance and uncertainty in recovered non-DC solutions, particularly those with isotropic or volume increase components. To address this we have developed a new joint long-period waveform and short-period first motion approach.

Scientific Approach: Seismic Moment Tensor Analysis

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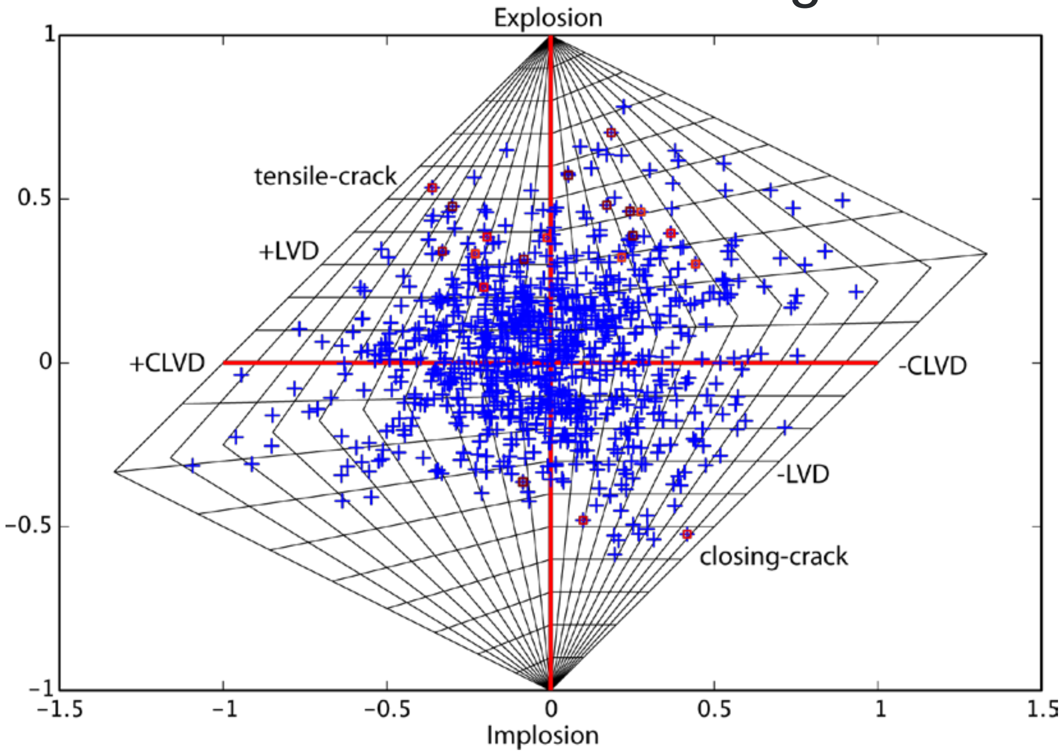
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 2.0-2.1 Initial seismic moment tensor analysis	Developed procedures for determination and review of MTs & their uncertainties	4th Qtr. 2012
Task 2.2 Full MT analysis	50 event catalog of deviatoric and full MT solutions, identification of anomalous events	2nd Qtr. 2013
Task 2.2, 4.1, 4.2 Full MT analysis	Investigation of full MT solution resolution and uncertainty for anomalous events	2nd Qtr. 2013
	Submission of manuscript to peer-reviewed journal	2nd Qtr 2013
Task 2.3 Kinematic finite-source analysis of larger earthquakes	To be initiated 3rd Qtr. 2013	

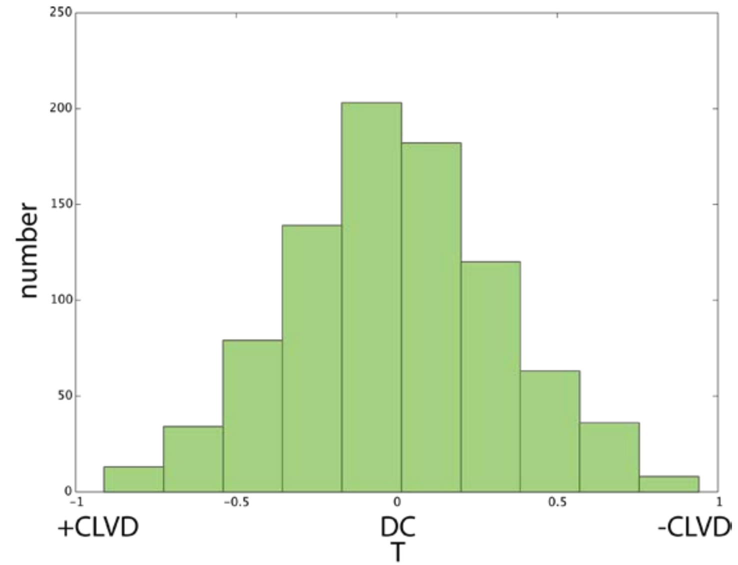
Scientific Approach: Seismic Moment Tensor Analysis

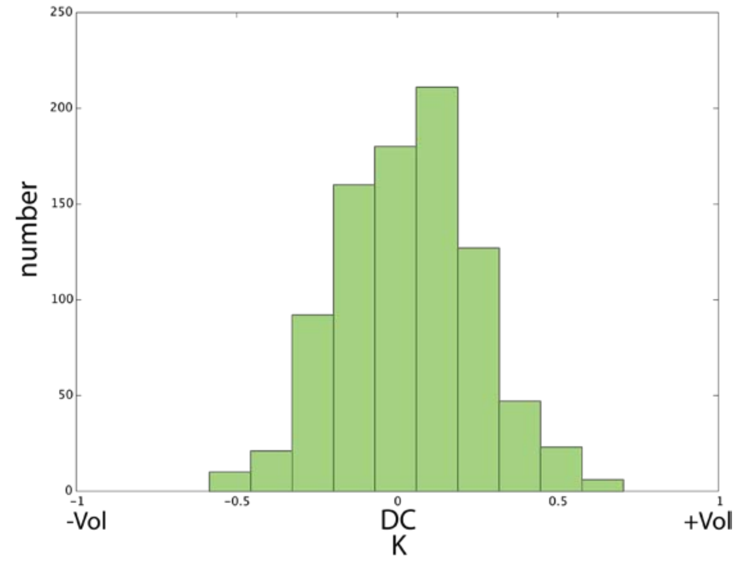
BSL Moment Tensor Catalog 1992-2012



$$\bar{T} = -0.01 \quad \bar{\kappa} = 0.04$$

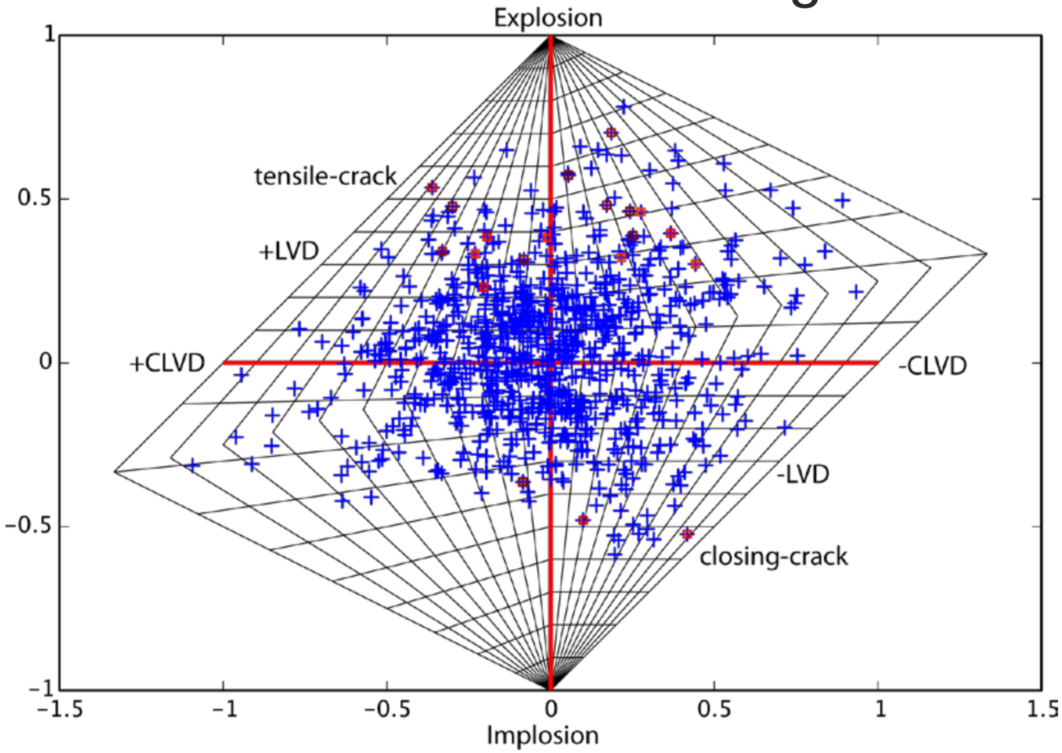
877 events – only 20 with F-test significance >90%

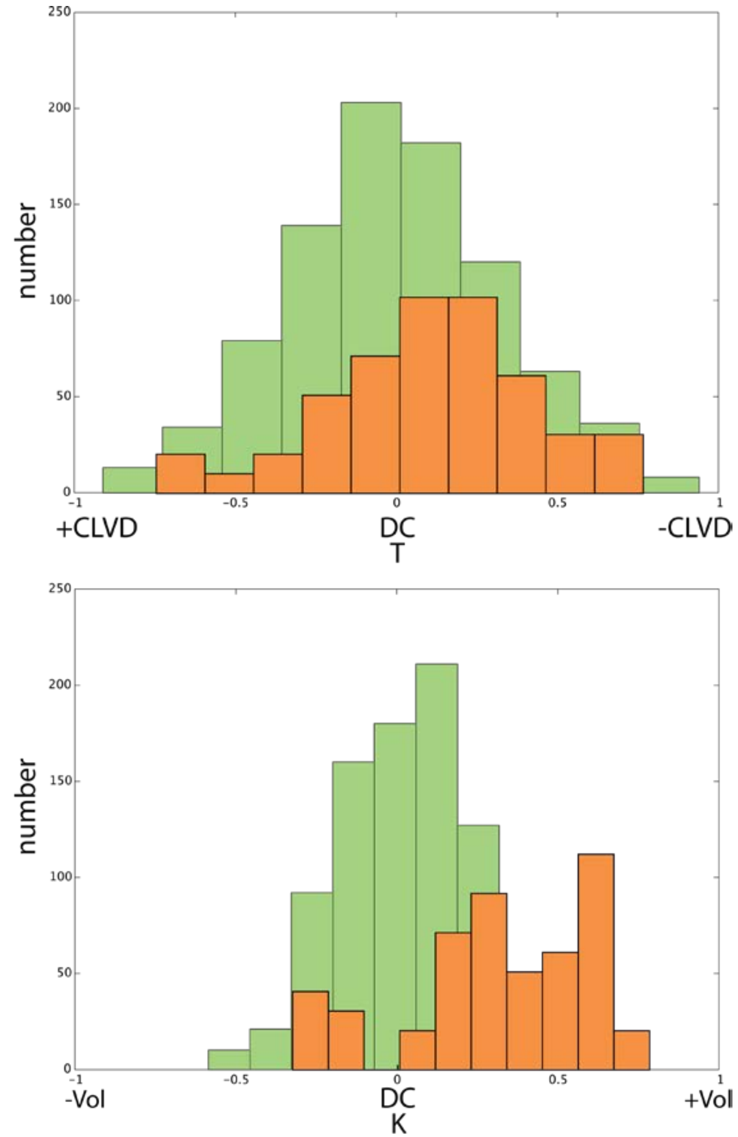




Scientific Approach: Seismic Moment Tensor Analysis

BSL Moment Tensor Catalog 1992-2012





$$\bar{T} = 0.08 \quad \bar{\kappa} = 0.32$$

The mean kappa for Geysers events is significantly larger than for the population for Northern California earthquakes.

Scientific Approach: Seismic Moment Tensor Analysis

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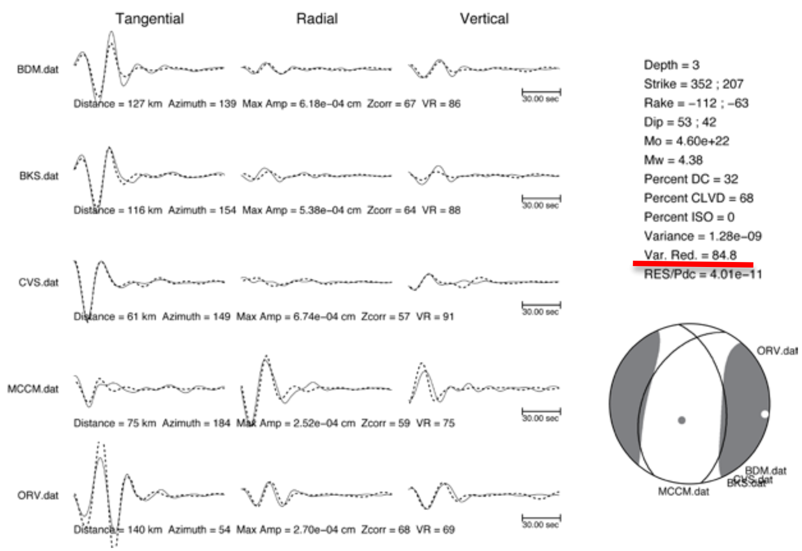
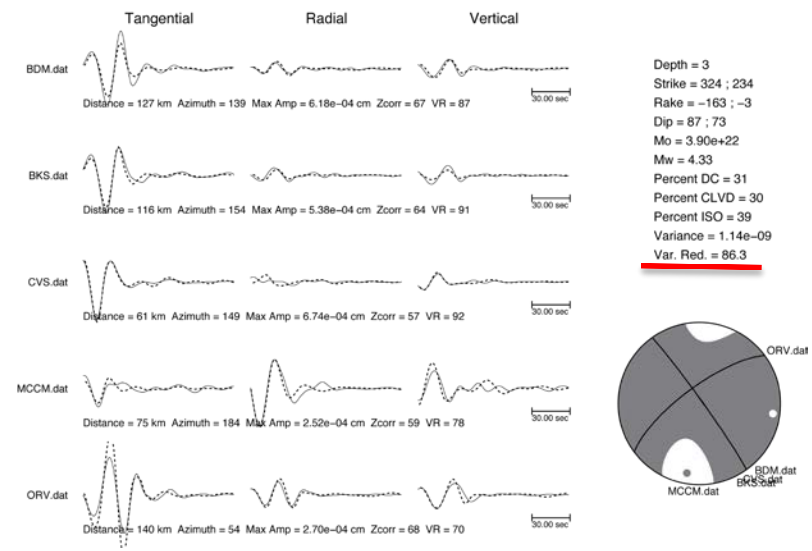
March 1, 2011 Event

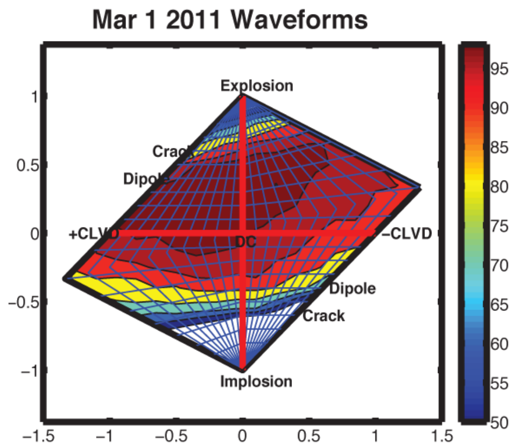
Events with relatively small isotropic components can be problematic in identifying source type

Deviatoric Inversion



Full MT Inversion



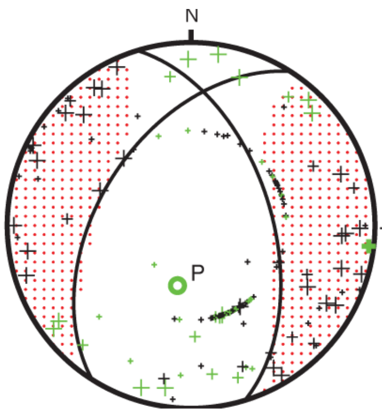


The deviatoric and full MT solutions fit the same. The NSS plot obtained by fitting 30 million uniformly distributed moment tensor solutions shows a tradeoff in source-type

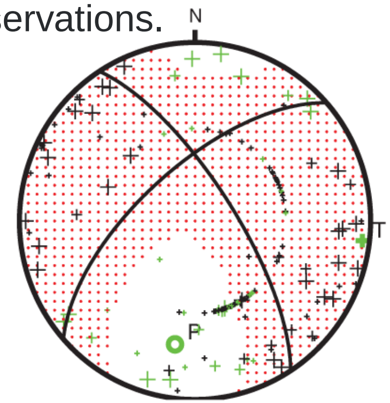
Scientific Approach: Seismic Moment Tensor Analysis

March 1, 2011 Event

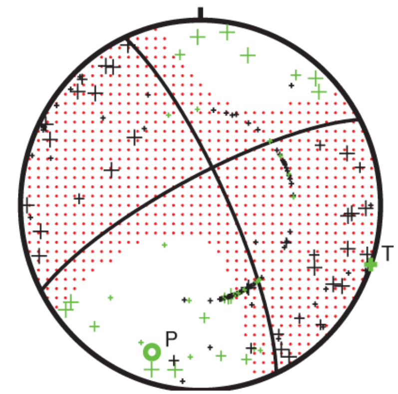
A problem is the deviatoric solution does not satisfy the first-motions.



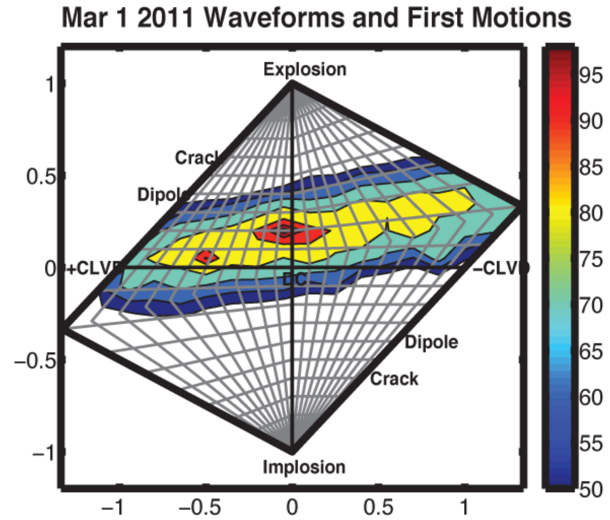
The full MT solution actually better satisfies the first-motion observations.



Best fitting solution to the long-period waveforms and first-motions



The waveform NSS output, consisting of 200,000 solutions are tested against first-motion observations greatly reducing the region of jointly acceptable solutions.



Summary of Accomplishments for Moment Tensor Analysis

- Catalogs of deviatoric and full moment tensor solutions has been compiled.
- Two decades of Northern California earthquakes (877 events M>3) show essentially zero mean in the deviatoric and volumetric source type parameters.
- The Geysers events as a population deviate significantly from Northern California events in which they show a bias towards volumetric sources. Some events do show large double-couple solutions and therefore the small to moderate isotropic components appear to be source related rather than due to unmodeled path bias.
- The sensitivity to station coverage has been explored for Geysers' event solutions and solutions are found to be stable.
- We have developed a new joint long-period waveform and first-motion method to determine full moment tensor solutions and to better resolve possible relatively small isotropic components.
- We are in the process of drafting a manuscript on the seismic moment tensor analysis to be submitted to a peer-reviewed journal

Future Directions: Seismic Moment Tensor Analysis

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Milestone or Go/No-Go	Status & Expected Completion Date
Moment Tensor Catalog	Completed
Anomalous Event Sensitivity and Uncertainty Analysis	Ongoing – Expected completion 2nd Qtr. 2013
Submission of moment tensor work for publication	Expected completion 2nd Qtr. 2013
Identify mainshock EGF event pairs	Expected completion 3rd Qtr. 2013
Estimation of seismic moment rate functions and analysis of source scaling	Expected completion 4th Qtr. 2013
EGF kinematic finite-source modeling of larger events	Expected completion 1st Qtr. 2014
Preparation and submission of kinematic finite-source analysis results for peer-reviewed publication	Expected completion 2nd Qtr. 2014

Scientific Approach
Geomechanical-Numerical Modeling

- Building of a regional 3-D thermo-hydro-mechanical numerical model of The Geysers and applying appropriate boundary conditions (Task 3.0)
- Model calibration and modeling of initial state of stress
- Modeling of injection, production induced thermo-poro-elastic stress changes (Task 6.0)
- Compare induced thermo-poroelastic stress changes with natural stress changes due to tectonics and earthquakes
- Estimate which process yields which contribution to change in stress as a function of space and time, and is most relevant for causing large scale (M > 3) events (Task 8.0)

Scientific Approach
Geomechanical-Numerical Modeling

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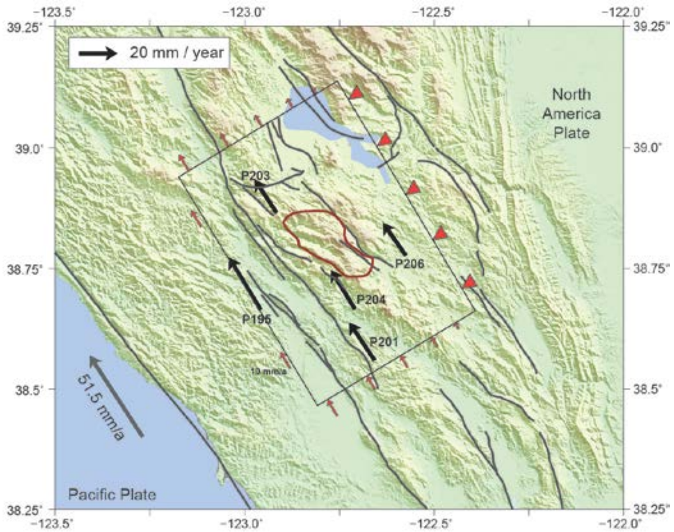
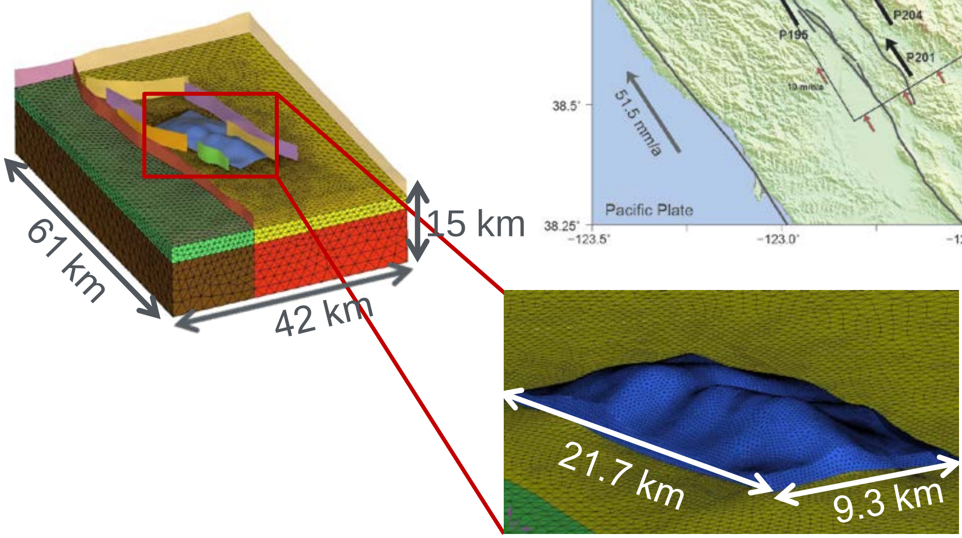
- 3-D geomechanical model including 7 major faults, complex reservoir geometry, 10 rupture planes of M > 4 events (modeling of co-seismic slip)
- Boundary conditions describing tectonic loading according to GPS velocities

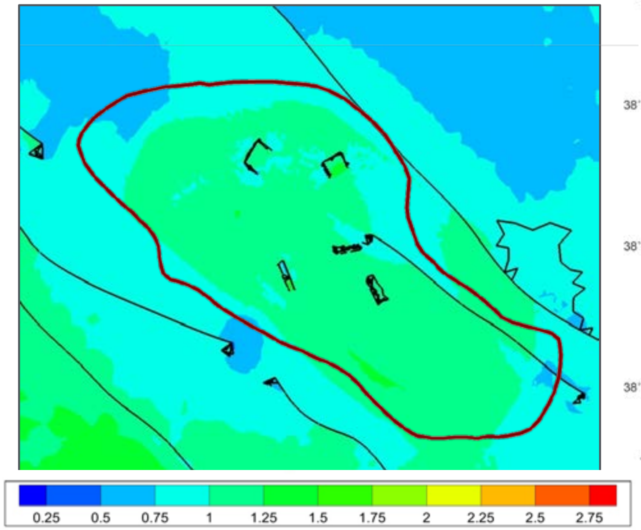




Task 3.0	Date Completed
Geometry and boundary conditions for the geomechanical model of The Geysers	Feb 2012

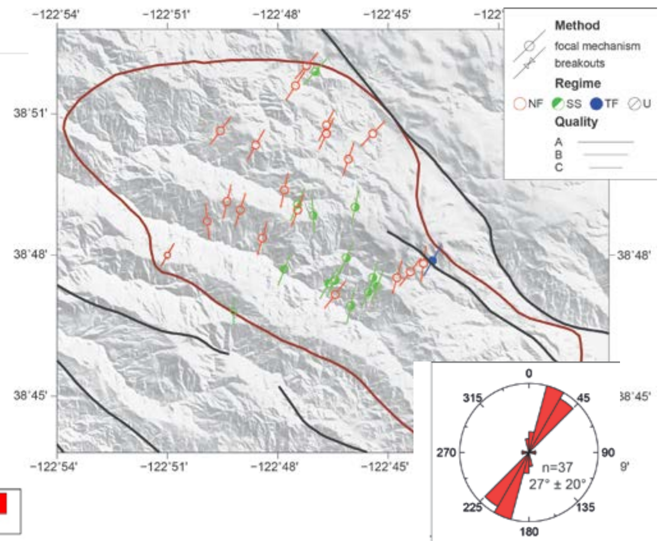
Scientific Approach
Geomechanical-Numerical Modeling

Modeled stress

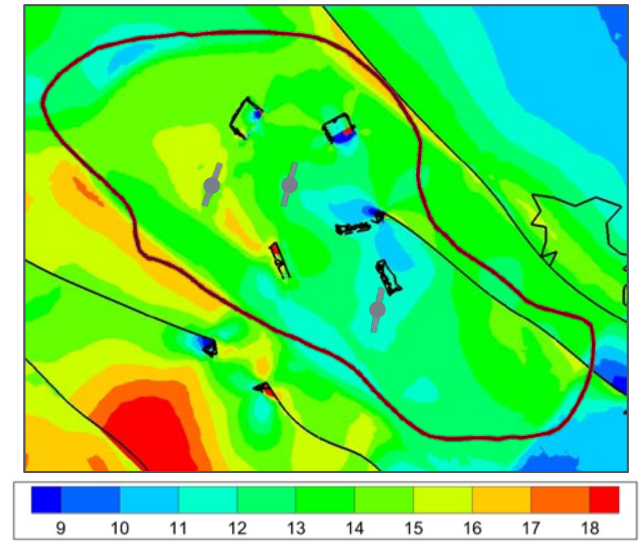


normal strike-slip thrust
Stress Regime

Observed stress regime and orientation of max. hor. stress



Modeled orientation of max. hor. stress



Degrees from north

Task 6.0	Actual Milestone/Technical Accomplishment	Date Completed
Simulation of stress evolution of The Geysers reservoir	Model calibration of initial stress state with data of stress regime and orientation of max. hor. stress	Dec 2012

Scientific Approach
Geomechanical-Numerical Modeling

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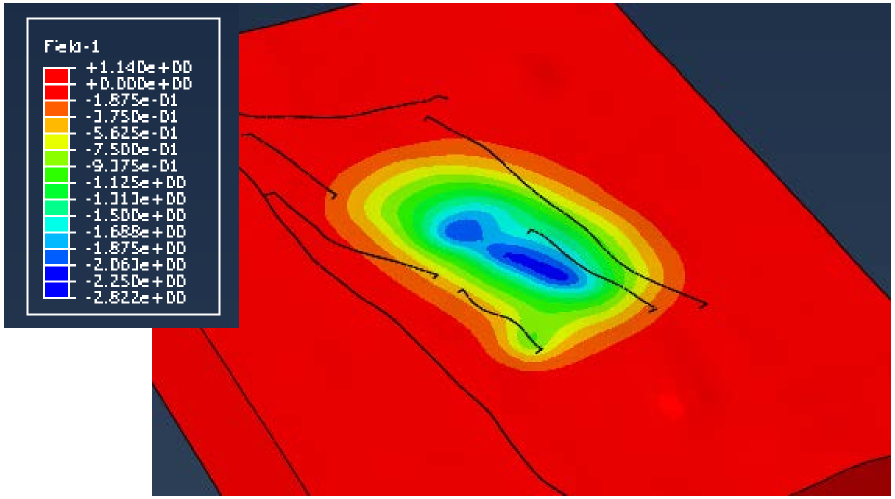
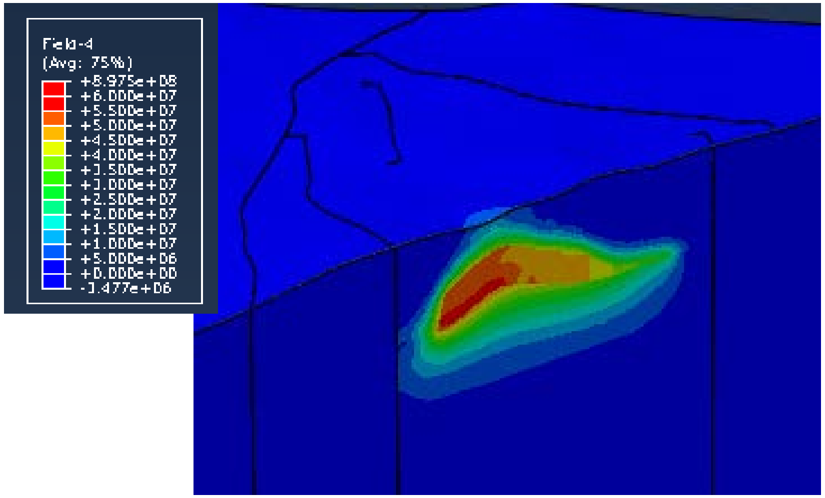
First results of total subsidence, pore pressure and stress changes after 15 years of injection and production with
(a) injection rates of 26 l/s at 10 SEGEP,
(b) 30 l/s at 13 SRGRP injection points and
(c) production rate of 46 l/s at 42 production points.





Task 6.0	Actual Milestone/Technical Accomplishment	Date Completed
Simulation of stress evolution of The Geysers reservoir	Modeling of fluid injection and production induced pore pressure and stress changes	Feb 2013

Future Directions: Geomechanical-Numerical Modeling

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- Model calibration against observed data (pressure drop, subsidence) due to injection and production (Task 6.0)
- Decision point: Does model match the observed data
  - If no, modify physical model parameters
  - I yes, proceed with Task 8.0
- Model parameters will by modified within their physical reasonable limits (Task 8.0)
  - Model stress changes due to injection and production for worst and best case scenarios
  - Perform slip tendency and fracture potential analysis
  - Assessment of contribution of different processes (tectonic loading, co-seismic slip, pore pressure diffusion, temperature changes) to stress changes, and which are most relevant for causing large scale (M > 3) events

Task	Status & Expected Completion Date
6.0: Simulation of stress evolution	Expected completion date in March 2013
8.0: Geomechanical parameter study, model results analysis	Starting in March 2013; Expected completion date in August 2013

Scientific Approach
Seismic Hazard Analysis

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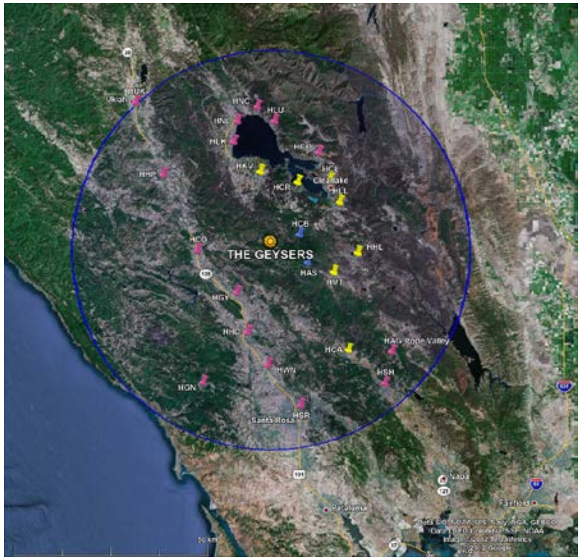
- We are applying four different methods to calculate seismic hazard from induced and natural earthquakes in a geothermal environment:
  - Linking a rate and state friction earthquake rupture model with pore pressure changes, and utilizing physics-based wave propagation
  - Linking pore pressure to “a”- & “b”-values to predict the occurrence of seismicity and utilizing empirical attenuation relations to calculate hazard
  - Linking empirical “a” & “b” values with quasi-dynamic earthquake rupture models and physics-based wave propagation,
  - Applying traditional PSHA based upon empirical “a” & “b”-values and attenuation relations.
  - The above methods have been written into software



- Study area with 50 km radius and locations where field data collected

Hazard Analysis

Technical Advantage and Challenges

- By implementing these approaches we can begin to include model uncertainty in the hazard calculations, and examine the effects each approach has on hazard calculations
- The technical challenge is that many earthquakes that contribute to hazard are induced and predicting their occurrence is uncertain.

Future Directions: Seismic Hazard Analysis

Milestone or Go/No-Go	Status & Expected Completion Date
Task 9.0-9.1 Estimation of Seismic Hazard Maps	Estimation of hazard and hazard maps depend on results from geomechanical modeling. Completion expected 3rd Qtr. 2013
Task 9.2 Calculation of Ground Motion	Calculation of ground motion will be performed when hazard maps are completed. Completion expected 4th Qtr. 2013

Summary

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- 3-D double difference tomography imaged low Vp/Vs-ratio structure in reservoir
- High Vp/Vs regions are correlated to seismicity (presence of water)
- Low Vp/Vs regions are correlated to high-temperature (presence of steam)
- The Geysers events as a population deviate significantly from Northern California events showing bias towards volumetric sources
- Some events show large double-couple solutions and therefore the small to moderate isotropic components appear to be source related rather than due to path bias
- Successfully generated 3-D geomechanical model including major faults, complex reservoir geometry, 10 rupture planes of M > 4 events
- Conducted model calibration of initial stress state with data of stress regime and orientation of maximum horizontal stress
- Modeled 15 years of injection and production with total subsidence, pore pressure and stress changes with varying injection/production rates
- Developed four different approaches to calculate seismic hazard in a geothermal environment
- Publications (see written summary)
  - 11 conference abstracts
  - 5 reviewed conference papers
  - 5 papers submitted to peer-reviewed journals

Project Management

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- Management activities include:
  - Dissemination of data between US and German project participants
  - Coordination of technical meetings, exchange of results and reporting of progress to DOE
  - The current project is integrated with the European GEISER project and results are continuously updated and exchanged
  - The integration between these two projects highlights the visibility of the current DOE project world-wide
  - A close collaboration has been established with Calpine staff to generate feedback on research activities, and continuously share results and data

  - The late signing of the contract caused delays in hiring a post doc (GFZ) and selecting a graduate student (UCB) and delayed research that was scheduled to build on each task
  - A no-cost extension has been granted by DOE through May 31, 2014

Timeline:	Planned Start Date	Planned End Date	Actual Start Date	Actual /Est. End Date		
	1/31/2010	1/31/2013	6/30/2010	5/31/2014		
Budget:	Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
	$1,164,143	$291,108	$1,111,000	$1,118,000	$844,000	$316,000

Thank you

Supplemental Slide: Seismic Imaging

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What are the Physics of the Observed Vp/Vs-Ratio?

- $Vp = \sqrt{\frac{K+(4/3)\mu}{\rho}}$ K = bulk modulus, μ = shear modulus, ρ = density
- $Vs = \sqrt{\frac{\mu}{\rho}}$ μ = shear modulus, ρ = density
- A) Traditional poroelastic theory predicts (Mavko et al., 1998):
  - \- change of pore fluid from water to steam
  - => decrease in K, constant μ => decrease in Vp, constant Vs => decrease Vp/Vs
- B) Laboratory measurements at The Geysers (Boitnott and Kirkpatrick, 1997):
  - \- temperature increase needed to change pore fluid from water to steam
  - => stiffens shear modulus μ
  - => decrease in K, increased μ => constant Vp, increased Vs => decrease Vp/Vs
- Question: Which is the observed mechanism at The Geysers?

Supplemental Slide: Seismic Imaging

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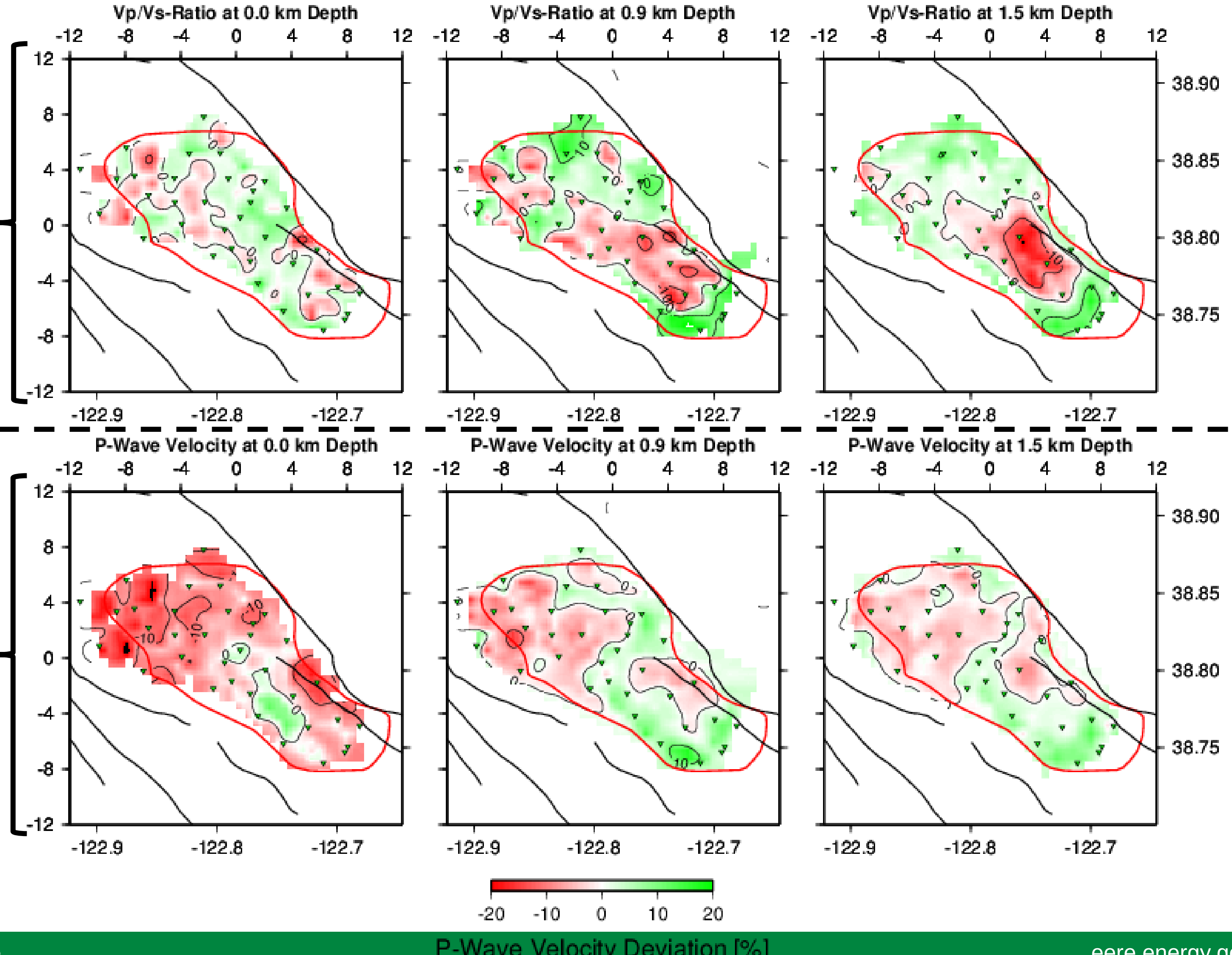
Vp/Vs-Ratio vs. Vp Estimates at 0.0 km – 1.5 km Depth

Vp/Vs-Ratio
0.0 – 1.5 km

Vp
0.0 – 1.5 km



Supplemental Slide: Seismic Imaging

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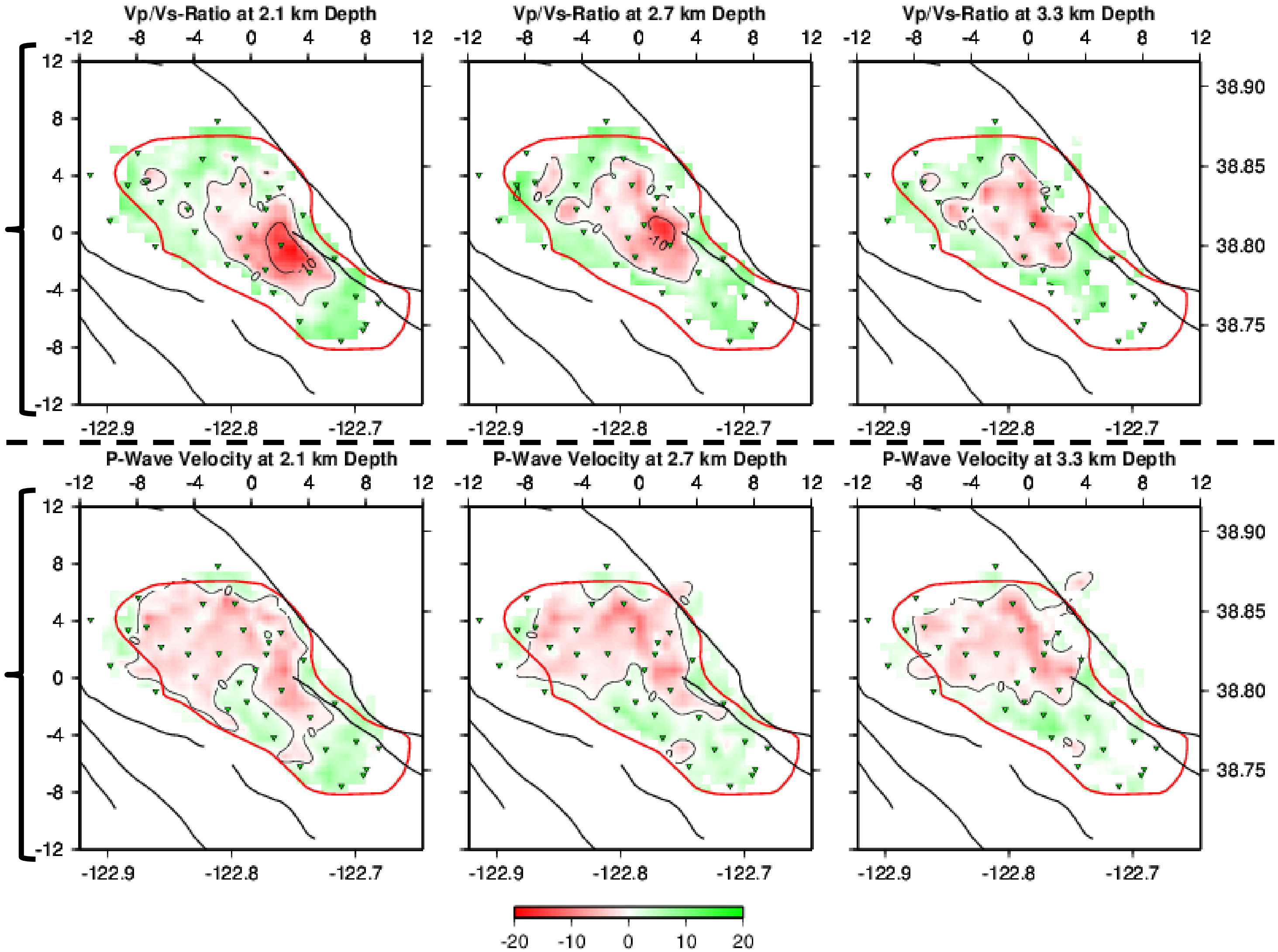
Vp/Vs-Ratio vs. Vp Estimates at 2.1 km – 3.3 km Depth

Vp/Vs-Ratio
2.1 – 3.3 km

Vp
2.1 – 3.3 km

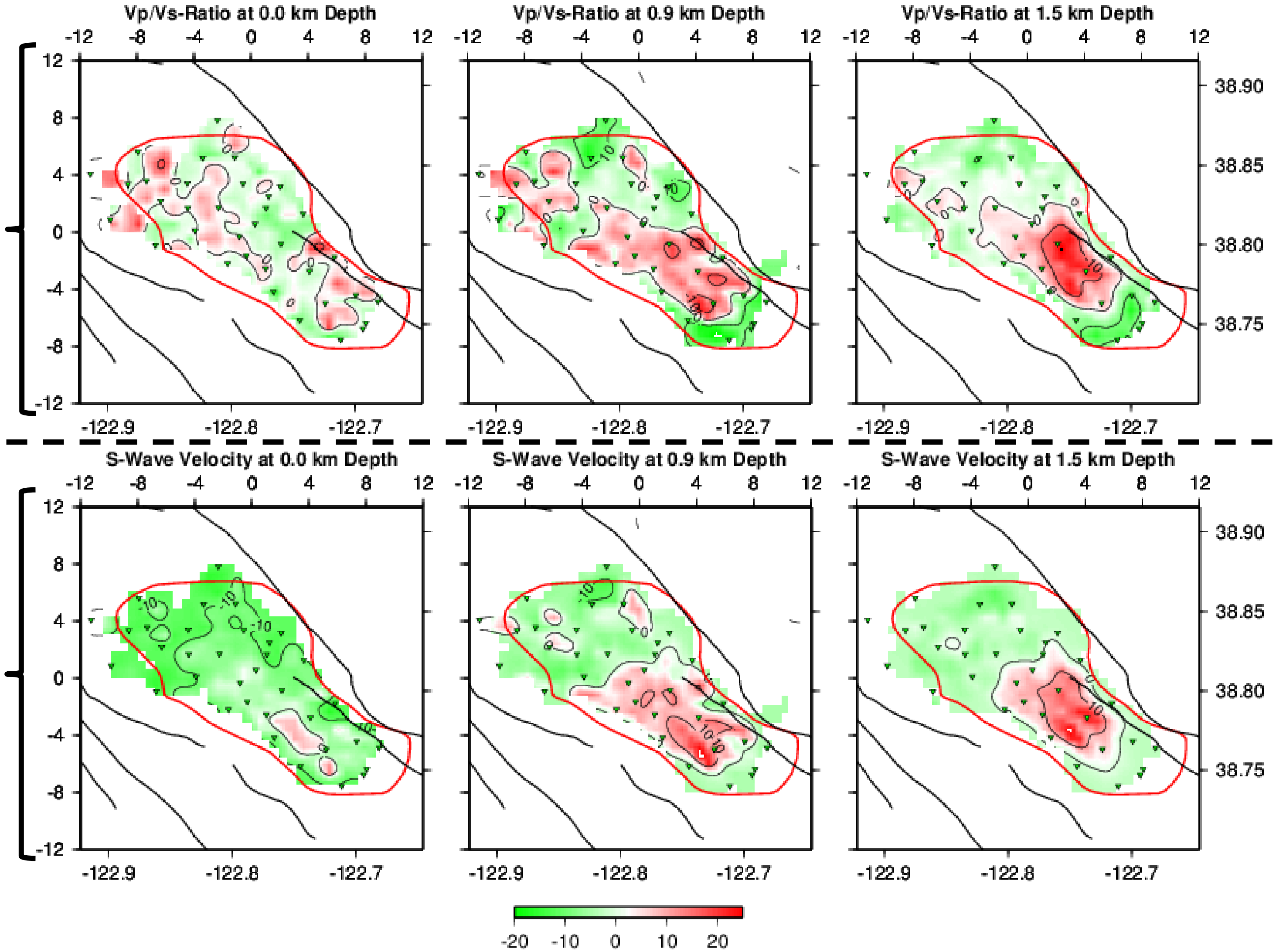


Supplemental Slide: Seismic Imaging

Vp/Vs-Ratio vs. Vs Estimates at 0.0 km – 1.5 km Depth

Vp/Vs-Ratio
0.0 – 1.5 km

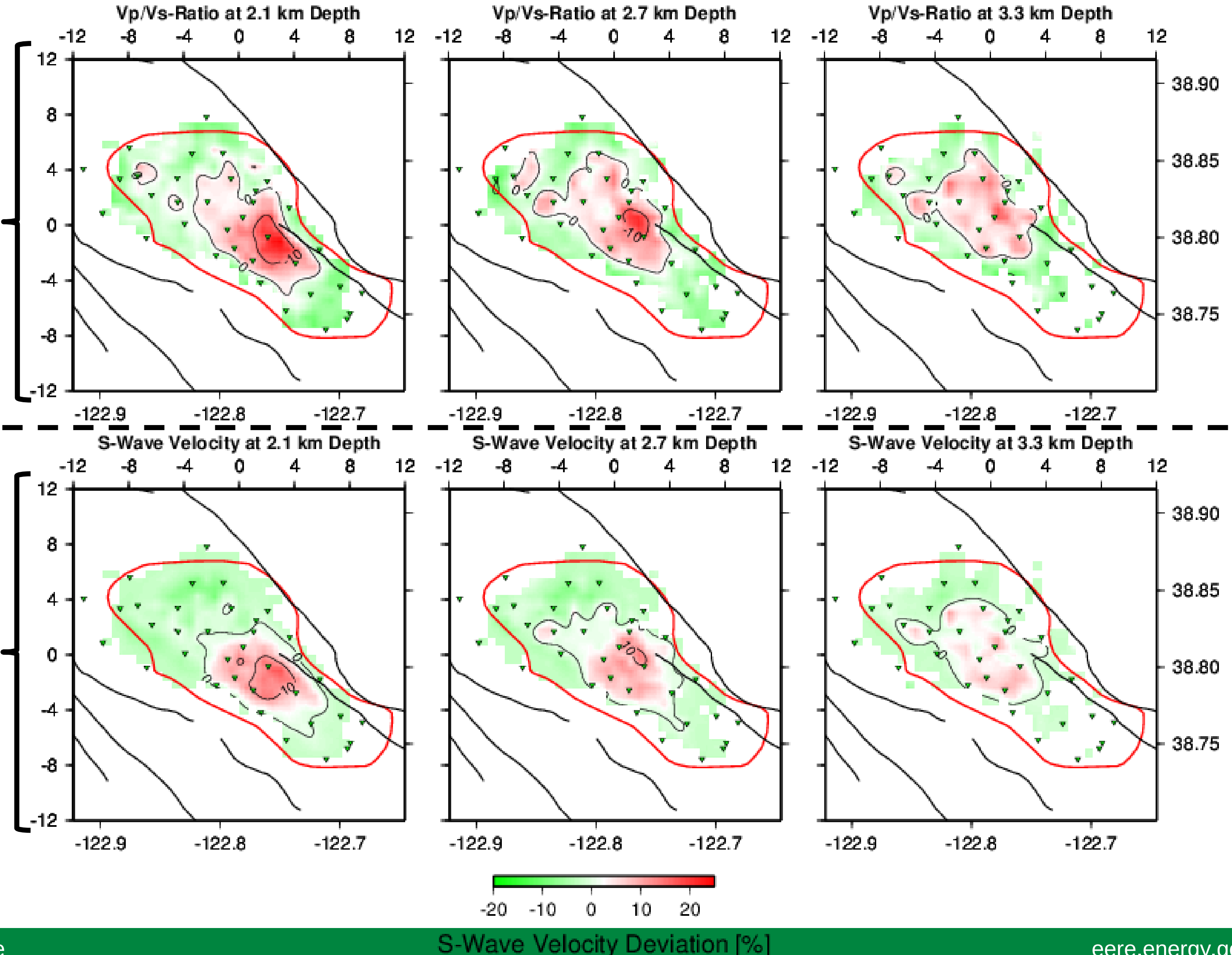
Vs
0.0 – 1.5 km



Vp/Vs-Ratio vs. Vs Estimates at 2.1 km – 3.3 km Depth

Vp/Vs-Ratio
2.1 – 3.3 km

Vs
2.1 – 3.3 km



Supplemental Slide: Seismic Imaging

The Physics of the Observed Vp/Vs-Ratio

- Vp/Vs-ratio appears to be uncorrelated to Vp
- Vp/Vs-ratio appears to be anti-correlated to Vs
- Traditional poroelastic theory does not appear to be applicable at The Geysers
- Theory of stiffening shear modulus with drying rock appears plausible at The Geysers
- Consequently low Vp/Vs-anomalies may be mapping hot regions (i.e., steam)

- Alternative interpretation: high Vs is correlated to closing fractures in felsite whereas Vp is not affected => low Vp/Vs-ratio is imaging felsite
- However, felsite also contains fractures and steam and observation is that Vs is deceasing with depth within the felsite

Supplemental Slide: Seismic Moment Tensor Analysis

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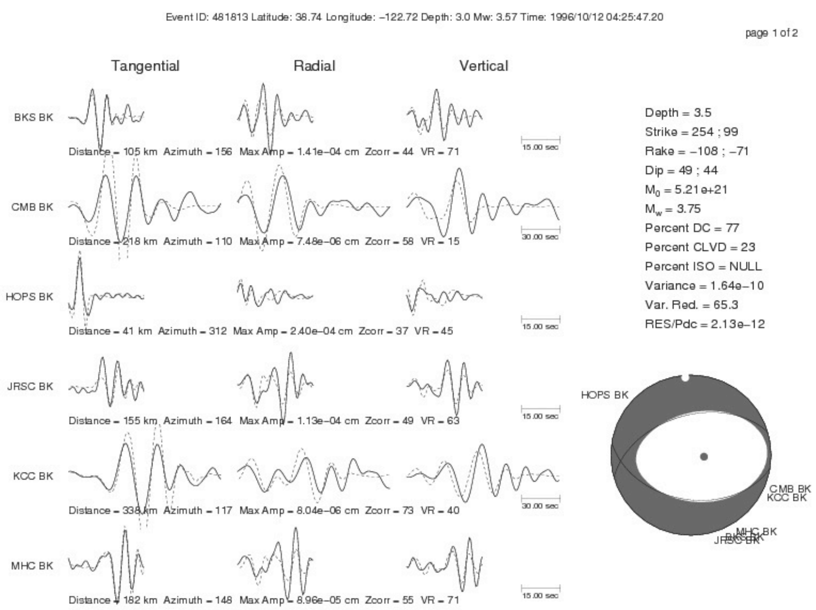
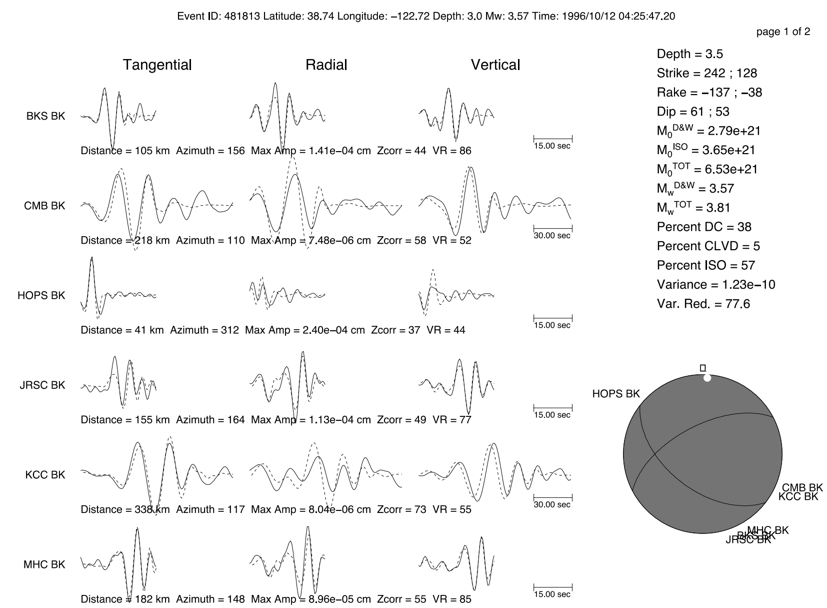
Deviatoric Solution



Full Moment Tensor Solution



Deviatoric and full moment tensor solutions are computed for all events. The variance reduction goodness of fit measure is used to assess the quality of each solution, and the F-test is used to assess whether the extra degree of freedom in the full moment tensor solution is statistically significant.

For this event the full moment tensor solution is statistically significant at better than 98%.

Supplemental Slide: Seismic Moment Tensor Analysis

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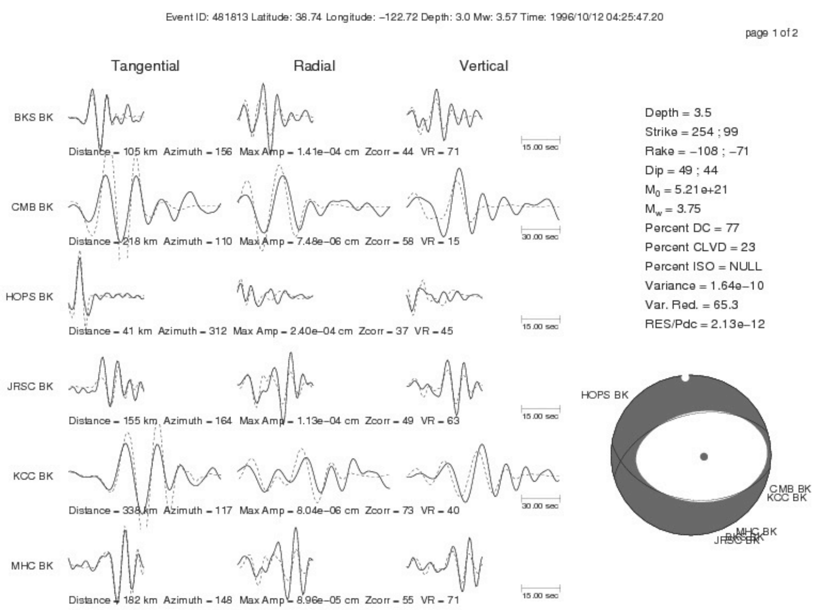
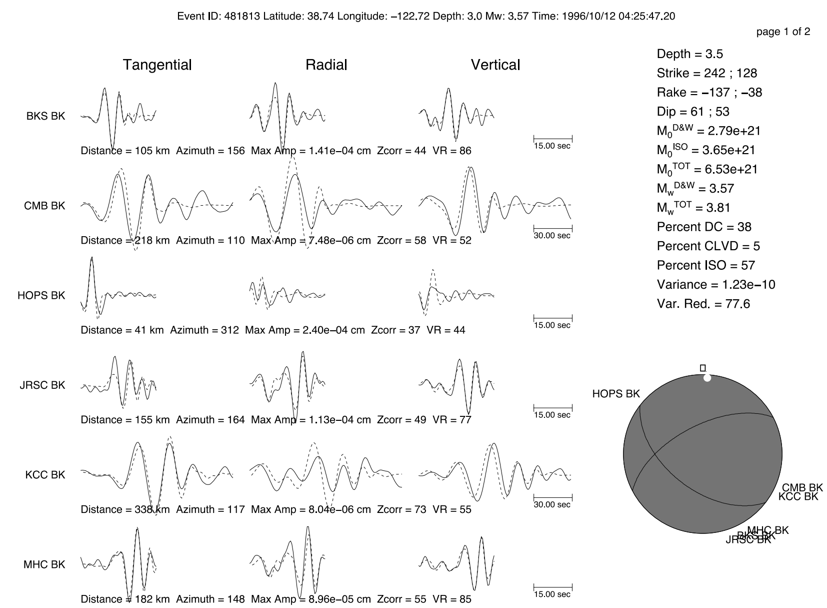
Deviatoric Solution



Full Moment Tensor Solution



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The combined waveform first-motion solution fits the long-period waveforms reasonably well.