Towards the Understanding of Induced Seismicity in Enhanced Geothermal Systems

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"The Good and the Bad of Induced Seismicity"

- 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

Objective

- To 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
- To investigate relationship between geothermal activities and large-size induced seismicity (M>3)
- To predict maximum magnitude of induced future earthquakes and associated ground motion
- Although The Geysers are no 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

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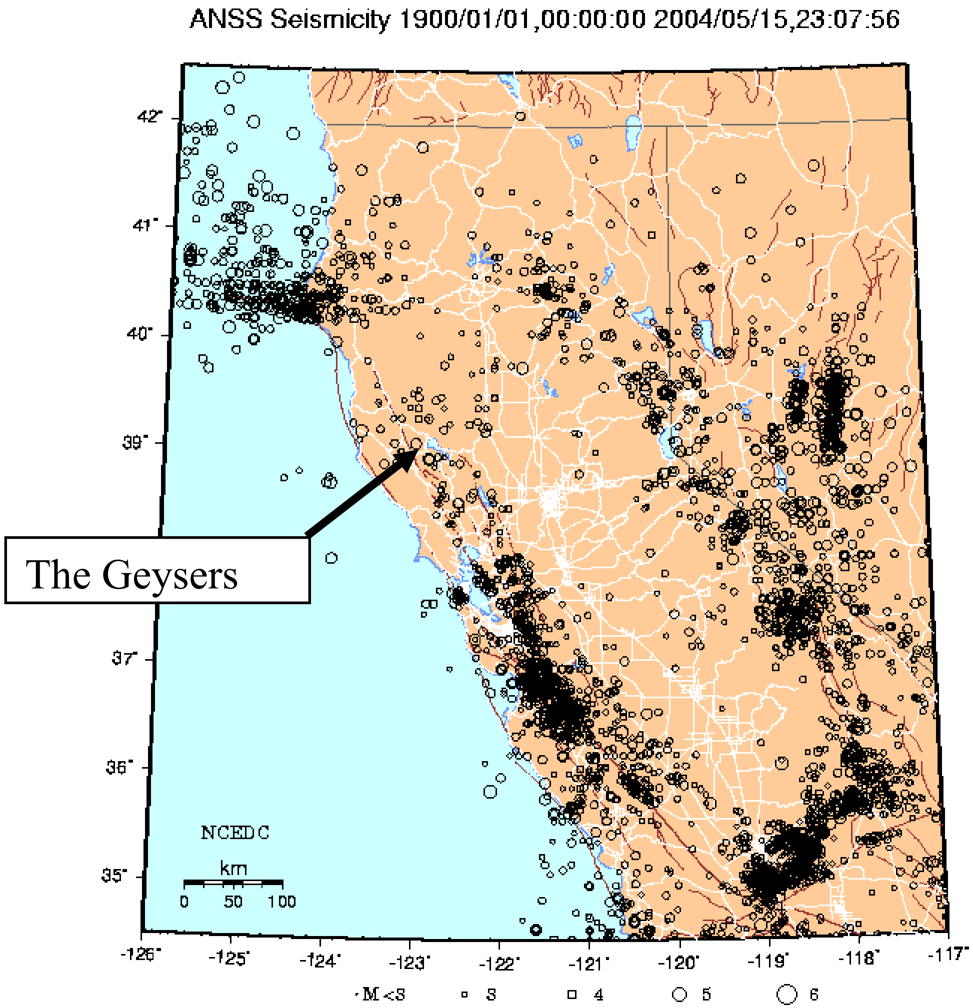
Overview

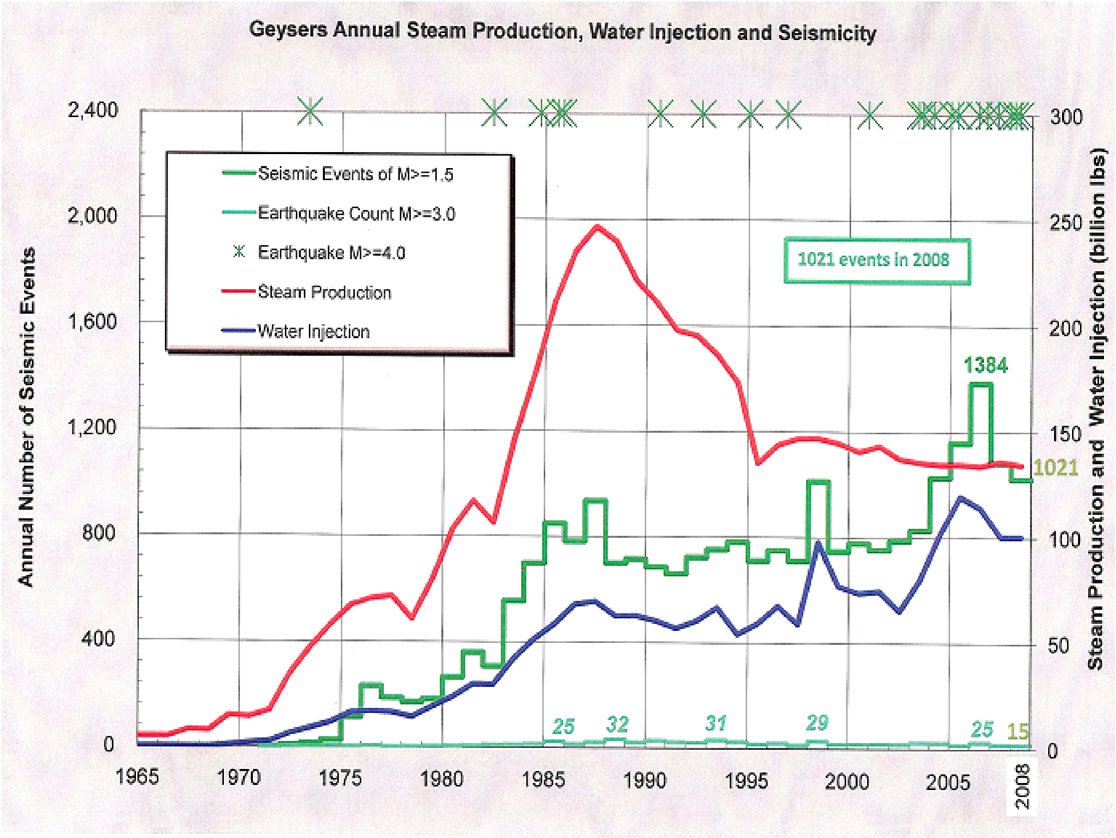
1. Timeline:
   - Start Jan 2010
   - End Jan 2013
   - Completion 2%
2. Budget:
   - Total $ 1,454,615
   - DOE Share $ 1,158,779
   - Awardee Share $ 290,473
   - Fund received 2010 $ 0
3. Barriers
   - No contract in place as of May 2, 2010
4. Partners
   - UC Berkeley
   - GFZ Potsdam
   - Lawrence Berkeley National Lab

Northern California Historical Seismicity (M 3.5 to 5.0) 1900-2005

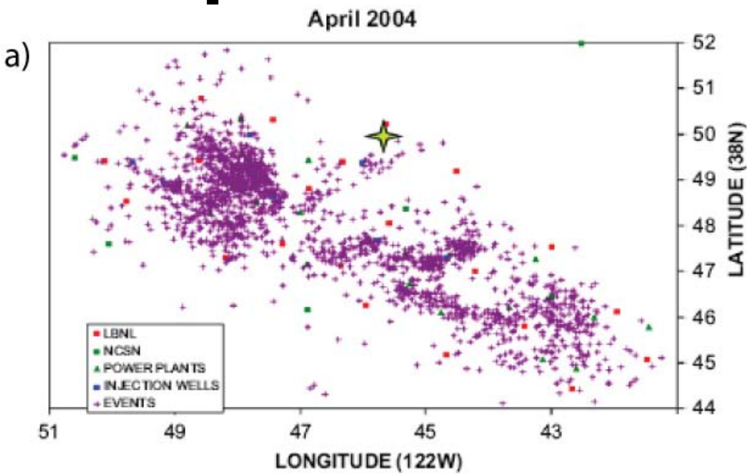


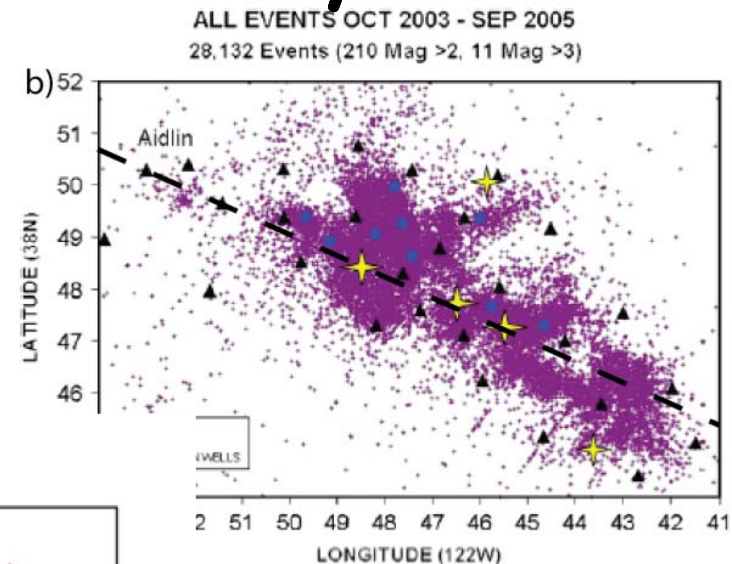
- Seismicity rate at The Geysers 10,000 events per month
- ~ 500,000 events since start of operations

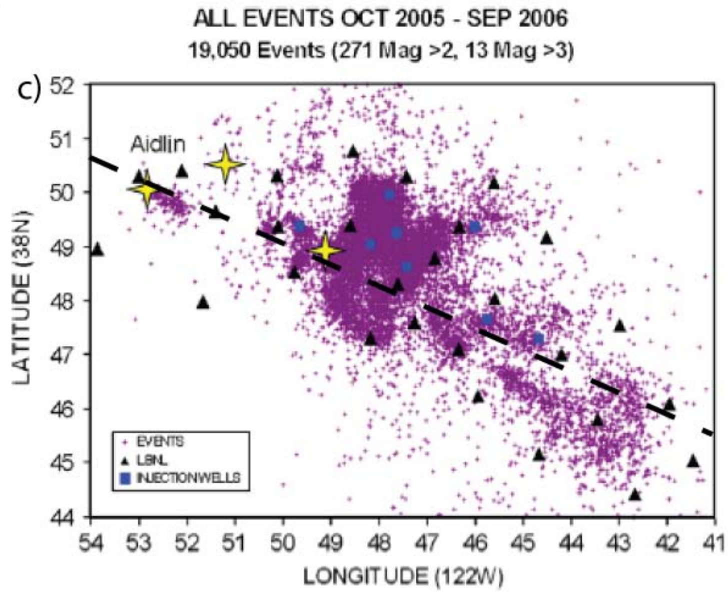
Correlation of Inj./Prod. vs. Seismicity



Spatial Distribution of Seismicity M>4

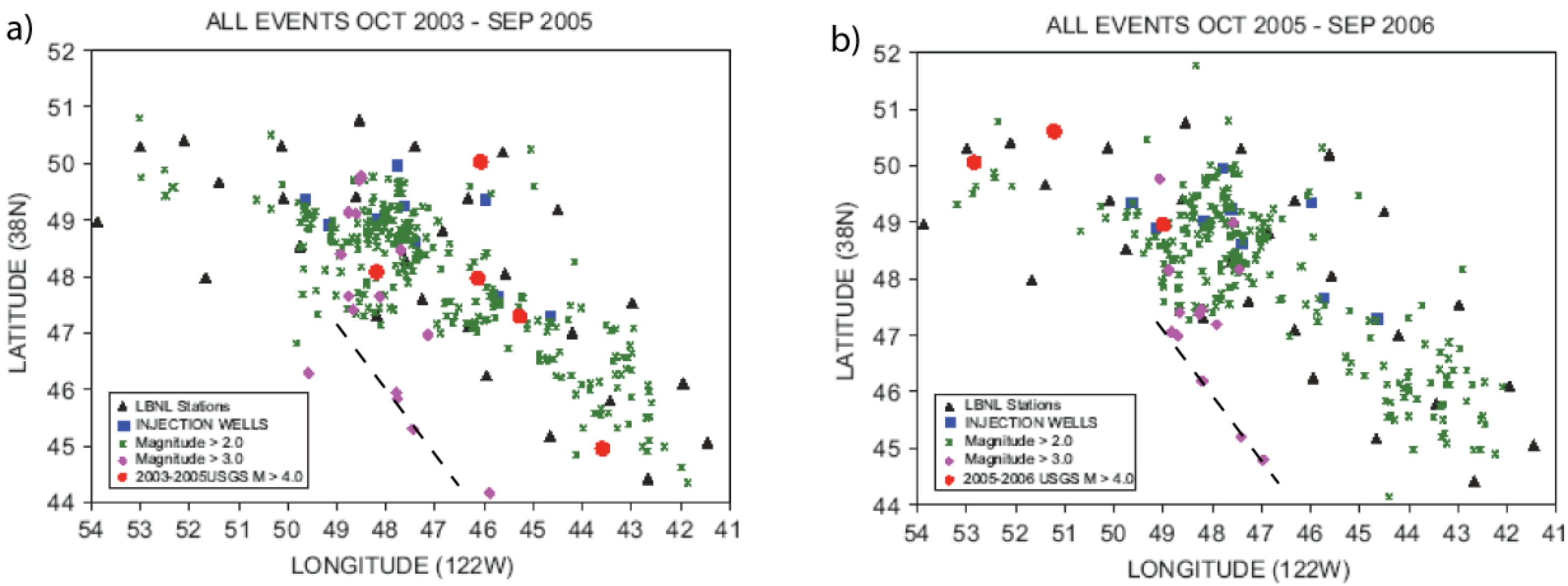






after Majer et al., 2007

Spatial Distribution of Seismicity M>3



after Majer et al., 2007

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Questions to be Answered

- Why does rate of large-size seismicity accelerate with time?
- Why do epicenters of large-size seismicity line up on liniments?
- Are large-size events triggered or induced?
- What is largest possible event given state of operations?
- What is largest ground shaking (hazard) associated with that event?
- Develop technology to answer these questions

Proposed Activity

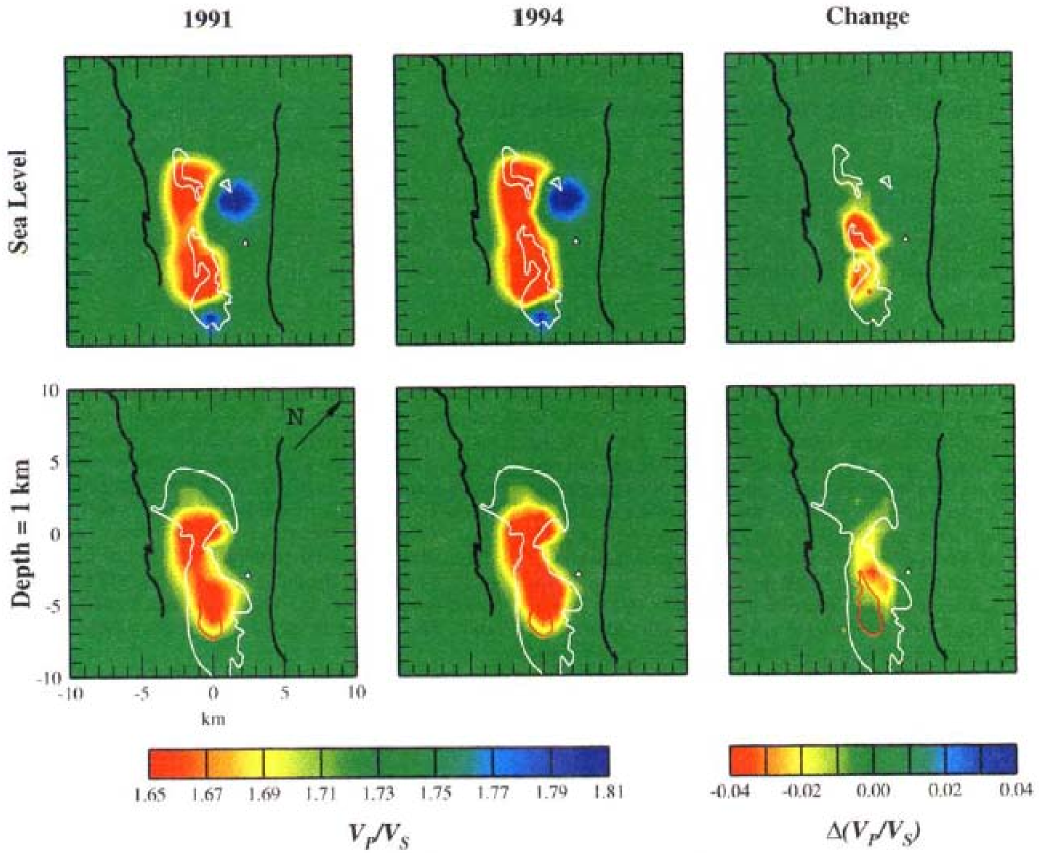
- 4-D Double Difference Tomography for Joint Hypocenter Locations and Vp & Vs Velocity Structure (AIT)
- Full Waveform Moment Tensor Analysis of Events M>3 (UCB)
- Geomechanical Analysis of Steam Production and Water Injection to Model Stress Evolution in the Reservoir (GFZ)
- Estimation of Seismic Hazard and Calculation of Ground Motion (LBNL)

Data to be Used

- Triggered 3-component waveform data from ~ 30 station network (USGS, LBNL, Calpine?)
- Steam production data of all publicly available wells
- Water injection data of all publicly available wells
- Borehole coordinates and deviation logs

UCB

4-D Double Difference Tomography for Joint Hypocenter Locations and Vp, Vs Velocity Structure (AIT)



Foulger et al., 1997

Observed Vp/Vs change: -9%

Change in Pore Property	V_p/V_s-Anomaly
Phase Change: Liquid-to-Vapor	-14 %
ΔT = +10 °C (Liquid)	-1.7 %
ΔT = +10 °C (Vapor)	+0.1 % to +0.7 %
ΔP = -1 MPa (Liquid)	-0.2 %
ΔP = -1 MPa (Vapor)	-6.6 % to -10 %

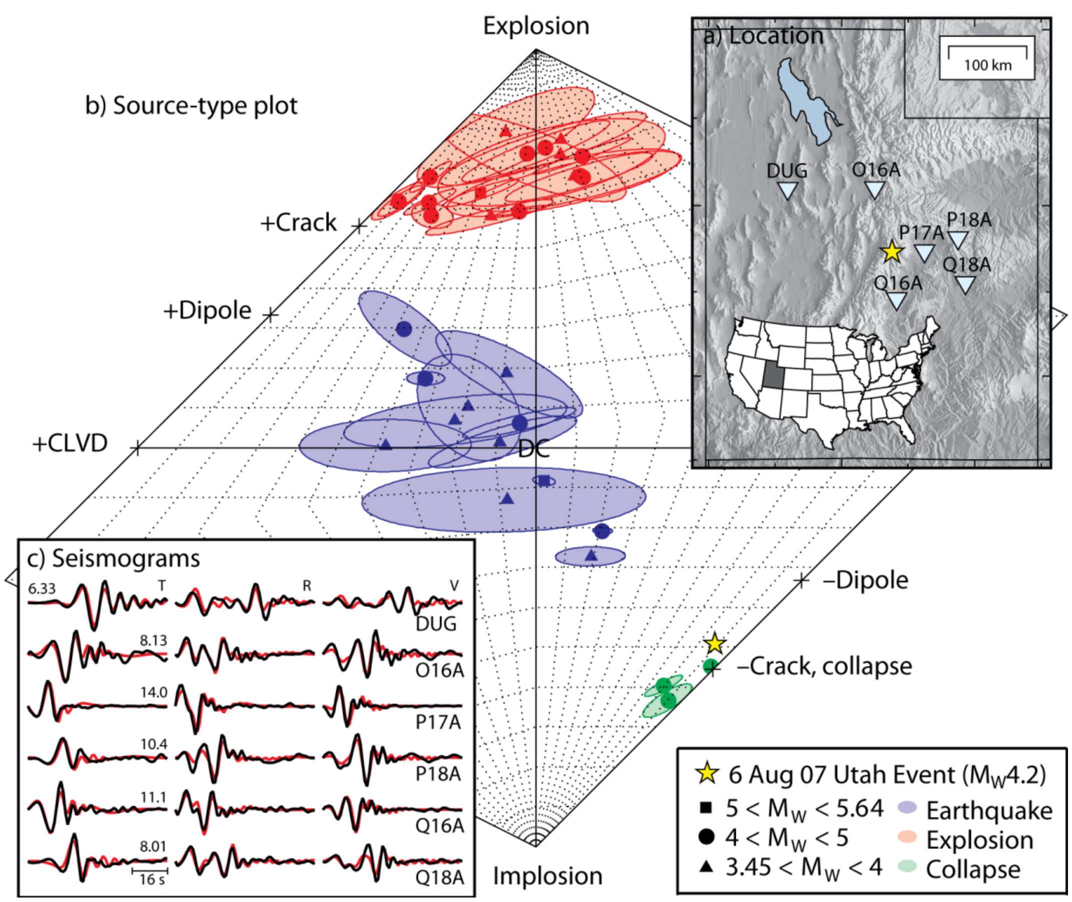
Julien et al., 1996

UCB

4-D Double Difference Tomography for Joint Hypocenter Locations and Vp & Vs Velocity Structure (AIT)

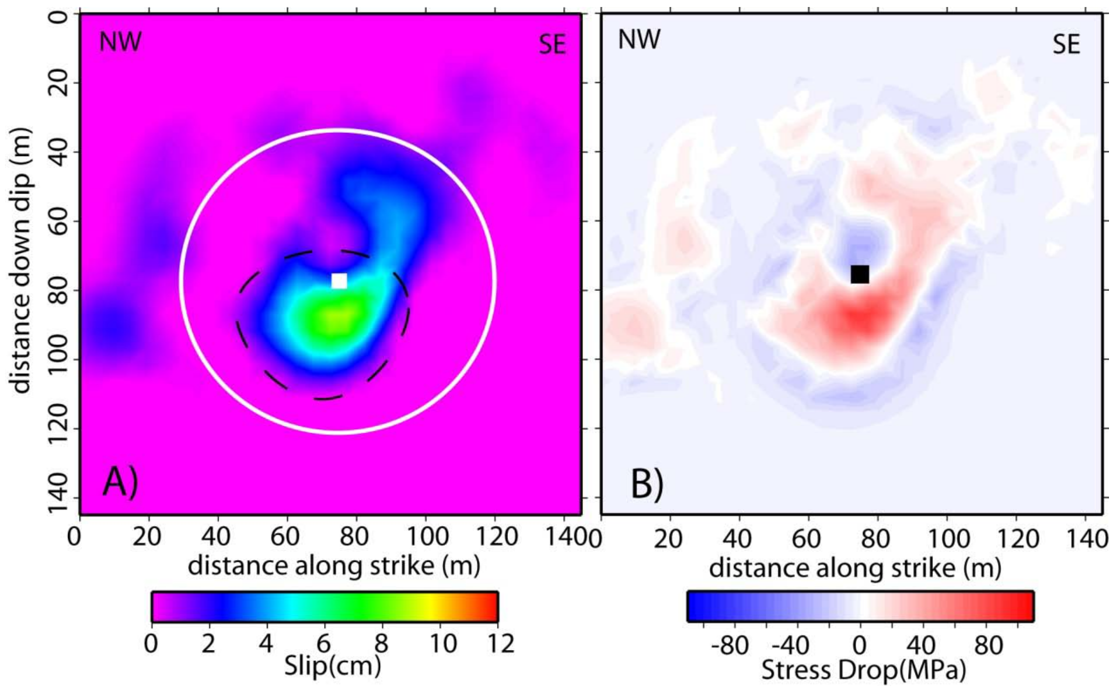
- Double difference method is based on joint inversion for hypocenters and velocity structure
- Hypocenters will be located both, absolutely and relatively (no collapsing or master event approach)
- Determine temporal changes in reservoir throughout 30 year operation history
- Determine magnitude of changes and model with equivalent medium theories
- Locate temporal changes throughout reservoir

Full Waveform Moment Tensor Analysis of Events M>3 (UCB)



- Use moment tensor analysis to determine orientation of slip on faults and state of stress in reservoir
- Full moment tensor analysis allows for non-double couple solutions, i.e. crack opening/dilation
- Source type plots (Hudson et al., 1989) allow to distinguish crack opening due to cooling of reservoir rock from slip events

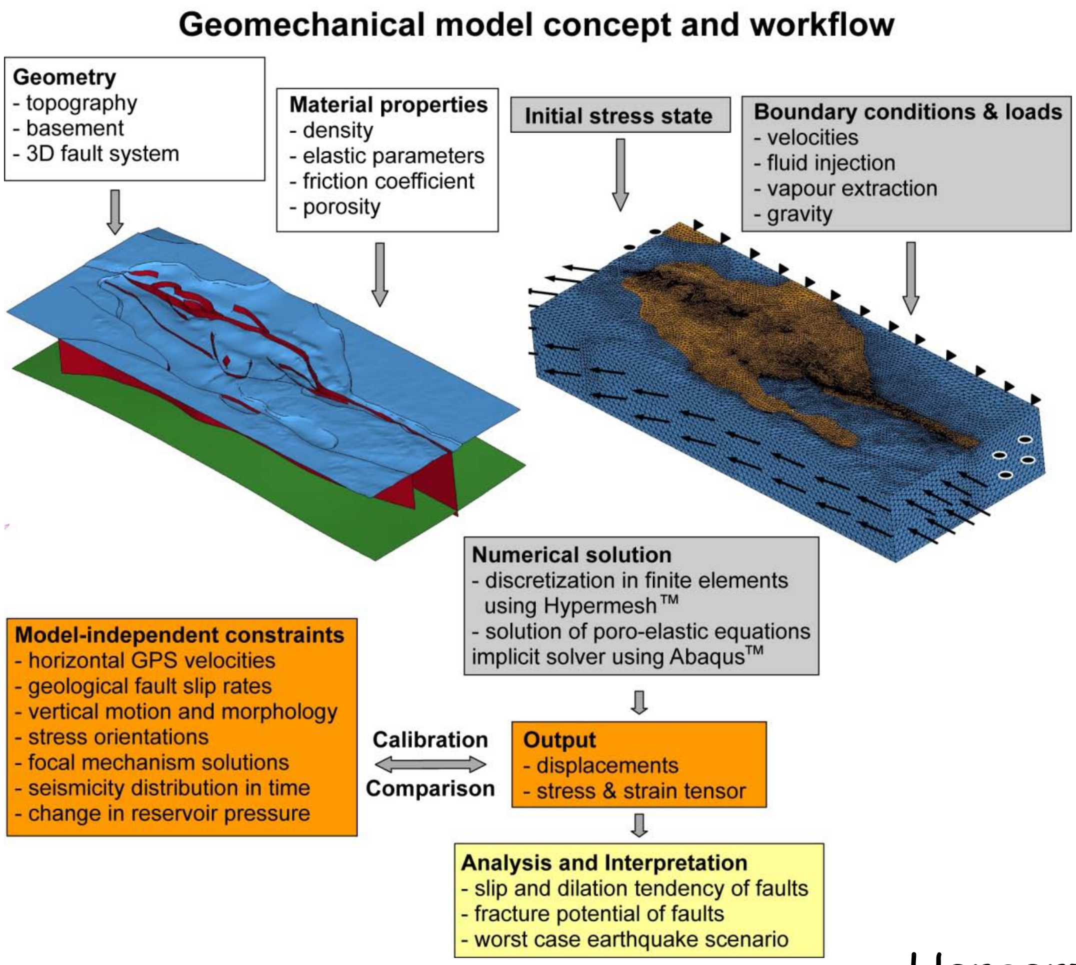
Full Waveform Moment Tensor Analysis of Events M>3 (UCB)



Dreger et al. (2007)

- Determine kinematic source parameters for larger events
- Utilize co-located smaller events for empirical Green function inversions
- Determine slip distribution and stress drop
- Example shows Mw=2.1 event from Parkfield, CA
- Small source dimension ~30 m yield high stress drop of 80 MPa

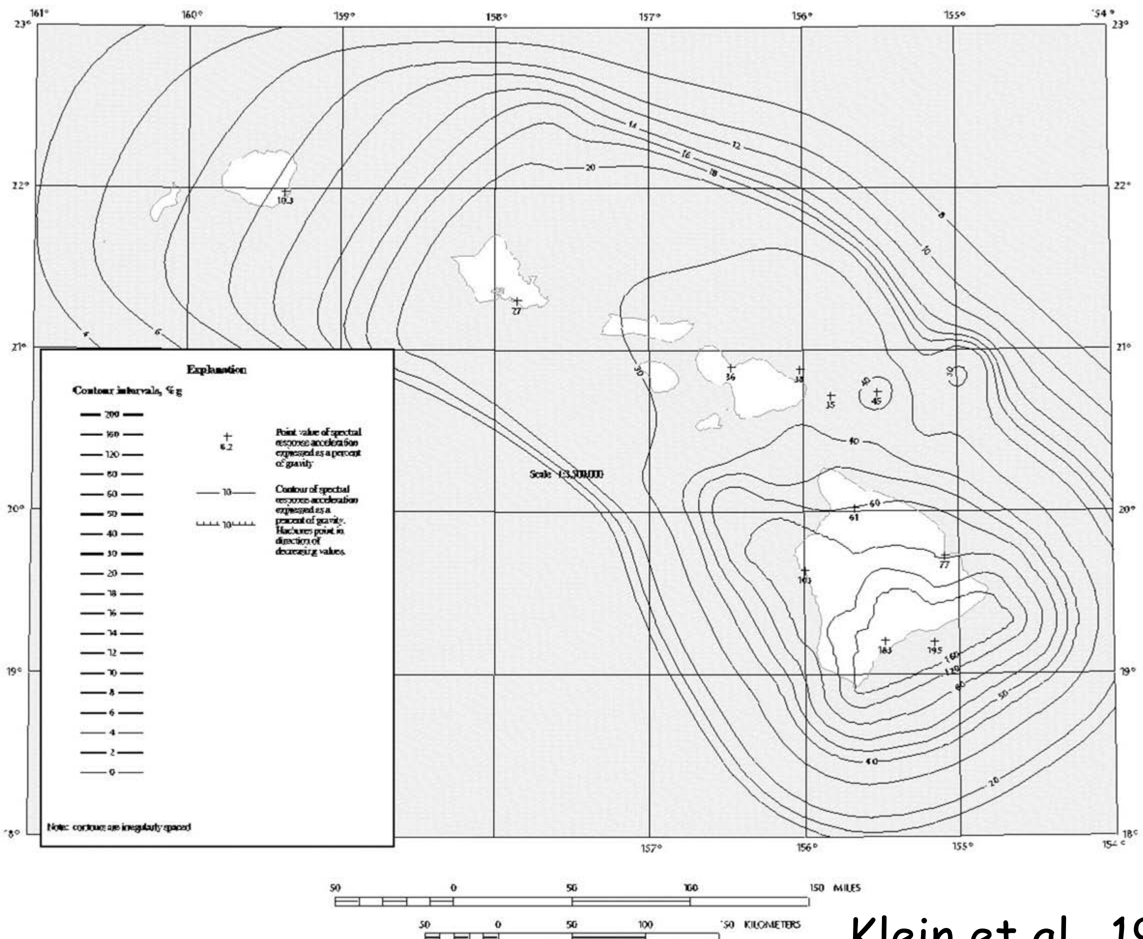
Geomechanical Modeling of Stress Evolution in Reservoir (GFZ)



- Use large-scale geometry and material properties to build reservoir model
- Use far-field stress state, fluid production and fluid injection to determine boundary conditions of reservoir
- Use results from moments tensor analysis, if consistent, to refine model
- Solve poro-elastic eqs. to estimate displacement and stress and strain tensor

Hergert and Heidbach, 2010

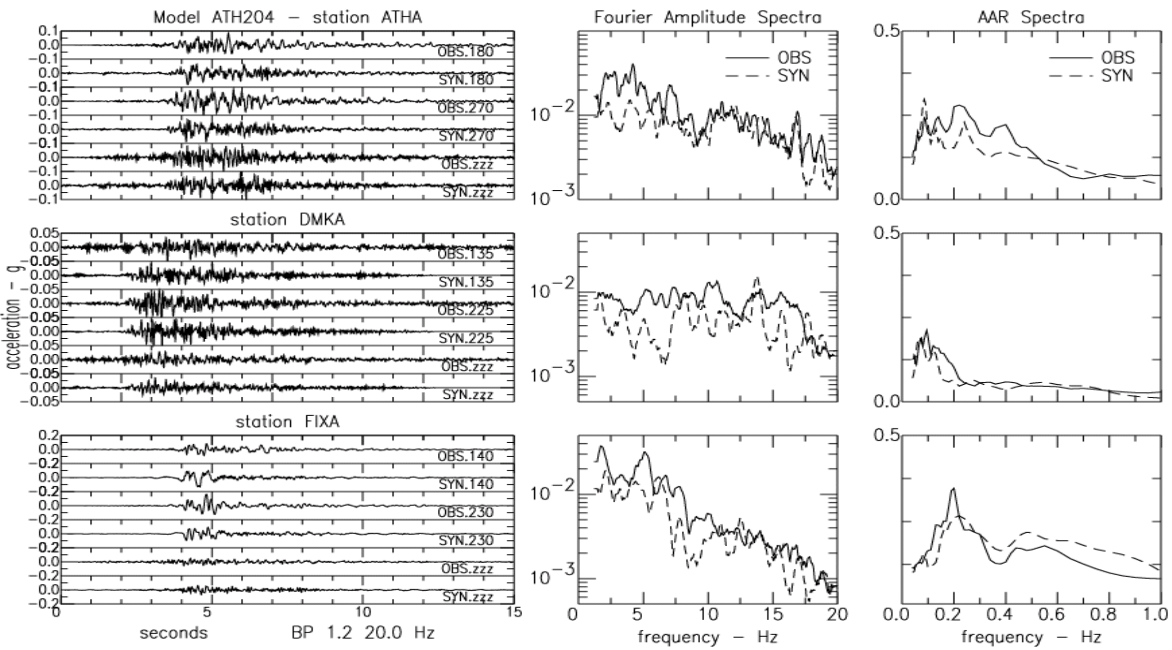
Estimation of Seismic Hazard and Ground Motion (LBNL)



Klein et al., 1996

- Use event hypocenters, velocity models, stress tensors from moment tensor analyses and geomechanical modeling
- Conduct PSHA to determine earthquake recurrence and ground motion amplitudes
- Compute ground motion using empirical Green functions and quasi-dynamic rupture models based on rupture velocity and stress drop from moment tensor analysis and geomechanical modeling

Estimation of Seismic Hazard and Ground Motion (LBNL)



- Calculate potential ground motion for specific faults identified through moment tensor analyses and geomechanical modeling
- Compare results to observed data
- Provides check for conventional PSHA studies
- Will provide source and site specific ground motion seismograms for field site

Hutchings et al., 2007

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Structure of Project

Organization	Task	Budget	Milestone	Year
AIT	4-D Double Difference Tomography for Joint Hypocenter Locations and Velocity Structure, Changes in Reservoir Parameters, Project Management	$ 627,123	01/2011 01/2012 01/2013	1-3
UCB	Full Waveform Moment Tensor Analysis of Events M>3	$ 276,859	01/2011 01/2012 01/2013	1-3
GFZ	Geomechanical Analysis of Steam Production and Water Injection to Model Stress Evolution in the Reservoir	$ 365,019	06/2011 01/2012 06/2012	0.5-2.5
LBNL	Estimation of Seismic Hazard and Calculation of Ground Motion	$ 184,765	06/2012 01/2013	3

Outcome

- Project offers a multidisciplinary approach to understand relationship between reservoir activities and large-scale seismicity
- Results will include geomechanical model of reservoir structure
- Results will provide link between reservoir operations and seismic hazard
- Project will develop technology for comprehensive reservoir analyses
- Project will generate first "complete" data set for The Geysers geothermal reservoir