Seismic Analysis of Spatio-Temporal Fracture Generation During EGS Resource Development

Project Officer: Lauren Boyd

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Dr. Roland Gritto
Array Information Technology

Track 3, EGS1

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Relevance of Research

- Enhanced Geothermal Systems (EGS) represent important pillars of the DOE's green energy portfolio, since most hydrothermal system have already been discovered
- EGS are based on the development of a subsurface fracture network to mine heat from rocks by circulating water through the engineered fracture network
- DOE seeks integrated innovative subsurface interrogation methods yielding empirical observation of critical geothermal reservoir parameters during Enhanced Geothermal Systems (EGS) development
- Most important barriers include the ability to characterize, subsurface fractures (length, aperture, density, orientation, conductivity, and connectivity), stress state (magnitude and orientation) and location of injectate to design optimal drilling, completion, and stimulation procedures

Relevance of Research cont.

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Present state of subsurface fluid characterization:

- At present, seismic applications to estimate the location and volume of injected fluids are typically limited to imaging the location and size of the induced micro-seismic cloud
- However, seismicity can be induced by transfer of stress and/or strain without the presence of fluids resulting in overestimation of fluid volume
- Electromagnetic (and/or electric) methods fair better in locating subsurface fluids but their resolution is limited
- Better methods are needed to detect subsurface fluids at improved resolution
- In the present project we directly address this problem by introducing a technique to better estimate the spatio-temporal variations and the volume of injectate during EGS development

Relevance of Research cont.

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Present state of subsurface fracture characterization:

- At present, numerous seismic methods are available to estimate the seismic moment tensor (MT) and finite-source models
- While the estimation of detailed finite-source kinematic rupture models is non-unique, leading to higher uncertainties, rupture dimensions such as length and area are typical well constrained. Seismic moment tensors can be determined reliably but interpretations are non-unique and ascertaining the source-type when it differs from deviatoric solutions is difficult
- Methods are needed to provide more reliable estimates of source type, slip and fracture area
- In present project we directly address the characterization of fracture network parameters (stress and fracture orientation, fracture aperture and dimensions, rupture velocity and activated fracture volume) by introducing a new integrated method to estimate these parameters with greater certainty

Objective of Project

Subsurface Fluid Imaging:

- Develop double-difference Wadati (DDW) method to estimate spatio-temporal variations of fluid saturation in subsurface and assess applicability during EGS development
- Evaluate sensitivity of method w.r.t. network topology, phase pick uncertainty, and availability of high-frequency and broadband data

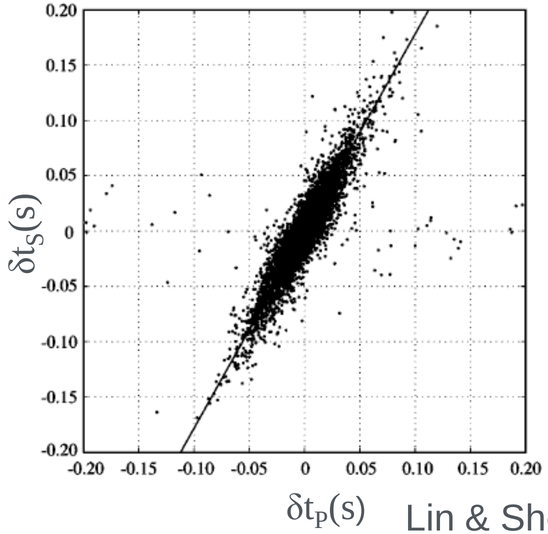
Subsurface Fracture and Stress Characterization:

- Compile first-motion mechanisms and determine source solutions for events spanning the volume of the stimulation experiment
- Examine solutions for possible non-double-couple, volumetric source components
- Develop an empirical rupture area – magnitude – corner frequency relationship to enable mapping of seismic fracture density
- Utilize source parameters to investigate the evolution of in-situ stress during the stimulation experiment

Scientific Approach (DDW)

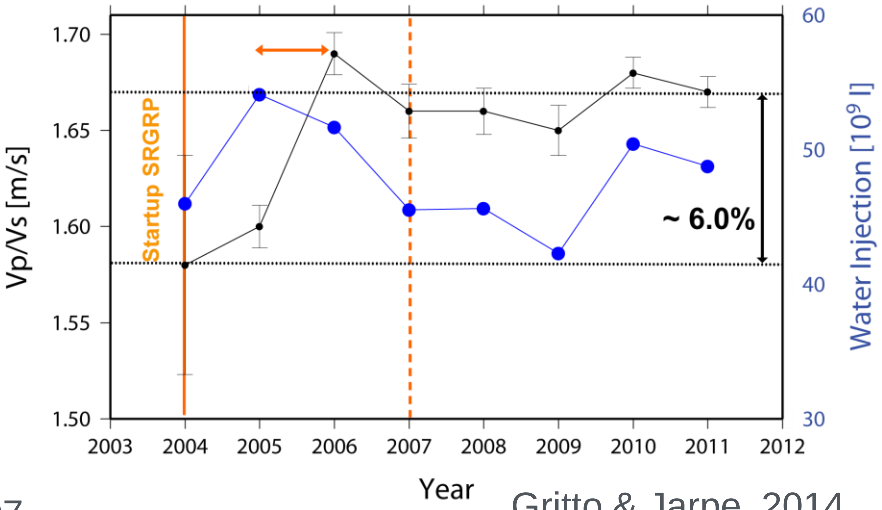
- Wadati method has been used to estimate Vp/Vs ratio of medium below seismic networks
- Double-differencing is common method to eliminate the effect of path between source and point of observation
- Double-difference Wadati method (DDW) uses double differences in P- and S-wave travel times from two neighboring earthquakes to same station to estimate fluid saturation via Vp/Vs ratio in the vicinity of micro-seismic events

Concept of DDW



Lin & Shearer, 2007

Vp/Vs and Water Saturation at The Geysers



Gritto & Jarpe, 2014

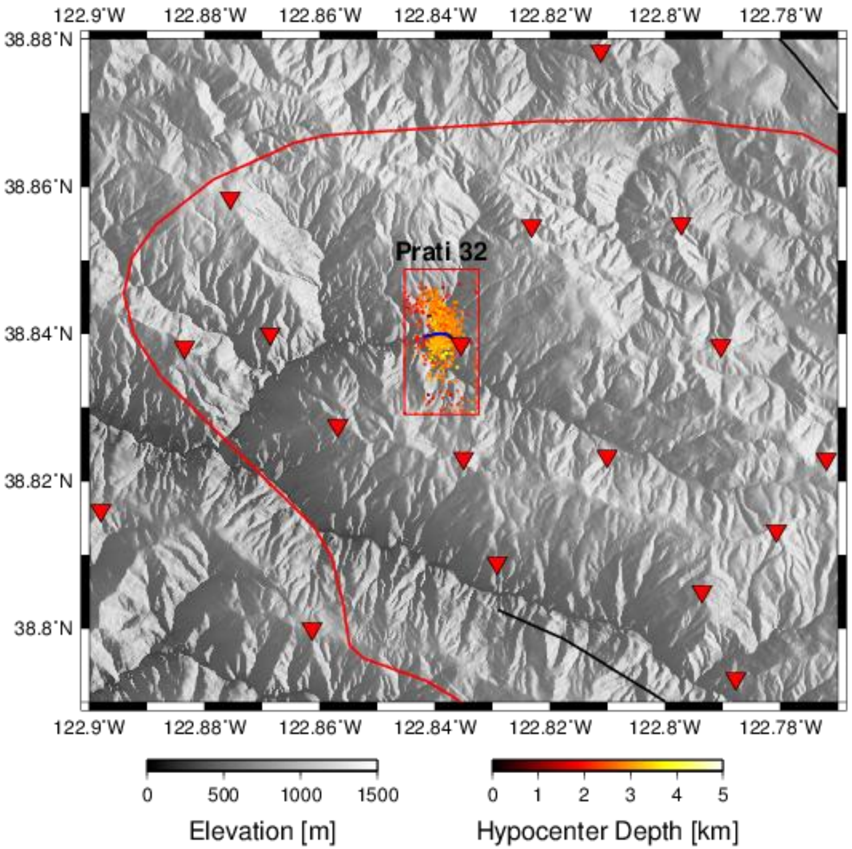
Scientific Approach (DDW)

- Apply DDW to seismic data recorded during EGS demonstration project at The Geysers (Prati 32)
- Leverage waveform data recorded by 34-station high-frequency geophone network (LBNL, DOE funded) and by 33-station broadband seismometer network (GEISER, EU funded)
- Determine spatio-temporal changes in fluid saturation via Vp/Vs from subsets of seismicity using phase arrivals from hand-picks and waveform cross correlation (with subsample precision on broadband data)
- Estimate aleatory and epistemic uncertainty of DDW results including network topology, uncertainty in phase arrivals and subsets of seismicity to evaluate applicability of DDW to EGS development

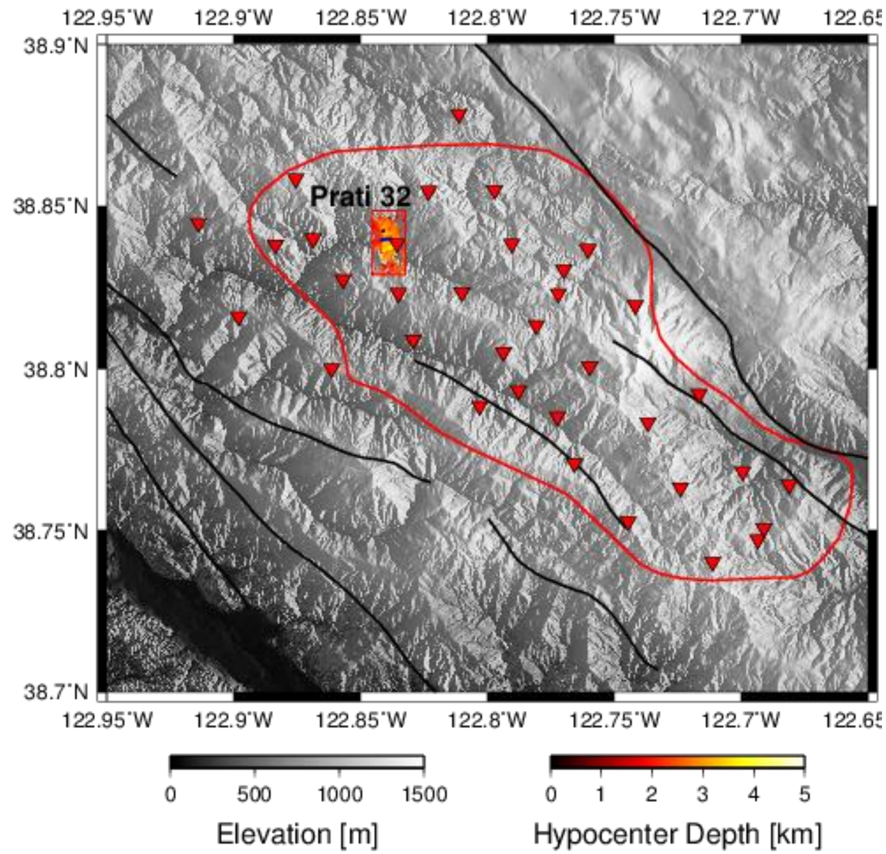
Scientific Approach (DDW)

- The Geysers and Prati 32 are perfectly suited to develop and to test statistical properties of DDW, due to high rate of seismicity and large number of seismic stations (high-frequency and broadband)

Seismicity at The Geysers EGS Site



Seismicity at The Geysers EGS Site



Scientific Approach (Fracture Size, Fracture Density, In-situ Stress)

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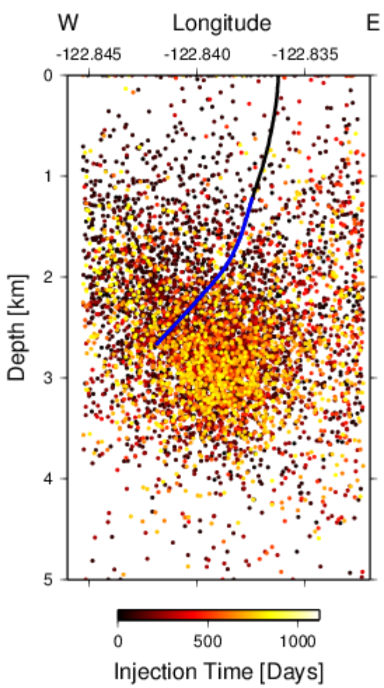
- Develop new integrated non-linear least-squares MT inversion in source-type space based on three independent datasets to improve recovery of MT source-type (Nayak and Dreger, 2015)
    - 3-component full waveform data
    - first motion polarization data
    - P/SV- and P/SH wave amplitude ratios
- Develop finite-source solutions to estimate slip, rupture area and orientation, and stress change (drop and increase) for events for which representative empirical Green functions (egf) can be found
- Utilize measured corner frequencies, magnitude and derived finite-source parameters to develop scaling relationships to enable estimation of fracture size and activated fracture volume
- Final parameters include: stress and fracture orientation, fracture aperture and dimensions, rupture velocity and activated fracture volume

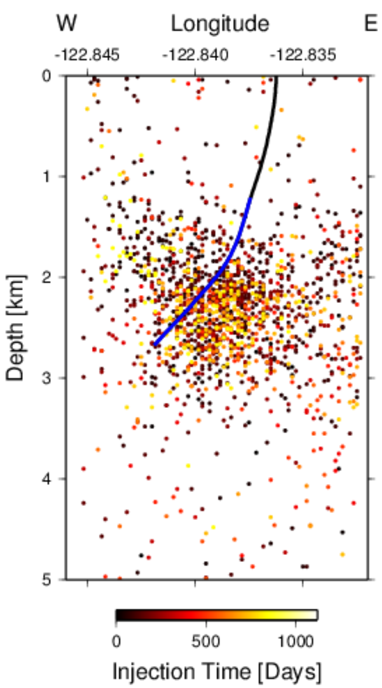
Progress (DDW)

- Duration of Project: 10/01/2014 – 12/31/2017
- Period of Performance: 01/01/2015 – 12/31/2017, due to programmatic commitments of the AIT and UCB in Q1 FY 2015
- Compiled four high-frequency seismicity catalogs for area in vicinity of the injection well Prati 32 from 10/06/2011 – 03/31/2015

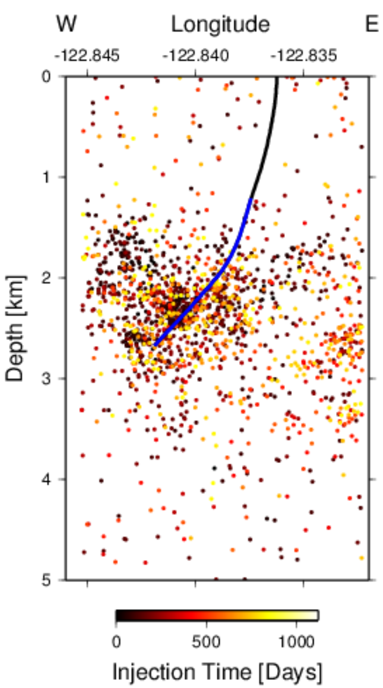
LBNL all Events



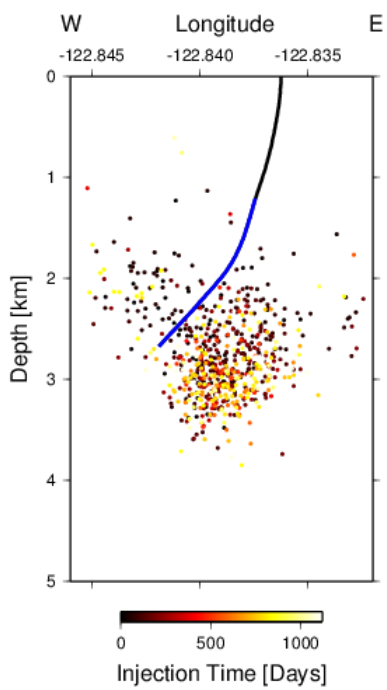
USGS Reviewed Events



DD-Events



LBNL High-Accuracy Events



Progress (DDW)

- Depth locations are questionable as evident from catalogs
- Need to re-locate events using simultaneous 3D inversion for P- and S-wave velocity structure and double-difference locations for region around Prati 32
- Apply DDW to newly developed catalog to estimate spatio-temporal changes in saturation via Vp/Vs and to assess statistical uncertainties

Progress (Fracture Size, Fracture Density, In-situ Stress)

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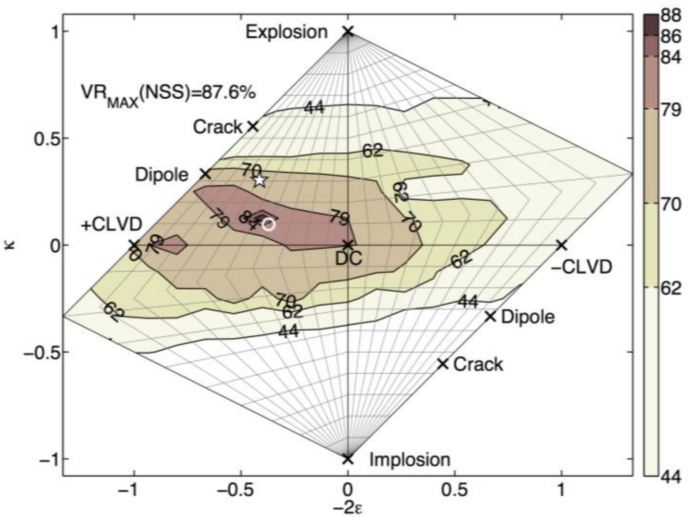
- We have demonstrated the feasibility of determining joint waveform first-motion source solutions and finite-source slip models
- The compilation of source rupture area vs magnitude for five events is found to be consistent with the extrapolation of a published area vs magnitude relationship

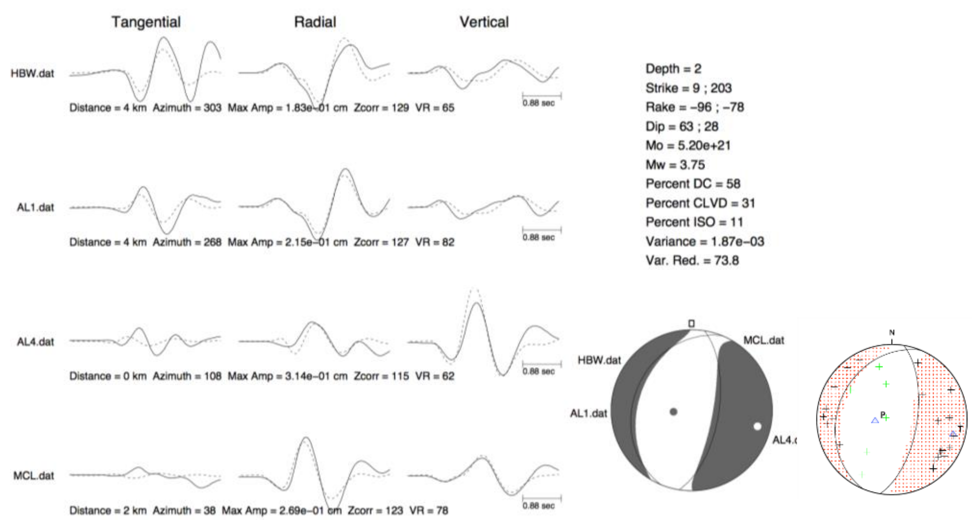
Joint Waveform First-Motion Moment Tensor Source-Type Inversion - January 21, 2014, Mw 3.7

Long-period waveforms (0.2 -1Hz) and P-wave first-motions are inverted using a new iterative least-squares approach for specific eigenvalue ratios (star: waveform solution; circle: joint data solution)



NSS, Ford et al. (2010), Nayak & Dreger (2015)

Waveform and First-Motion Fit for Best Solution



Progress (Fracture Size, Fracture Density, In-situ Stress)

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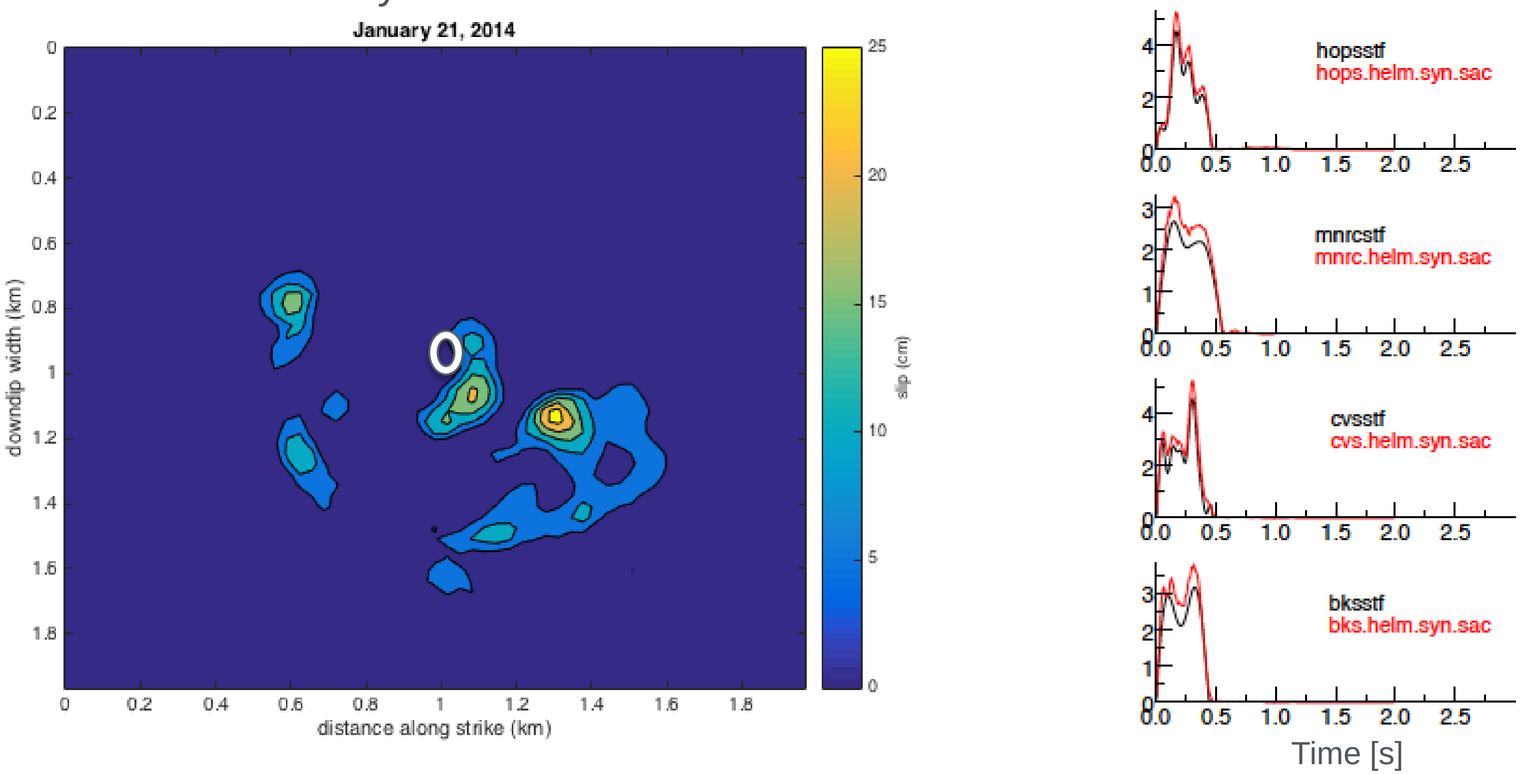
- Seismic moment rate functions of a Mw 3.7 event obtained by deconvolution of waveforms from nearby Mw 2.55 event
- Records are inverted for finite-source parameters using method of Mori and Hartzell (1990) as applied in Dreger (1997); white ellipse marks hypocenter

Preliminary Finite-Source Inversion of Seismic Moment Rate Functions



Progress (Fracture Size, Fracture Density, In-situ Stress)

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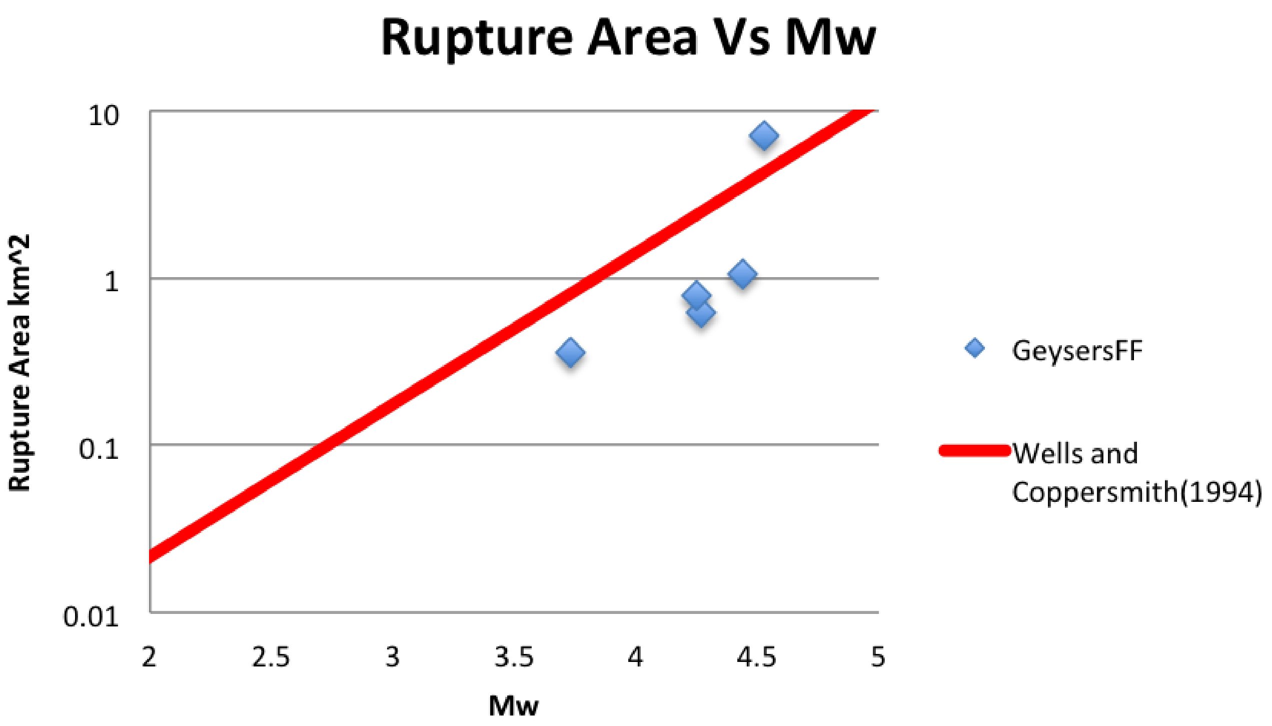
- Rupture area obtained from finite-source models plotted against Mw, considering only regions with slip larger than 10% of peak slip
- The red line represents relationship by Wells and Coppersmith (1994)

Rupture Area Scaling



Accomplishments, Results and Progress

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1: Determine spatio-temporal changes in fluid saturation, conduct uncertainty estimation of DDW for high-frequency data (12/31/2015)	Compiled four high-frequency data catalogs	03/31/2015
Task 2: Determine MT, finite-source kinematic slip models, empirical rupture-area vs magnitude vs corner frequency scaling relationship (12/31/2015)	Developed a joint waveform – first motion – amplitude source-type moment tensor inversion method. Demonstrated feasibility of determining joint waveform and first-motion source solutions and finite-source slip models. Source rupture models vs magnitude for five events were found to be consistent with extrapolation of a published area vs magnitude relationship.	03/31/2015

Future Directions (DDW)

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Milestone or Go/No-Go	Status & Expected Completion Date
MS Task 1: Select events recorded at well distributed stations with an azimuth gap of less than 150 degrees. The standard deviation in the resulting Vp/Vs estimates should be less than 0.2.	**Status:** Compiled four seismic catalogs **Next:** Relocate events with joint 3D inversion for double-difference locations and P/S velocity structure; determine phase arrivals through waveform cross correlation, estimate spatio-temporal subsurface saturation; conduct statistical analysis of uncertainty **Expected Completion Date:** 12/31/2015
MS Tasks 3,5,6: See Three-Page GTO Project Summary	See Three-Page Project Summary

Future Directions (Fracture Size, Fracture Density, In-situ Stress)

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Milestone or Go/No-Go	Status & Expected Completion Date
MS Task 2: Recover uncertainties in focal parameters for the moment tensor within 20 degrees or better and in moment by a factor of two or better. It is also desirable to recover the moment rate functions at three or more stations covering more than 180 degrees in azimuth around the source.	**Status:** Demonstrated feasibility of determining joint waveform & first-motion source solutions and finite-source slip models. Compiled source rupture area vs magnitude for five events and found it to be consistent with the extrapolation of a published area vs magnitude relationship **Next:** Incorporate existing amplitude ratio code into joint inversion code. Continue analysis of source mechanisms and finite-source solutions. Develop regression of rupture area, source corner frequency and magnitude data for a Geysers specific scaling relationship **Expected Completion Date:** 12/31/2015
MS Tasks 3,4,7: See Three-Page GTO Project Summary	See Three-Page Project Summary

Summary

- Project started three months ago (at time of slide preparation)
- Project addresses key barriers to the ability to characterize subsurface fractures, stress state and location of injectate to design optimal drilling, completion, and stimulation during EGS development
- Project aims to develop new integrated technologies to address these barriers
- Project is based on unique leveraged datasets (high-frequency and broadband seismic data)