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

Project Officer: Lauren Boyd

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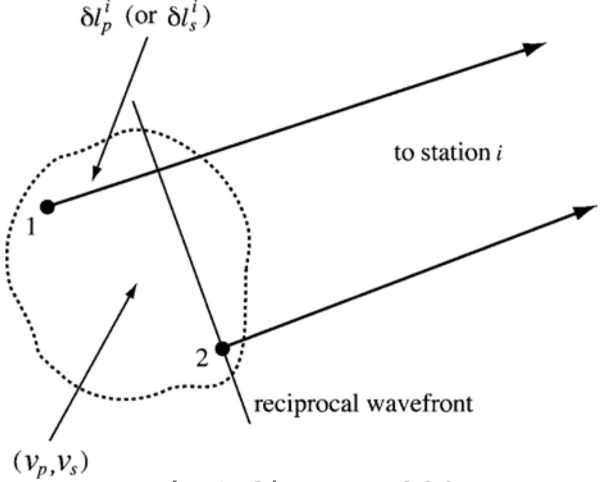
Track 3, EGS GEOPHYSICS

Relevance and Objectives of Research

- Most important barriers to EGS development include ability to characterize subsurface fractures (length, aperture, density, orientation, conductivity, connectivity), stress state (magnitude/orientation) and status and location of injectate
- The goals of our project include the development of technology to overcome these barriers, and to be able to apply the technology to other EGS systems
- The Geysers are an ideal setting for the development of seismic technology due to the high rate of seismicity and controlled environment (injection and production wells)
- Develop double-difference Wadati (DDW) method to estimate spatio-temporal variations of fluid saturation in subsurface and assess applicability during EGS development
- Develop semi-automatic MT technique to analyze evolving state of activated EGS volume including stress orientation and temporal stress changes and total activated fracture area

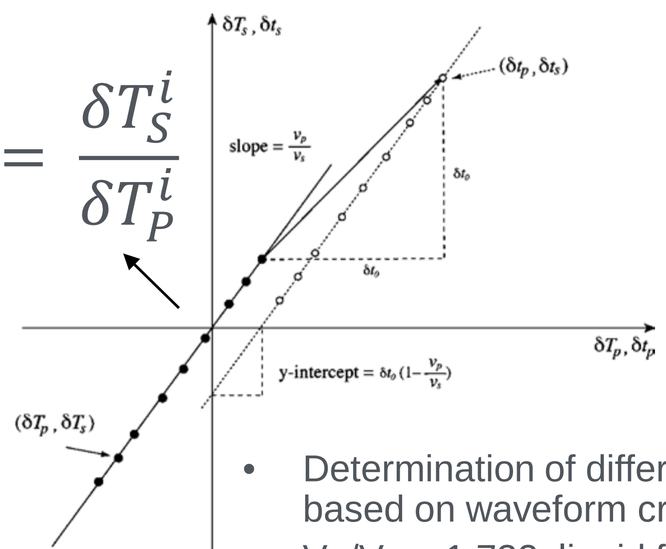
Scientific Approach (DDW)

- Wadati method has been used to estimate Vp/Vs ratio of medium below seismic networks
- Apply DDW to seismic geophone and broadband data recorded during EGS demonstration project at The Geysers (Prati 32) Determine spatio-temporal changes in fluid saturation via Vp/Vs from recorded seismicity using phase arrivals from waveform cross correlation



Lin & Shearer, 2007

$$\frac{V_P}{V_S} = \frac{\delta T_S^i}{\delta T_P^i}$$



- Determination of differential arrival times based on waveform cross correlation
- Vp/Vs > 1.732 liquid fluid saturation
- Vp/Vs < 1.732 gaseous fluid saturation

Scientific Approach (In-situ Stress and Fracture Characterization)

- Develop semi-automated moment tensor procedure for the analysis of numerous small events using 3-component full waveform data.
- In some cases waveforms and first-motion polarities are combined to improve recovery of MT source-type (e.g. Nayak and Dreger, 2015).
- Utilize source parameters (strike, dip, rake) to invert for stress field orientation and temporal changes during fluid injection.
- Develop finite-source solutions to estimate slip, rupture area for using both empirical (e.g., Dreger et al., 2007) and theoretical (e.g., Dreger et al., 2015) Green's function methods.
- Develop scaling relationships between Mw and fracture area to enable estimation of fracture area and activated fracture volume
- Estimate activated fracture area within the Prati 32 study region.

Progress (DDW)

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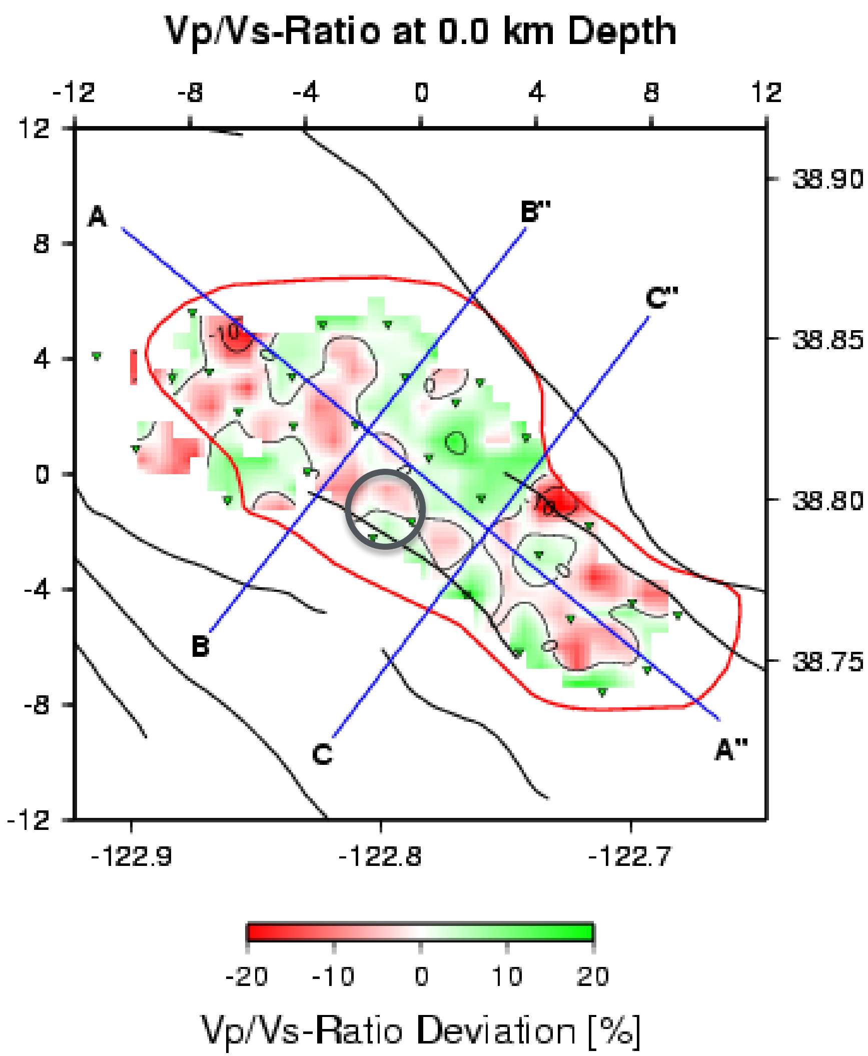
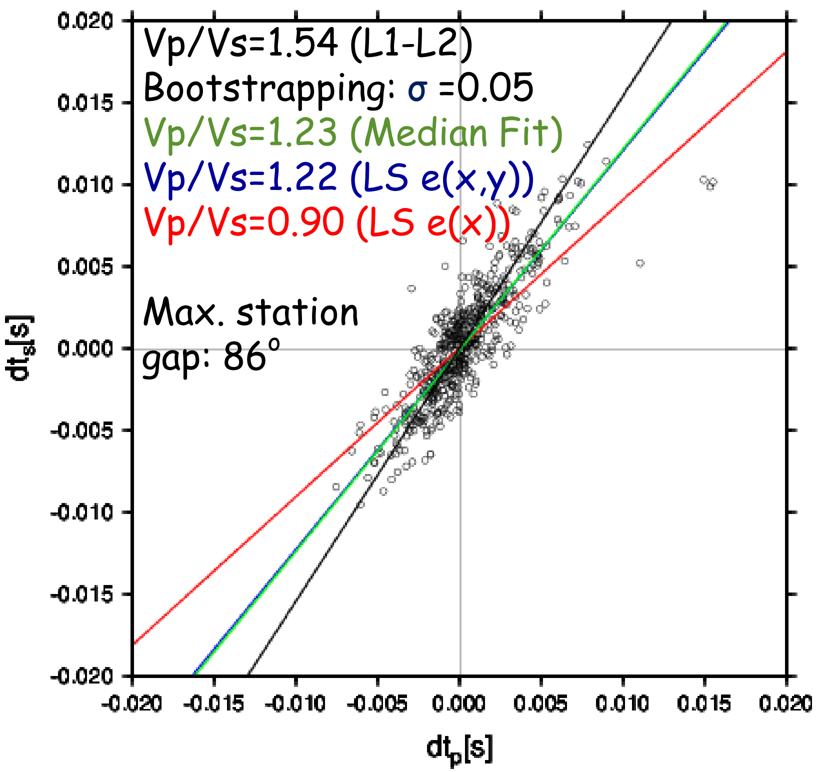
- Compiled high-frequency seismicity catalog of seismicity recorded by LBNL geophone network for area in vicinity of injection well Prati 32 for pre- and post-injection time intervals
- Performed waveform cross correlation for complete catalog to obtain differential travel times
- Implemented robust L1-L2 fitting norm to account for travel time uncertainty and outliers
- Tested DDW in reservoir area with known steam presence (Fumaroles)
- Performed DDW analysis on pre- and post start-of-injection seismicity recorded by geophone network
- Analyzed previous unavailable (leveraged) broadband seismic waveform data, located seismicity and performed waveform cross correlation to obtain differential travel times
- Compiled a new seismicity catalog from broadband data comprised of 65,000 events throughout The Geysers

Progress (DDW)

Gritto et al., 2013, DE-EE0002756



Result of DDW Analysis at The Fumaroles Area



Progress (DDW)

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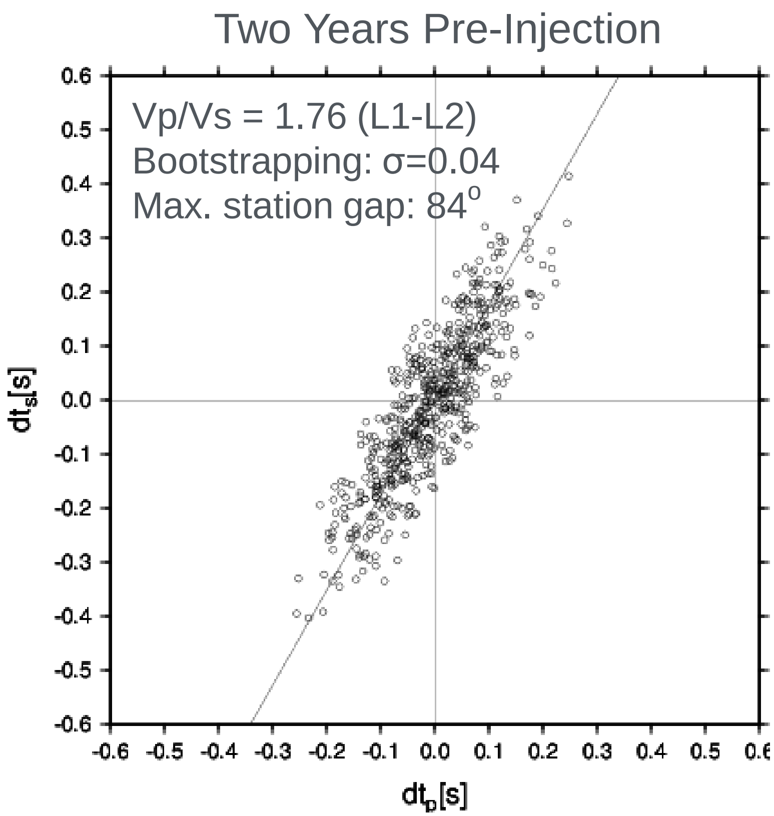

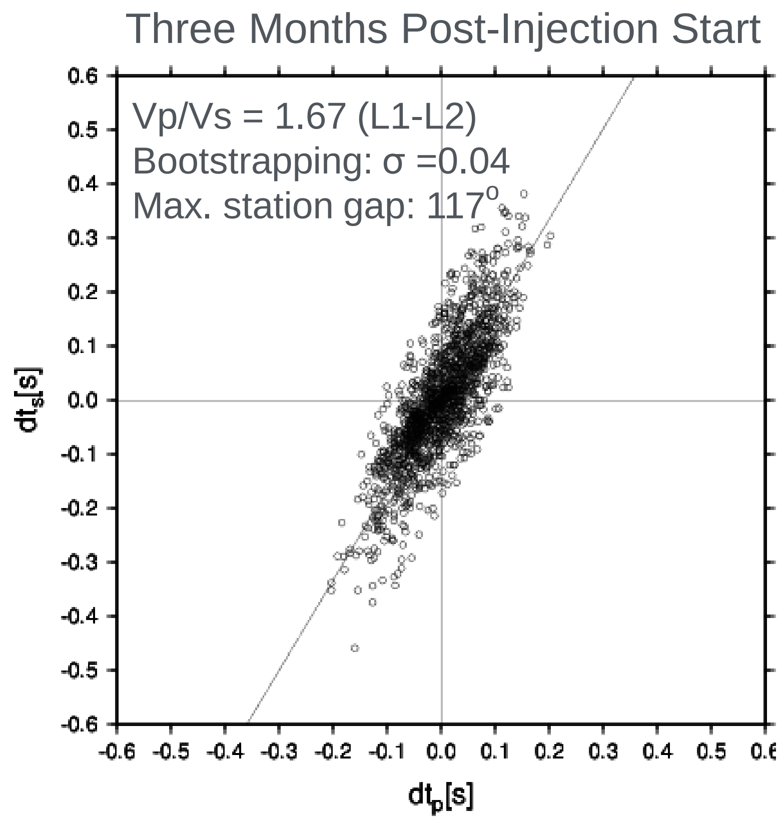

- Injection of water in high-temperature reservoir (~ 300 °C) will likely result in water flashing to steam
- Observed change from Vp/Vs = 1.76 (pre-injection) to Vp/Vs = 1.67 (during three months post-injection start) is in agreement with an increase in steam saturation below Prati 32

Progress (In-situ Stress and Fracture Characterization)

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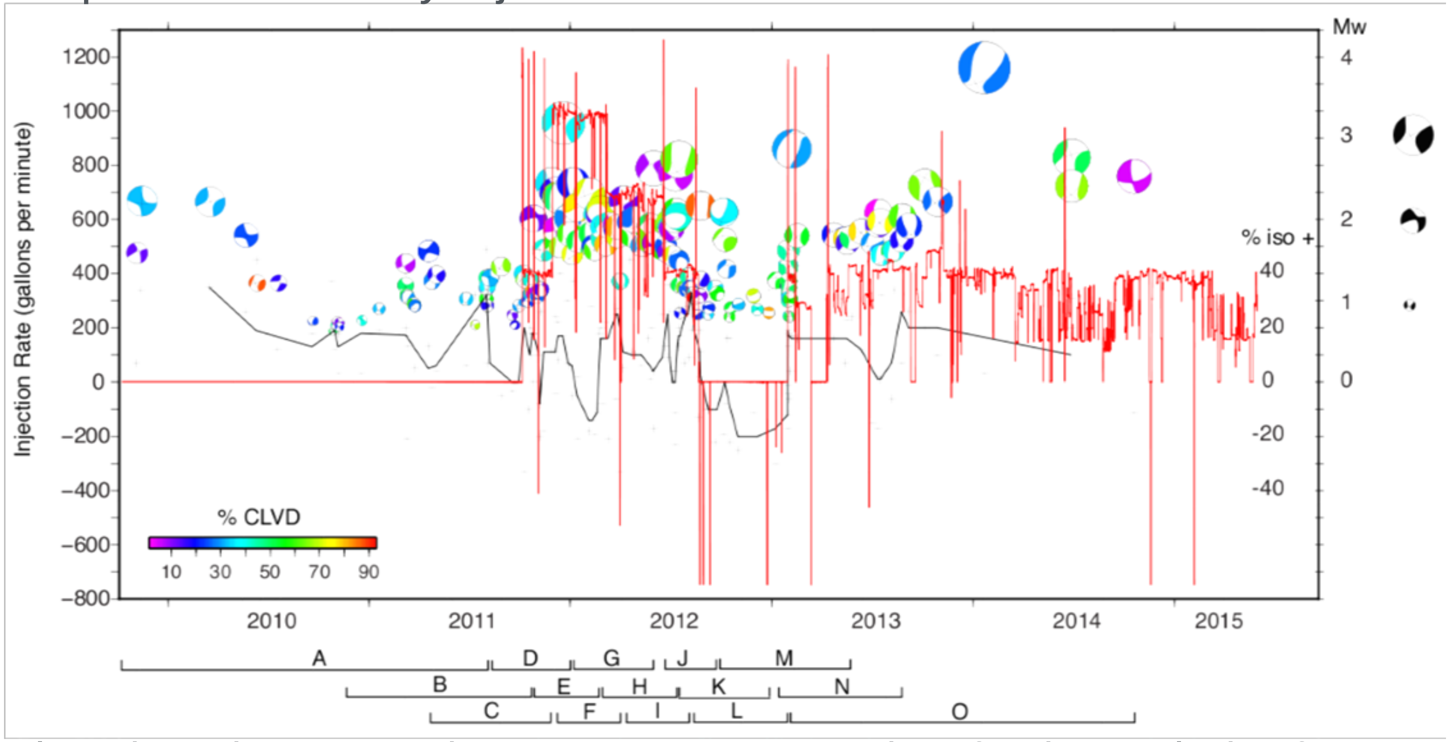
Comparison of Hourly Injection Rate at Prati 32 and 168 MT Solutions



- Developed semi-automated moment tensor procedure for the analysis of numerous small events and compiled a catalog of 168 MT solution 0.7 ≤ Mw ≤ 3.9 (see above)
- Increase in both frequency and magnitude of events following the injection of fluid
- Largest events appear correlated with changes in injection rate
- Variety in focal mechanisms is greater prior to and during the first ten months of injection
- Subsequent focal mechanisms following multiple shut-in periods become more uniform and consistent with the tensile stress direction inferred from previous studies

Progress (In-situ Stress and Fracture Characterization)

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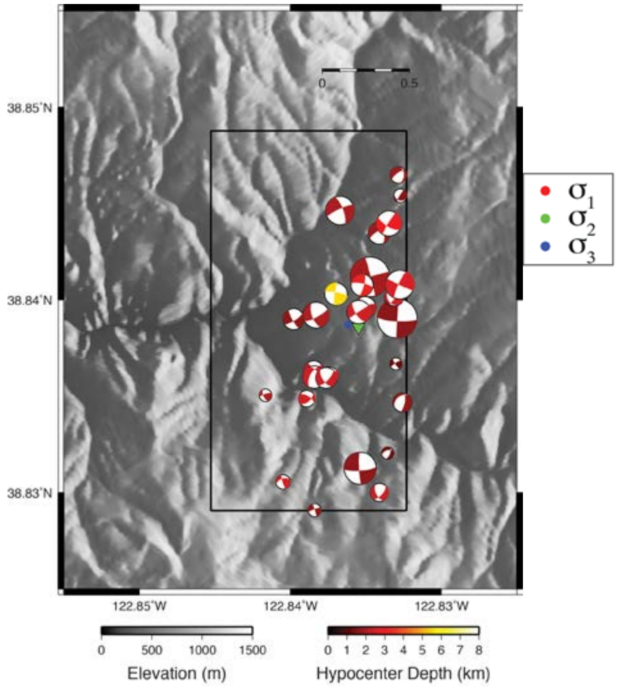
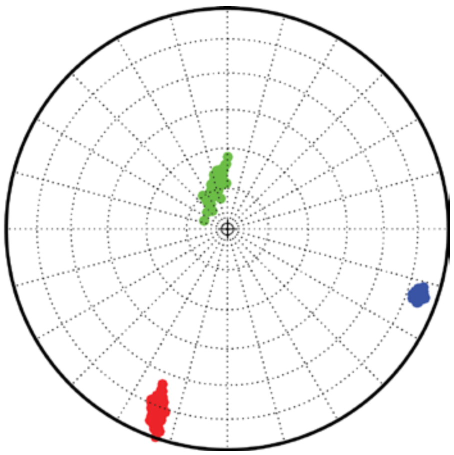
Example Stress Inversion (STRESSINVERSE, Vavrycuk 2014) for a Time Window with 30 Earthquakes





- Iterative method is used to invert MT results (strike, dip, rake) to find the nodal plane most consistent with stress field given fault frictional properties
- Maximum compressive stress σ_1 (red), σ_2 (green) and the least compressive stress σ_3 (tensile, blue)
- Distribution of points provides 95% confidence region for estimates

Progress (In-situ Stress and Fracture Characterization)

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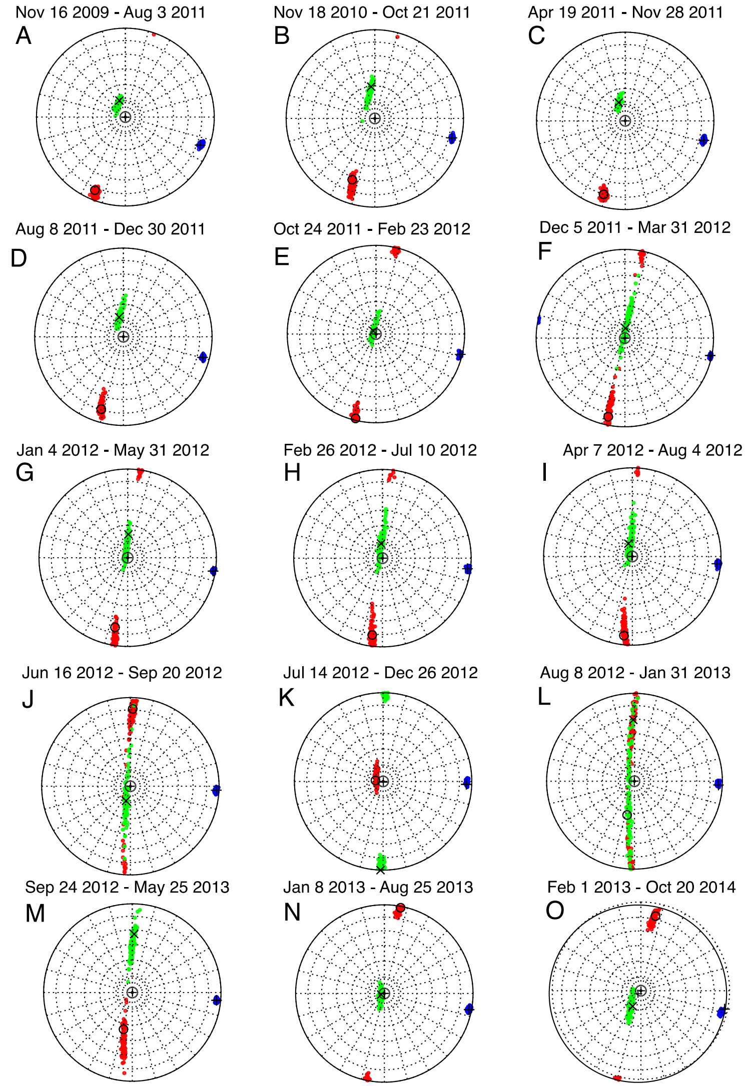
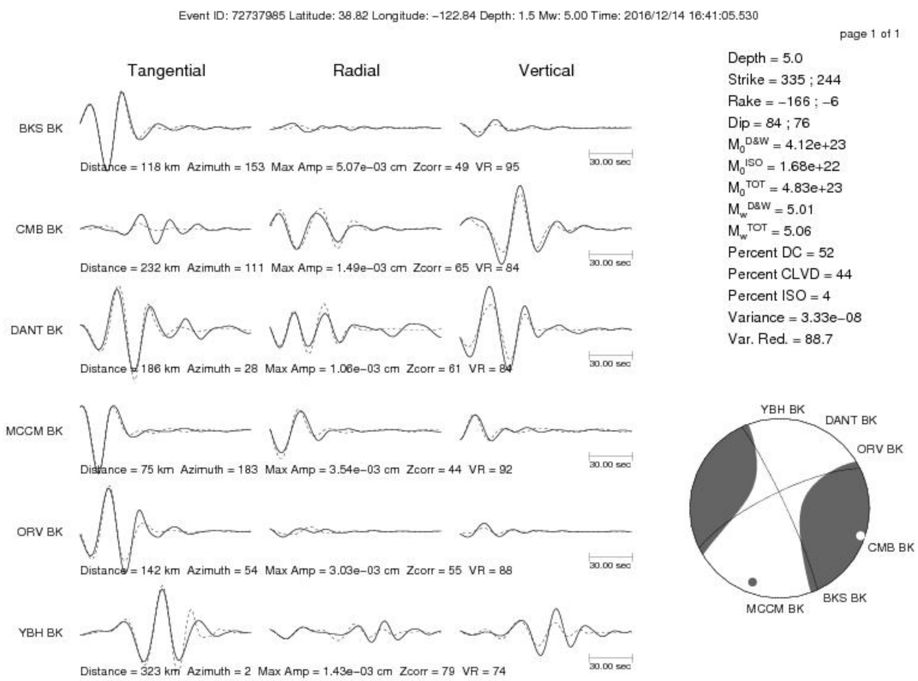
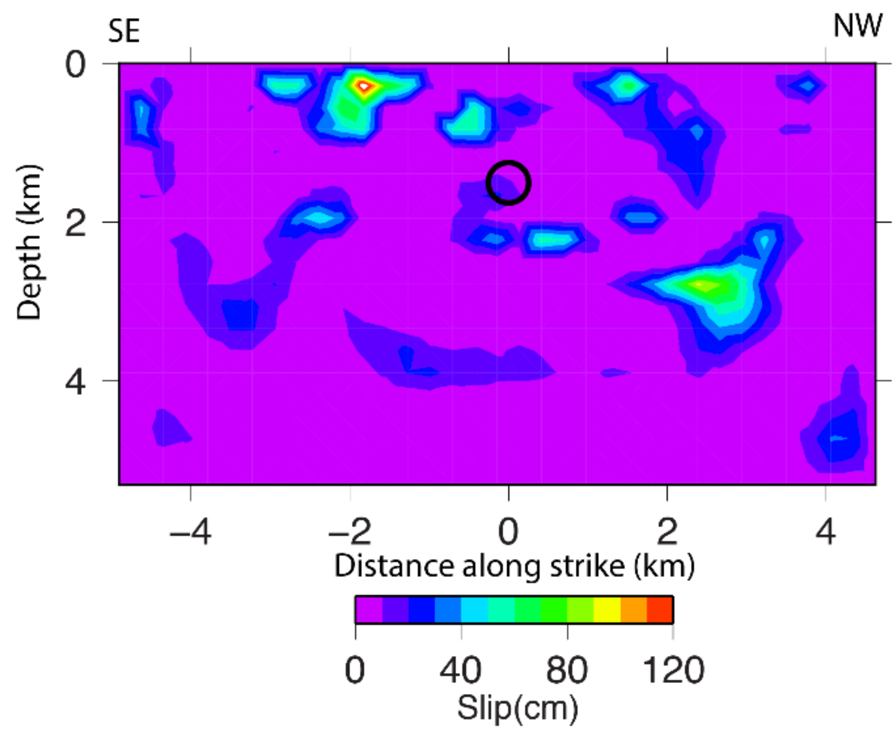
Stress-Tensor Inversion Results for 15 Time Windows

- First panel represents pre-injection time period, spanning the most time due to the low pre-injection seismicity rate
- During-injection results show systematic counter-clockwise rotation of stress-tensor (most clearly seen for σ_3 (blue))
- σ_1 (red) rotates from horizontally oriented to near vertically oriented and then back
- Rotation of σ_1 (red) and σ2 (green) indicates system is evolving to more tensile faulting state
- Consistent with moment tensor solutions shown in previous slides, which change from predominantly strike-slip (pre-injection) to mix of strike- and normal-slip focal mechanisms (during injection)

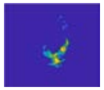


Full Moment Tensor Inversion and Fault Slip Distribution of Mw5 Event at The Geysers





Finite-Source Models for a Mw2.8 Earthquake



Progress (In-situ Stress and Fracture Characterization)

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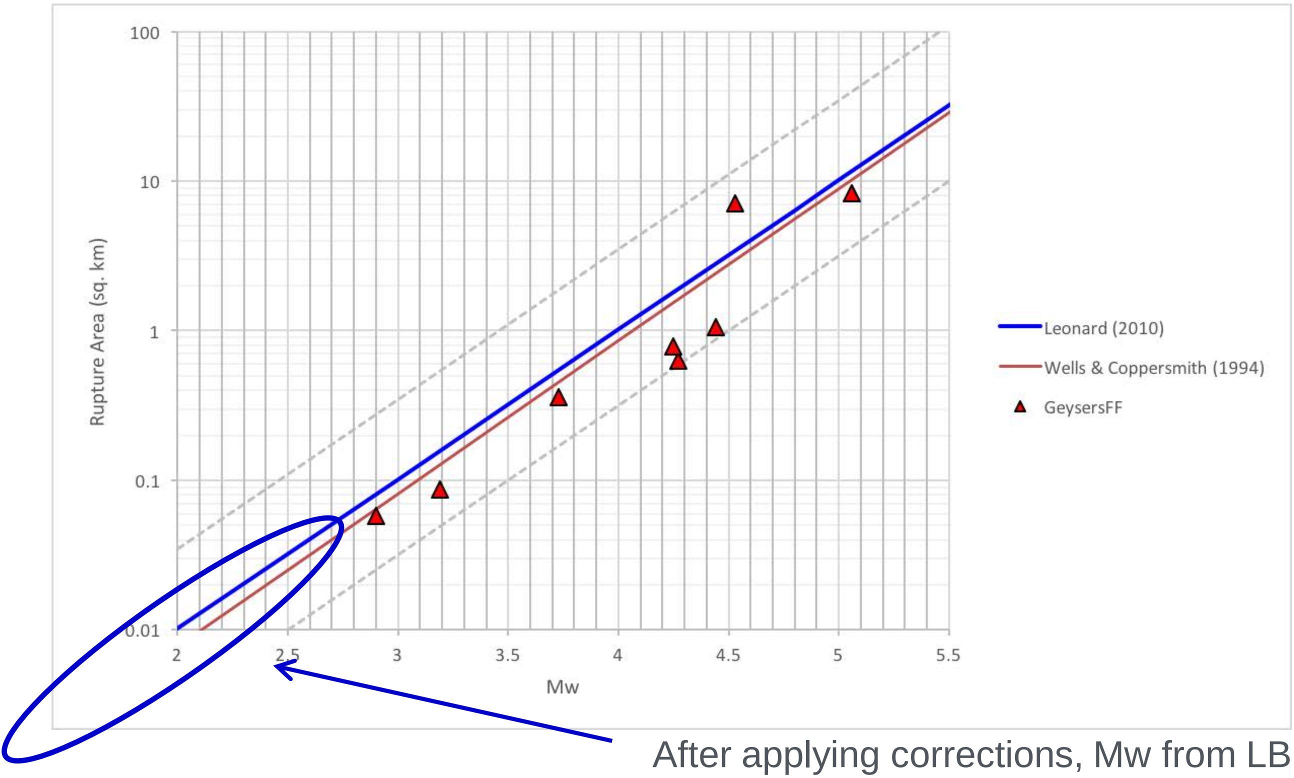
Rupture Area Estimation Derived from Moment Magnitude

- Rupture area obtained from finite-source models plotted against Mw, considering only regions with slip larger than 10% of peak slip



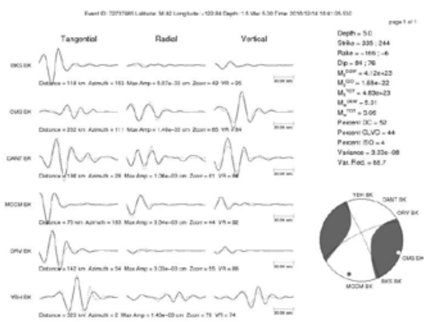
After applying corrections, Mw from LBNL catalog will be mapped to rupture area

- Rupture area for Geysers events is compared to scaling relationships by Wells and Coppersmith (1994) and Leonard (2010), each developed for M≥5.5
- Very high correlation with Geysers rupture area data indicates relations can be extrapolated to small magnitude and are appropriate for the Geysers

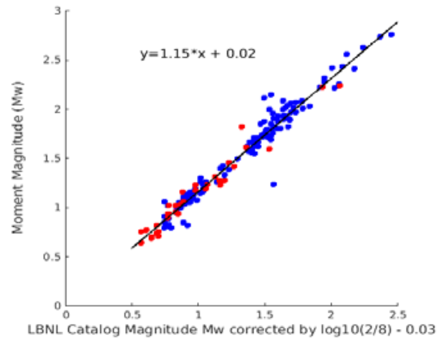
Progress (In-situ Stress and Fracture Characterization)

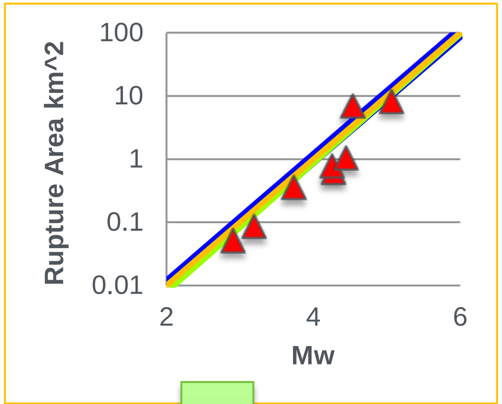
Flow Chart: Moment and Finite-Source to Fracture Density

Seismic Moment Tensor

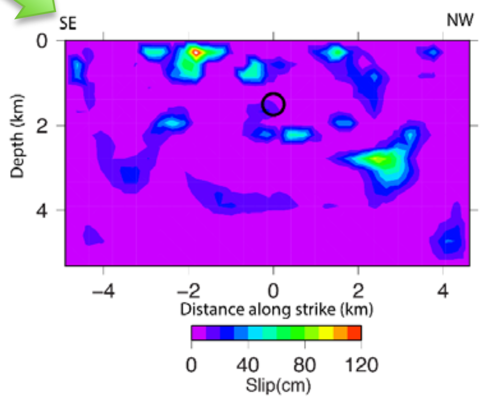


Calibration of Catalogued Mw

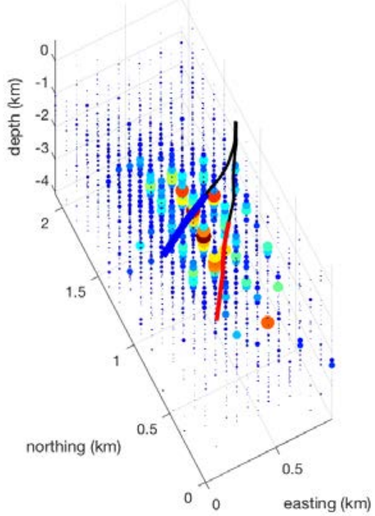




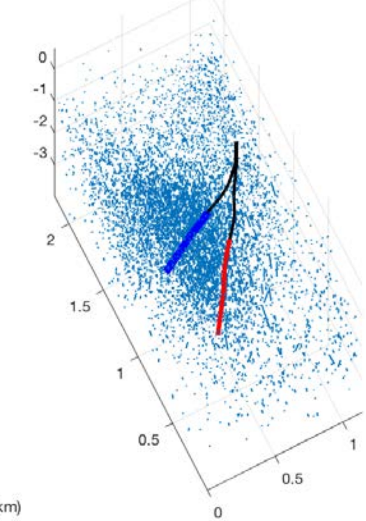
Finite-Source Slip Inversion



Fracture Density

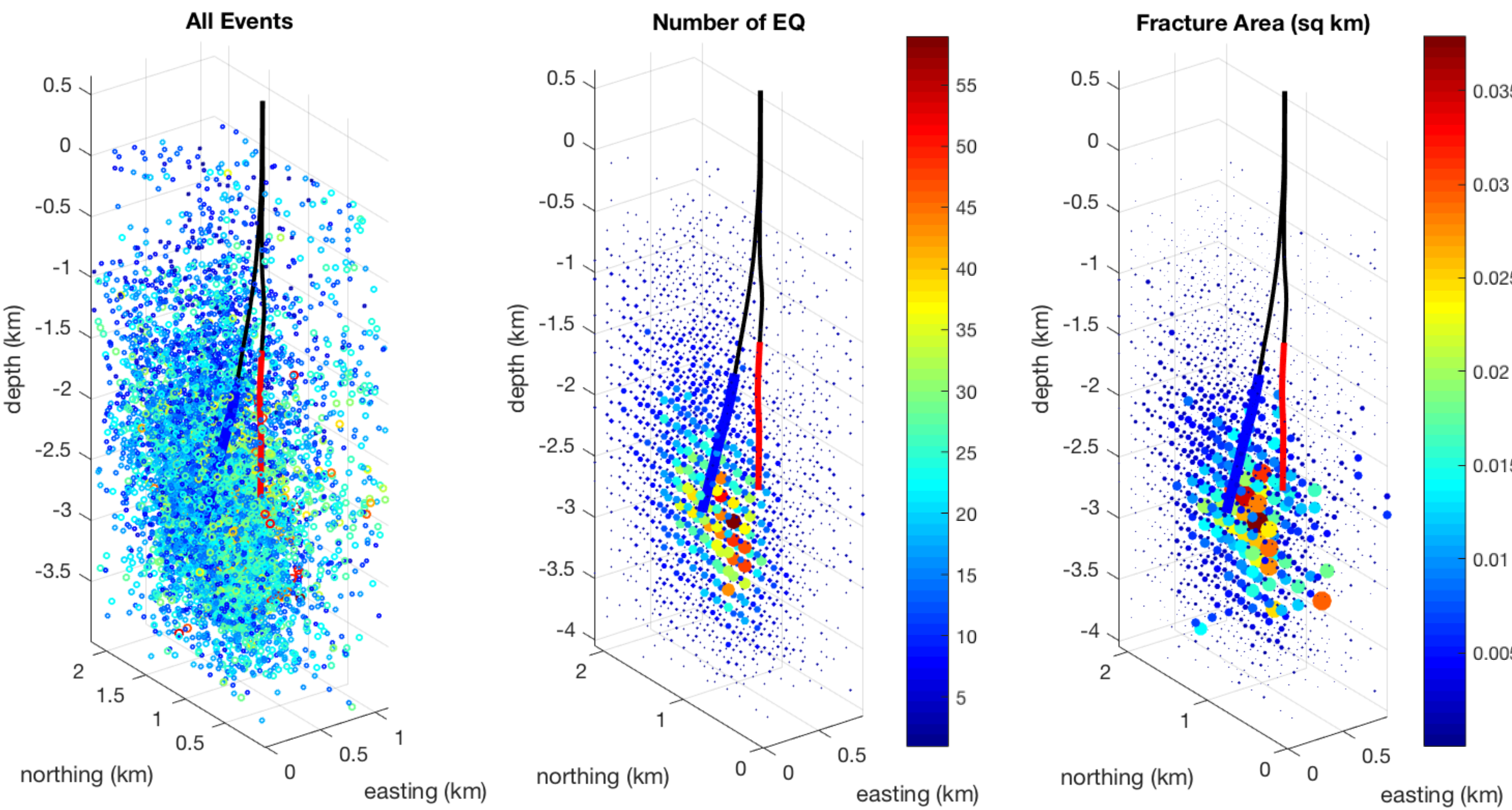


Fracture Dimension



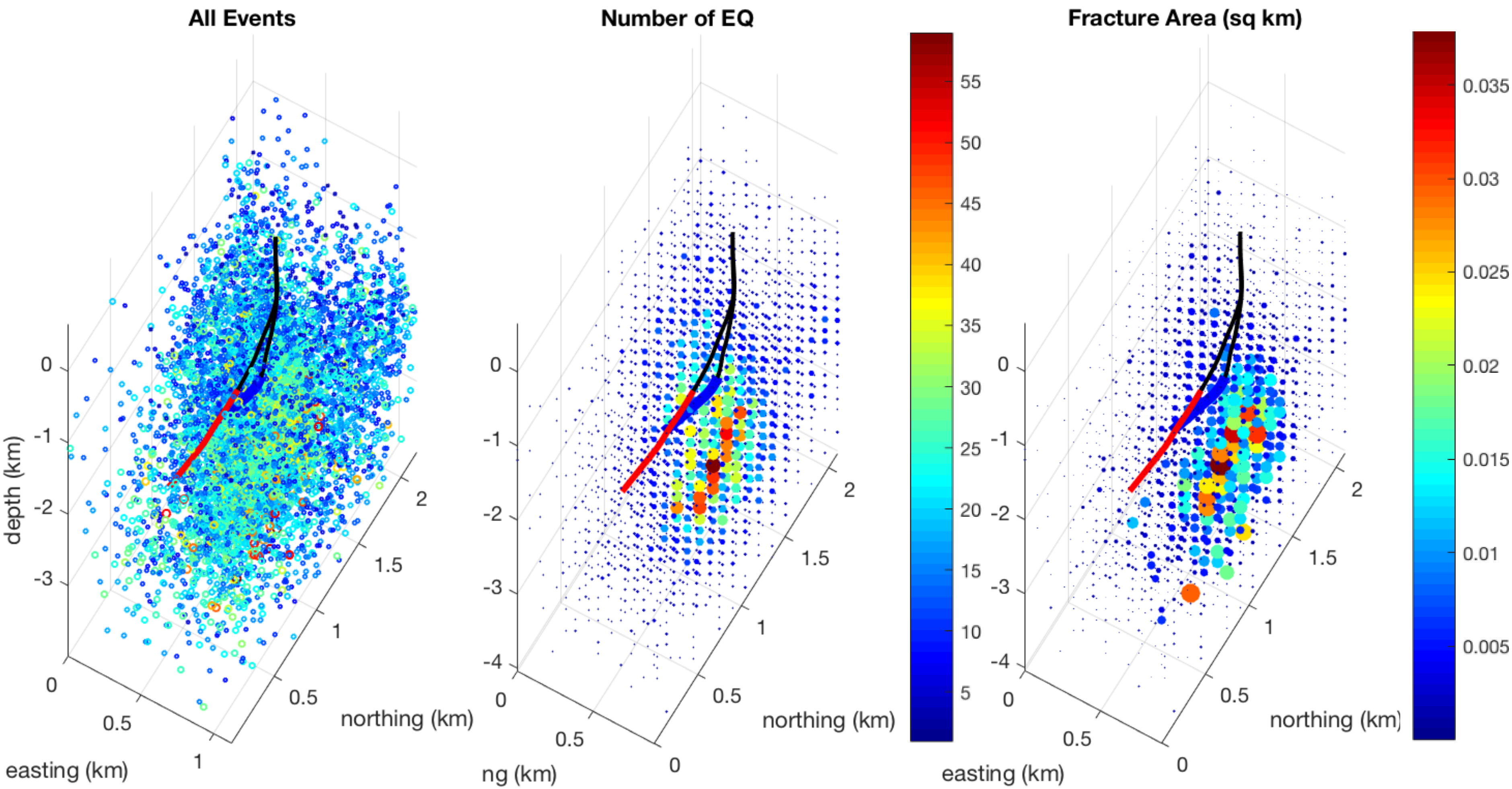
Progress (In-situ Stress and Fracture Characterization)

Estimated Rupture Area – View from SW



Progress (In-situ Stress and Fracture Characterization)

Estimated Rupture Area – View from SE



Accomplishments, Results and Progress

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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)	As reported above. For details refer to three-page GTO Project Summary	12/31/2015
Task 2: Compile MT catalog of small-scale seismicity (12/31/2015)	As reported above. For details refer to three-page GTO Project Summary	12/31/2015
Task 3: Analyze leveraged broadband seismic data throughout The Geysers and in the vicinity near the Prati 32 EGS demonstration well (12/31/2016)	As reported above. For details refer to three-page GTO Project Summary	02/28/2017
Task 4: Estimate in-situ stress orientation and temporal changes in stress orientation (12/31/2016)	As reported above. For details refer to three-page GTO Project Summary	02/28/2017
Task 7: Determine finite-source kinematic slip models and empirical rupture-area vs magnitude scaling relationship and activated fracture network (12/312017)	As reported above. For details refer to three-page GTO Project Summary	12/31/2017

Future Directions, Research Collaboration, Technology Transfer

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Milestone or Go/No-Go	Status & Expected Completion Date
Task 5: Appraise uncertainty of the DDW method related to geometry at Prati 32 injection site. Appraise aleatory and epistemic uncertainty due to stations topology and errors in phase picks (12/31/2017)	**Status:** Started appraisal of station topology **Next:** Appraise effects of travel time and system related uncertainty **Expected Completion Date:** 03/31/2018
Tasks 6: Estimate Vp/Vs-ratio in the injected fluid volume and locate injectate within fracture volume (12/31/2017)	**Status:** Not started yet **Expected Completion Date:** 05/31/2018

- The current project is a collaboration between Array Information Technology, UC Berkeley and Calpine Corp.
- As part of this research, a graduate student will receive her Ph.D.
- Seismic MT catalog, and catalog of newly analyzed broadband data will be available on the Berkeley Seismological Laboratory's website
- Calpine will receive all results to optimize production procedures at The Geysers EGS site
- This technology is readily applicable to other EGS sites with seismicity

Summary

- 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 developed new integrated technologies to address these barriers
  - estimation of subsurface fluid saturation and temporal changes
  - stress orientation and temporal changes
  - total activated fracture area