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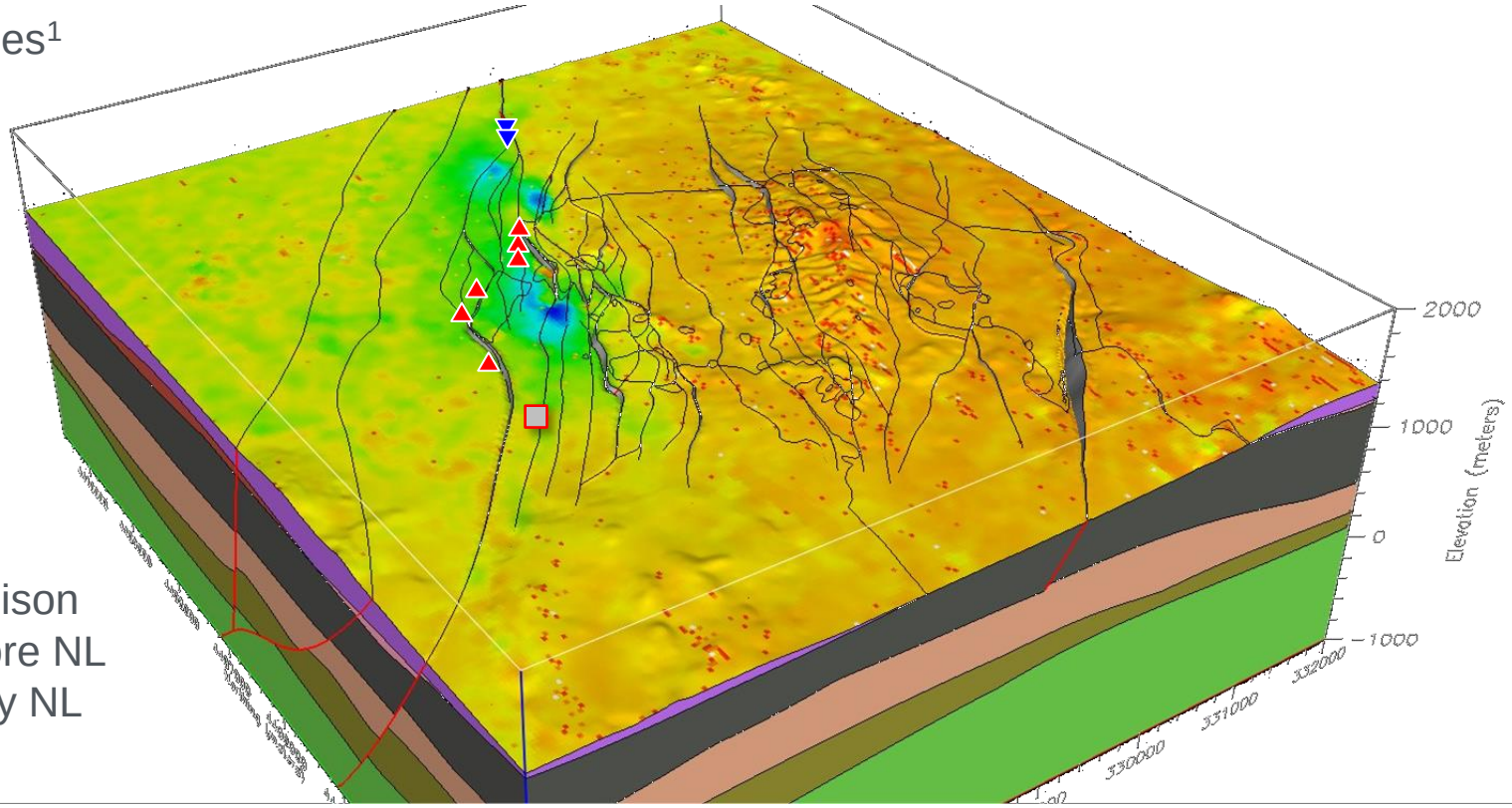


InSAR and MEQ

Project Officer: Lauren Boyd
Total Project Funding: $1,463,000
May 12, 2015

PI: Nicholas C. Davatzes, Temple University

Track 4: EGS

Relevance/Impact of Research

Goal: The primary technical target is to constrain the geometry and properties of the reservoir by monitoring surface deformations and seismicity as responses to injection/production (as well as tectonics).

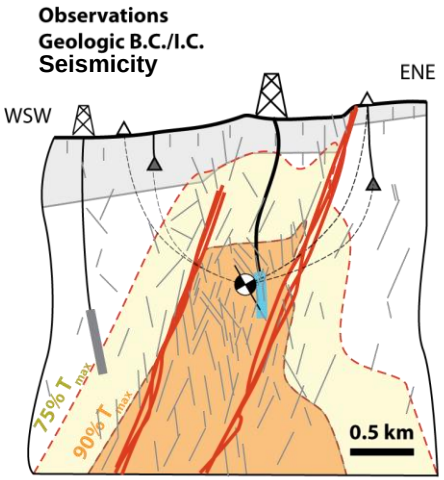
This project is designed to meet the objectives of the GTO by:

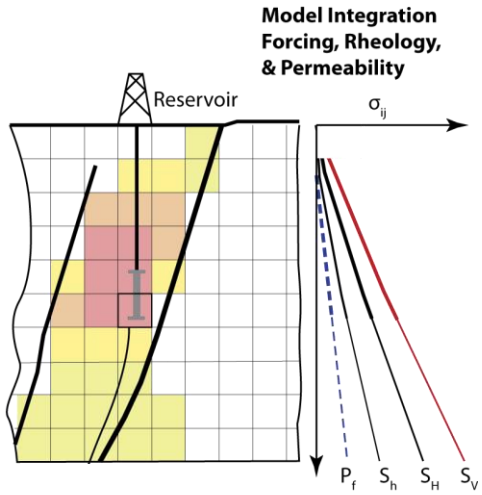
(1) Providing rapid development of technology to monitor and guide stimulation;

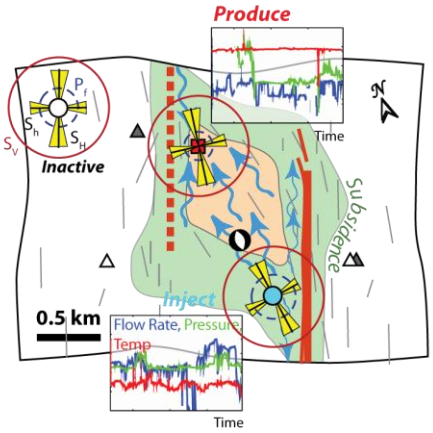
(2) Providing tools to enhance the use of seismicity in monitoring stimulation or production activity;

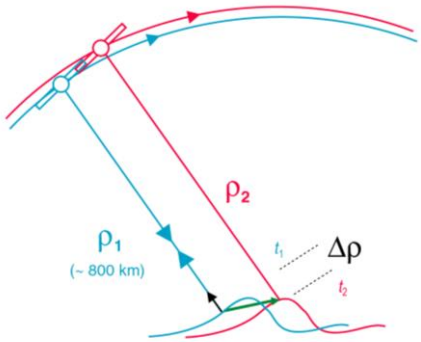
(3) Providing tools to define the geometry of the geothermal reservoir and measure fluid pressure fluctuations correlated to pumping activity;

(4) Integrating these tools into a data collection framework facilitating assessment of stimulations and injection/production management.









Surface displacement

Scientific/Technical Approach

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Barrier: *Currently, no tool effectively provides direct monitoring of the progress of fluid pressure into the natural fracture network or surrounding formation.*

Exploit multiple responses to pumping to produce a spatially and temporally rich constraint.

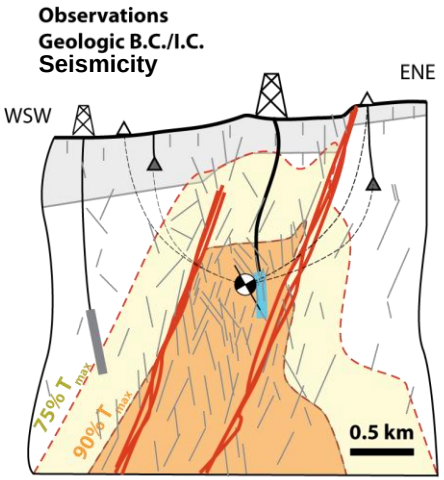
Measure history of deformation:

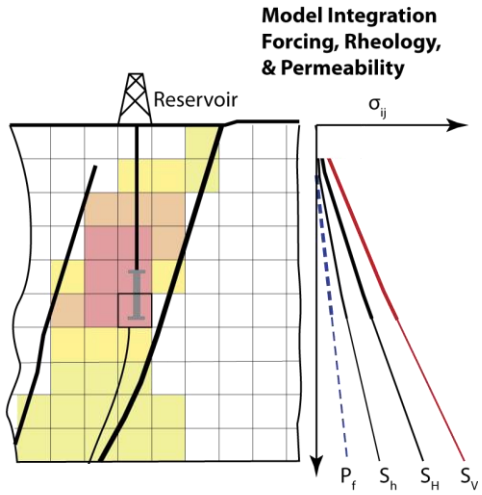
- *Surface*: **S**ynthetic **A**perture **In**terferometric **R**adar (**InSAR**)
- *Subsurface*: Seismicity

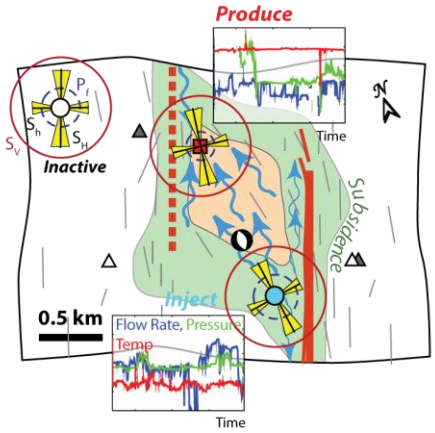
Model deformation history as ***response*** to ***forcing*** by pumping to infer:

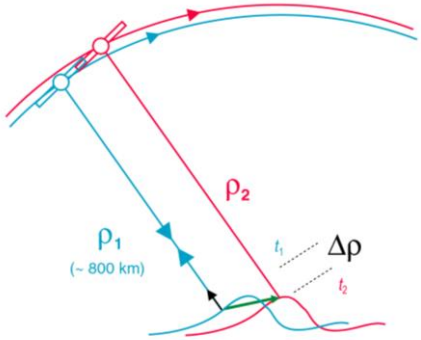
- Pore pressure field
- Volume hosting fluid flow
- Evolution of flow paths

Develop an integrated set of **software tools** to ***monitor*** the evolution of permeability and fluid flow during both the stimulation and production phases









Surface displacement

Scientific/Technical Approach

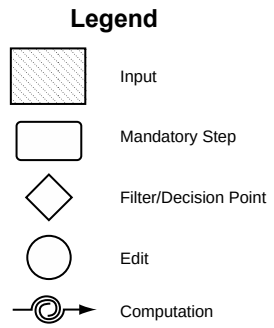
Goal: The primary technical target is to constrain the geometry and properties of the reservoir by monitoring surface deformations and seismicity as responses to injection/production (as well as tectonics).

- Develop software tools to conduct analyses and pass data between steps in the workflow to assess reservoir characteristics from: (1) Surface deformation; (2) Seismicity; (3) Pumping history.
- Develop a database to support tool development and testing.
- Characterize time history of deformation from (1) InSAR and (2) Seismicity.
- Model deformation history as a *response* to pumping history using appropriate rheologies to infer the development and geometry of the (1) pore pressure field and (2) permeable volume hosting fluid flow.

Project Team:

- Surface deformation: Feigl, (Ali), Mellors, Kreemer
- Seismic: Mellors, Foxall, (Singh)
- Geology, geomechanics: Davatzes, Wang (Ali)
- Reservoir Analysis: Wang, (Ali), Feigl, Foxall
- Integration and management: Davatzes
- Coordination with operator: ORMAT: Peter Drakos, John Akerley, Paul Spielman, Ezra Zemach

Workflow
of Integrated Analysis



Impulse

Pumping History (Stimulation)
- Injection (Flow, Pressure, Temperature)
- Production (Flow, Pressure, Temperature)

Response

Surface Deformations
- SAR Scene (e.g., *ALOS, TeraSAR-X*)
- InSAR - Pairs - Time Series
- Minimize Residuals
- Source Model

Micro-Earthquakes
- Catalog (Event seismograms, Initial locations)
- Velocity Model - VELEST - Ambient Noise
- Adv. Tools - DD Reloc. - Detection (e.g., bayesloc, waveform x-cor., matched-field processing)
- MEQ Source Characteristics (Focal Mechanisms, Moment)

Properties, B./I. C.

- Geologic Model (*type andgeometry of lithologic units, fault geometry, slip distribution, slip history/seismicity*)
- Geomechanics (*Stress state,* fault and fracture populations)
- Rock Mechanics (*Young's Modulus, Poisson's Ratio, strength,* friction, porosity, permeability, thermal exansivity, Biot Coeff., Skempton's Coeff.)
- Reservoir Characterization (*Tracer Tests,* well tests [pressure tansient and intererence, injectivity)

Simulator

- Finite Element Simulator Input (*3-D volume mesh, rock properties, boundary conditions*)
- output (*fluid pressure field,* surface deformations coulomb failure)
- Adjust B.C. or rock properties
- Adjust flow unit geometries
- Test Simulation Predictions
- Loop
- Loop

Outcomes

Best-Fit Model

Reservoir Geometry, Fluid Pressure Field, Coulomb Stress Field

Crustal Rheology

Sensitivity Analysis (*Record Model Predictions for each* Boundary Condition or Reservoir Geometry)

Uncertainty
Uniqueness

Accomplishments, Results and Progress

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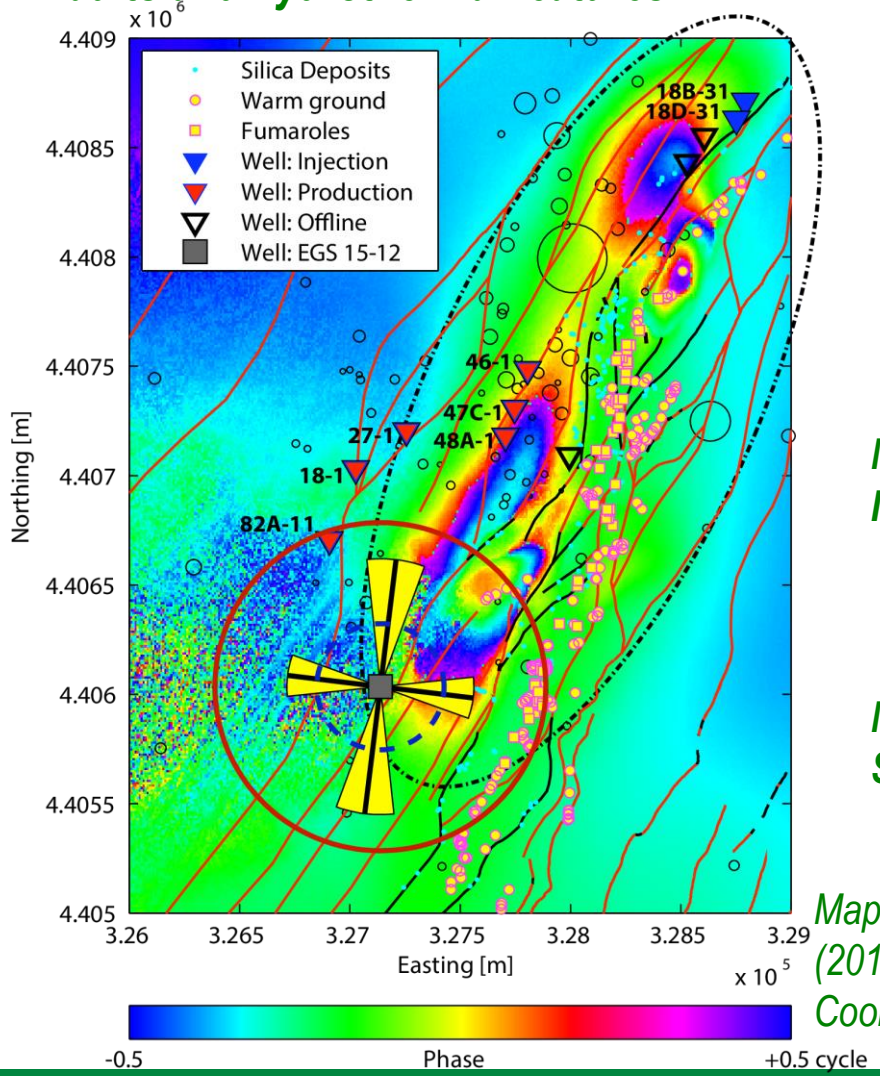
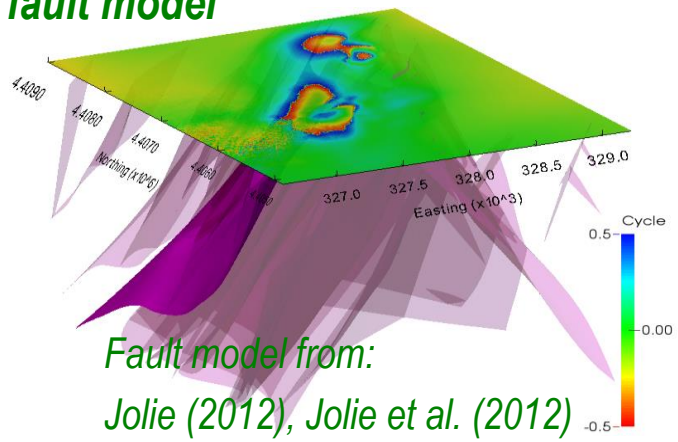
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1 Milestones: SURFACE DEFORMATION		
Obtain Archived and new, recurring SAR Imagery(see Subtasks 1.1 and 1.3)	• Data Set: 96 archived ERS1, ERS2, Envisat, and ALOS retrieved for period from 1992-2010. • Data Set: >125 TSX scenes purchased from 2011-present. • All scenes through 2014 processed	Archived: 1992-2008 New: 2011-present As acquired
Complete InSAR analysis of archived data (see Subtasks 1.2)	• Data Set: Interferograms generated spanning 1992-present. • Data Set: Annualized rates of surface deformation calculated.	2015-03-30
Development of software tools to stream-line analysis (see Subtask 1.6)	• Tools developed/implemented to: (1) conduct SAR, (2) generate Interferograms; (3) estimate subsurface volume change; (4) generate surface deformation time series • Workflow established to conduct analysis	2015-03-30 2015-03-30

Example Interferogram with Well Locations, Faults and hydrothermal features



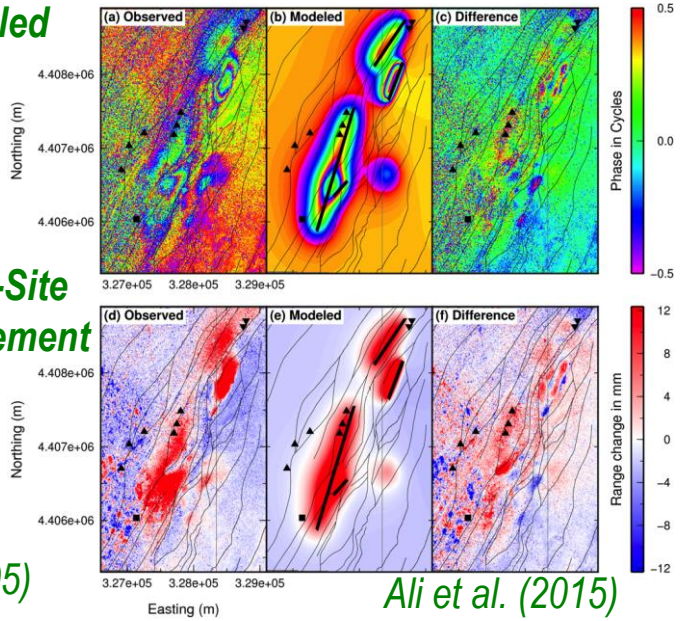
Perspective view of Interferogram with 3D fault model



Fault model from:
Jolie (2012), Jolie et al. (2012)

Measured/ Modeled InSAR Phase

Modeled Line-of-Site Surface Displacement



Mapping by: Faulds (2011, pers. Comm.), Coolbaugh et al. (2005)

Ali et al. (2015)

WORKFLOW: InSAR Analysis:

- (**Step -1**: Task Satellite to acquire image, e.g., TerraSAR-X)
- **Step 0**: Downloading of SAR data (Subtask 1.1 and 1.3) (WinSAR Database or Commercially acquired images)
- **Step 1**: Processing of SAR data (Subtask 1.2 and 1.4) (GMTSAR + Scripts, GiPhT + Scripts)
- **Step 2**: Inverse modeling of SAR data using simple semi-analytical models (Subtask 1.5) (includes sensitivity / uncertainty analyses)
- **Step 3**: Time series analysis (Subtask 1.2 and 1.4)

Accomplishments, Results and Progress

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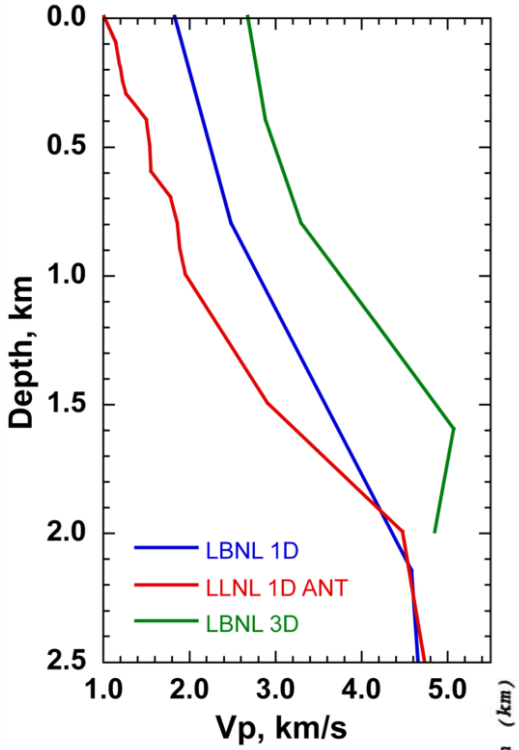
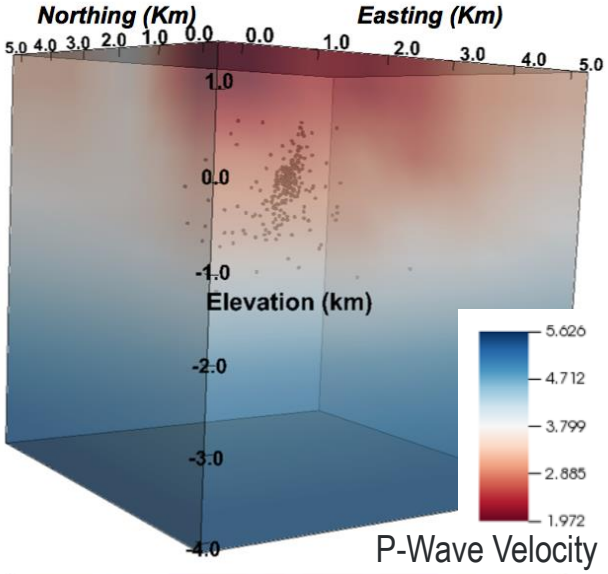
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 2 Milestones: Seismicity		
Catalog of event locations with error estimates (see Subtasks 2.1 and 2.2)	• Meta-data on station history • Acquired catalog of triggered seismicity and continuously recorded data • New tomographic model for relocation: (1) Ambient Noise; (2) Simultaneous inversion • Relocated Earthquakes	2012 +updates 2012, 2014 2014 2014-12-31
Development of software tools to stream-line analysis (see Subtask 2.4)	• Tools developed/implemented to: (1) derive velocity model, (2) relocate earthquakes, (3) derive focal mechanisms • Tools in continued development: (1) Techniques to improve detection of small mag. earthquakes; (2) Analyze & locate long period, low freq. earthquakes in continuously recorded data • Data sets in development: (1) improved catalog of small mag. earthquakes; (2) focal mechanisms & stress drops • Workflow established to conduct analysis	2015-03-30

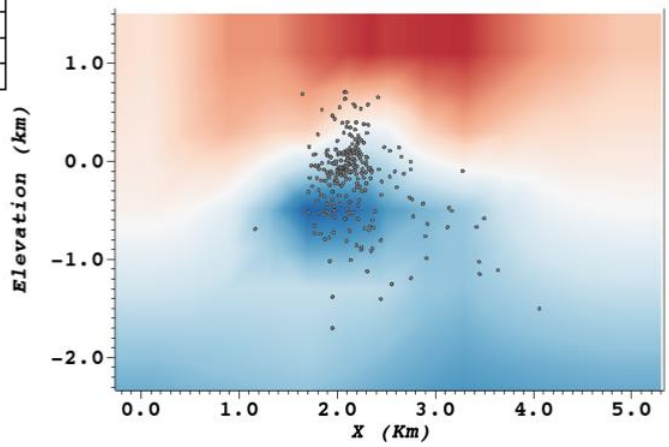
1D Velocity Model
(Ambient Noise Tomo.)



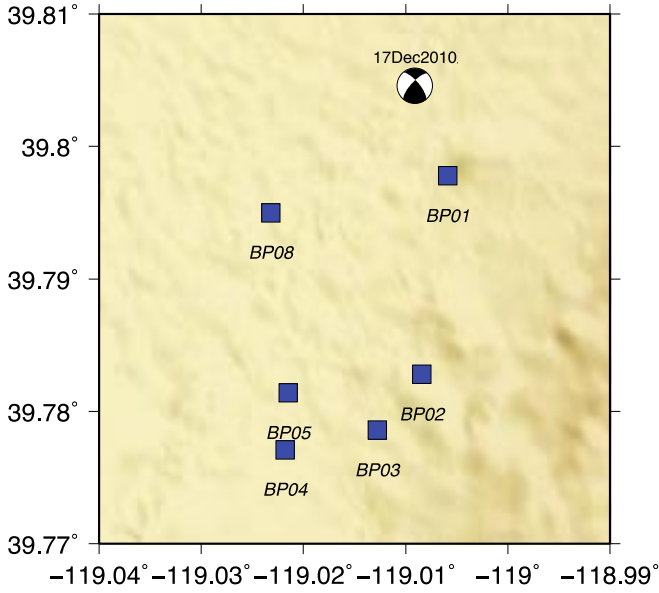
Comparison of velocity models

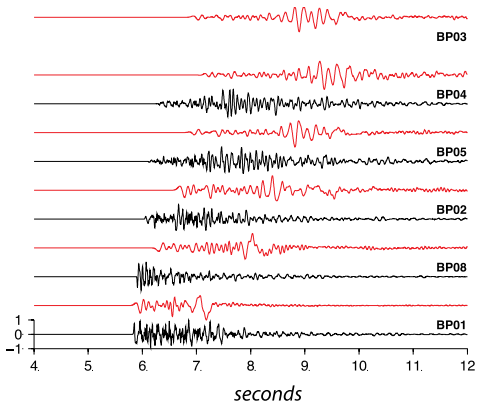
3D Velocity Model
(MEQ Tomography)



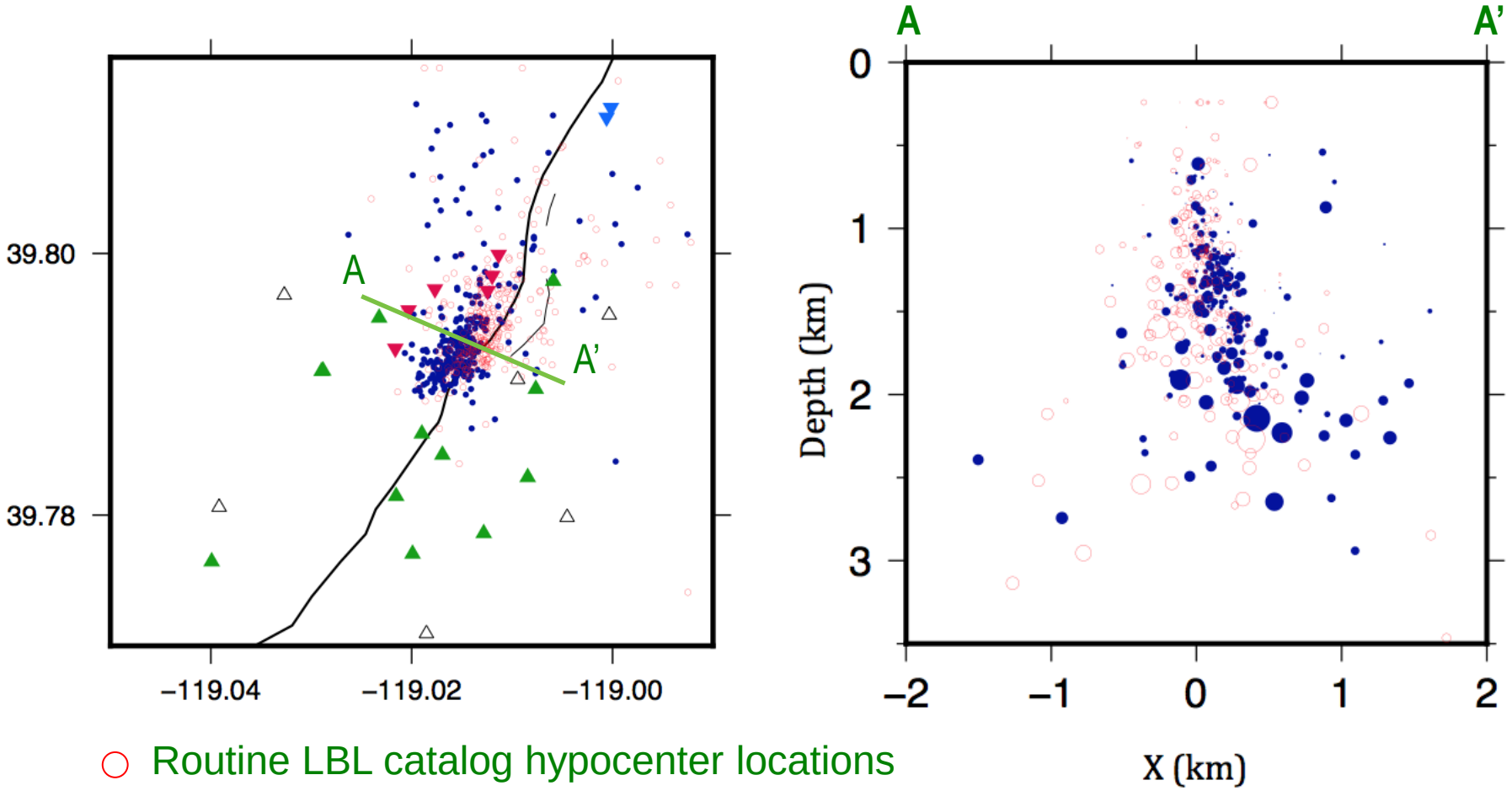


Focal Mechanisms



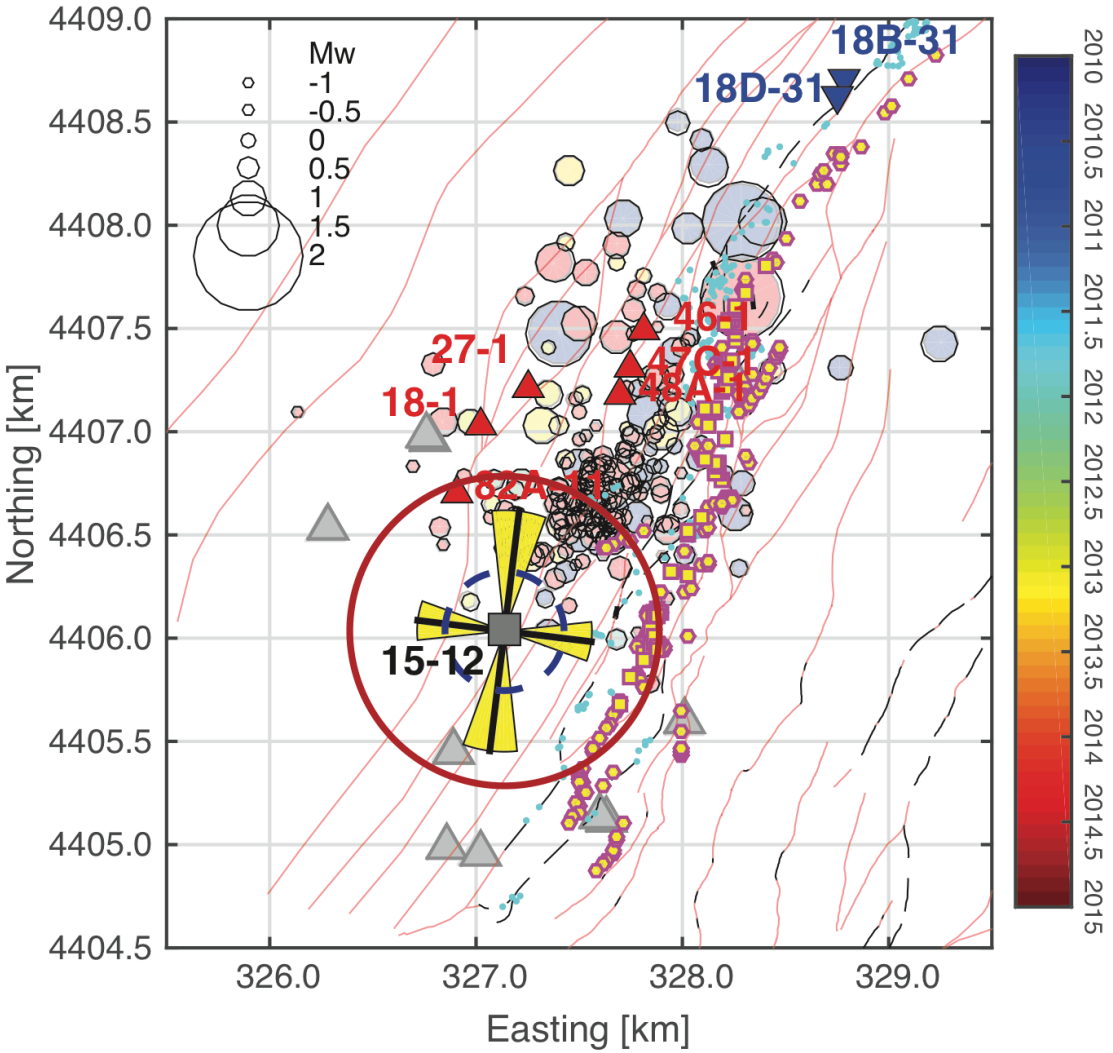


Comparison of Initial and Improved MEQ Locations

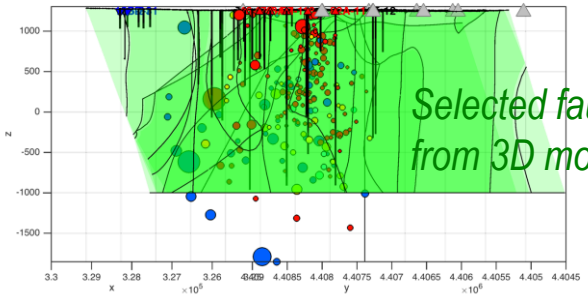


- ○ Routine LBL catalog hypocenter locations
- ● Relocations using SimulCR (this project)

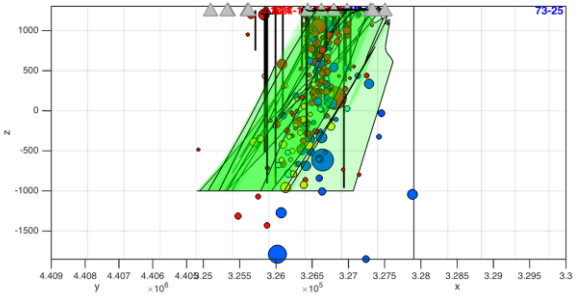
Geologic Structures, Wells, & Seismicty



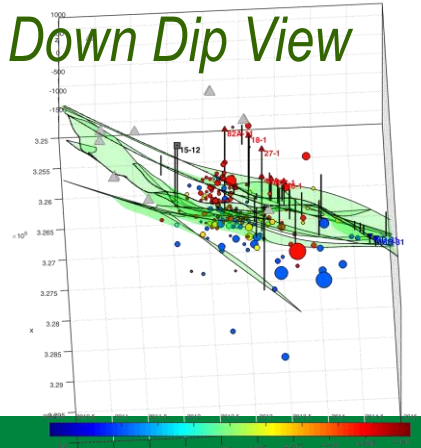
Strike Normal View



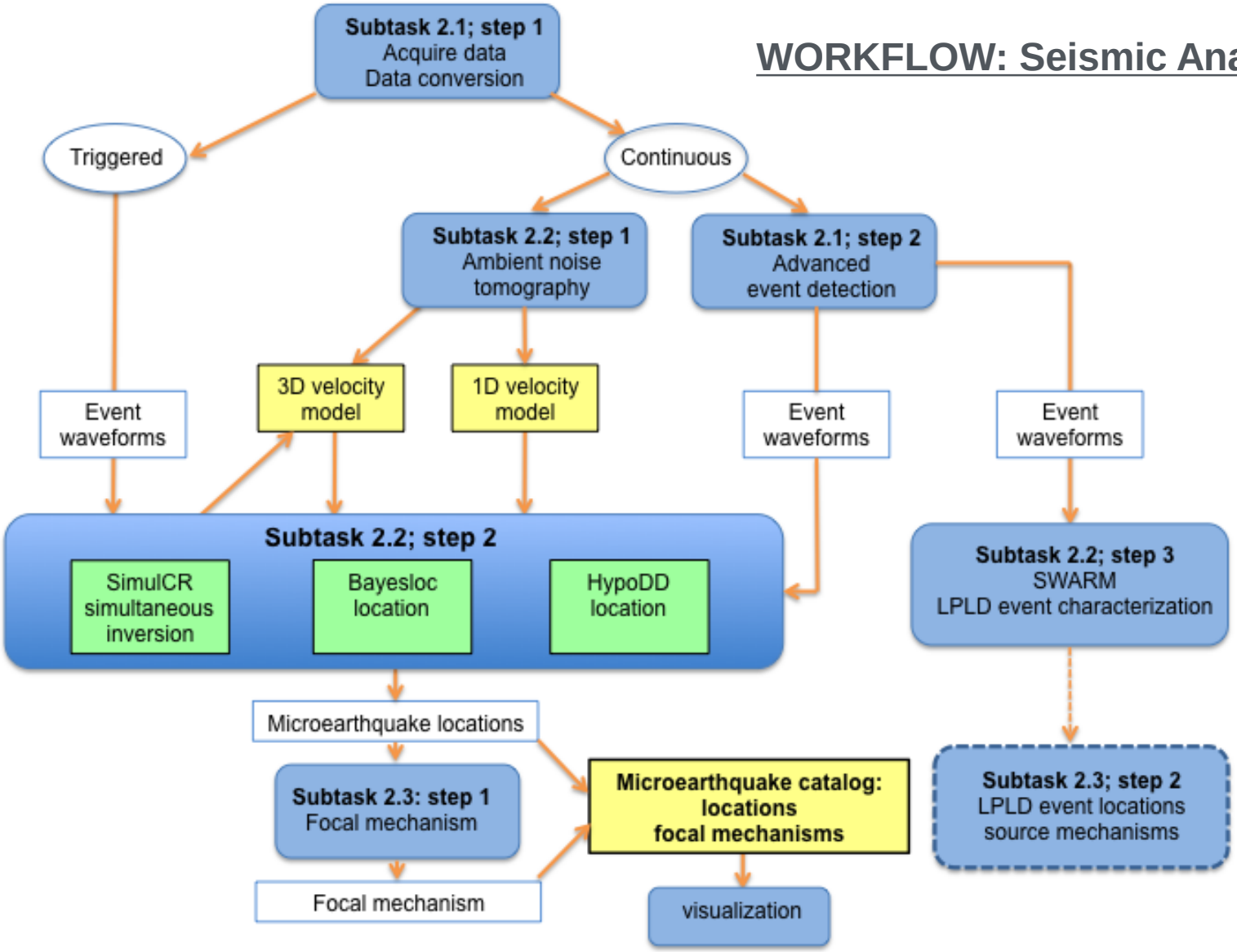
Strike Parallel View



Down Dip View



WORKFLOW: Seismic Analysis:



Accomplishments, Results and Progress

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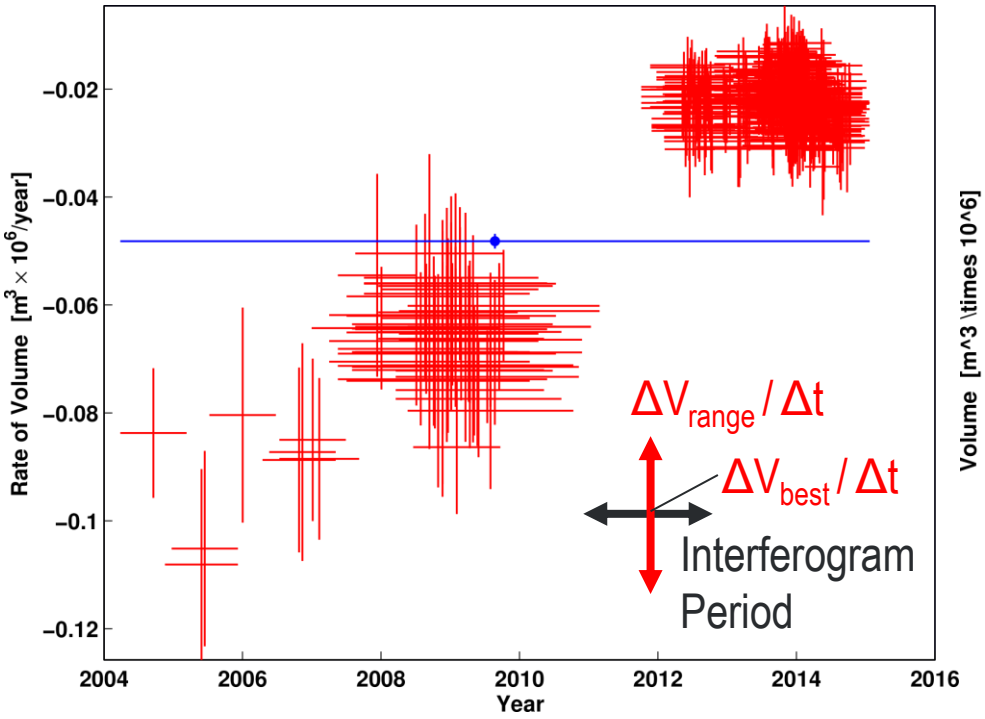
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 3 Milestones: GEOMECHANICAL RESERVOIR MODELING		
Complete Geologic and Reservoir Database (see Subtask 3.1)	• Database assembled including: (1) well locations; (2) rock mechanical properties; (3) pumping records of flow, pressure, temp. (2004-2014); (4) 3D geologic model; (5) geomechanical stress model.	2012 +updates
Development of software tools to stream-line analysis (See Subtask 3.5)	• Tools have been developed/implemented to: (1) geomechanical modeling of the reservoir; (2) Rheology: elastic & poroelastic; (3) calculate coulomb stress change • Tools in continued development: (1) Rheology: thermoelastiity, poroplasticity. • On-going: compare coulomb stress change with focal mechanism catalog • Workflow established to conduct analysis	2015-03-30

Temporal & Spatial Evolution: Surface Deformation

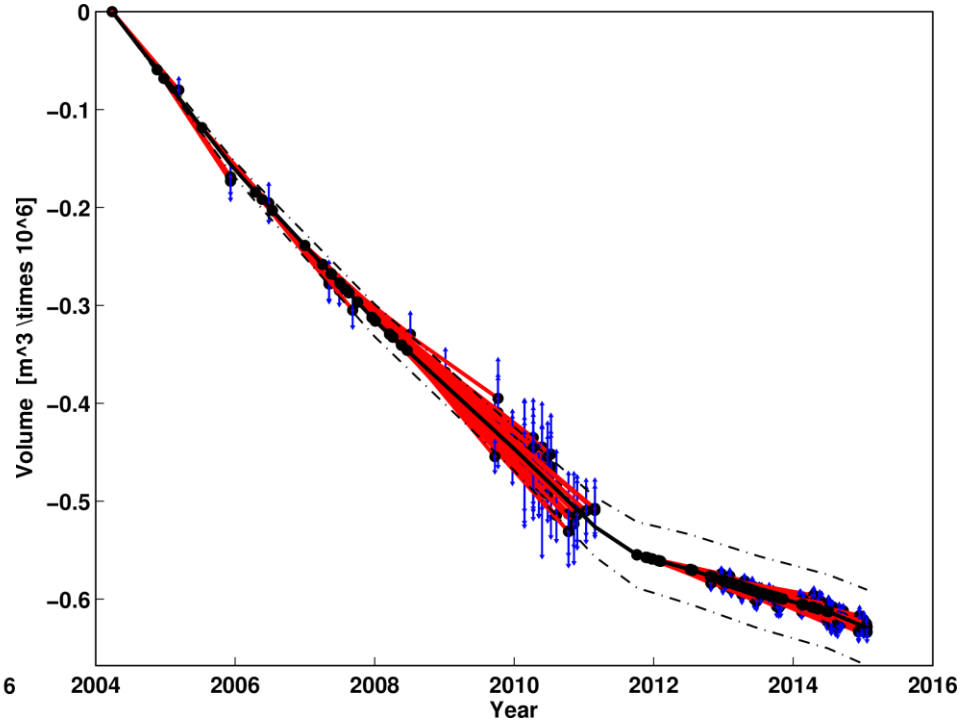
Cumulative Rate

(each interferogram, varying period)

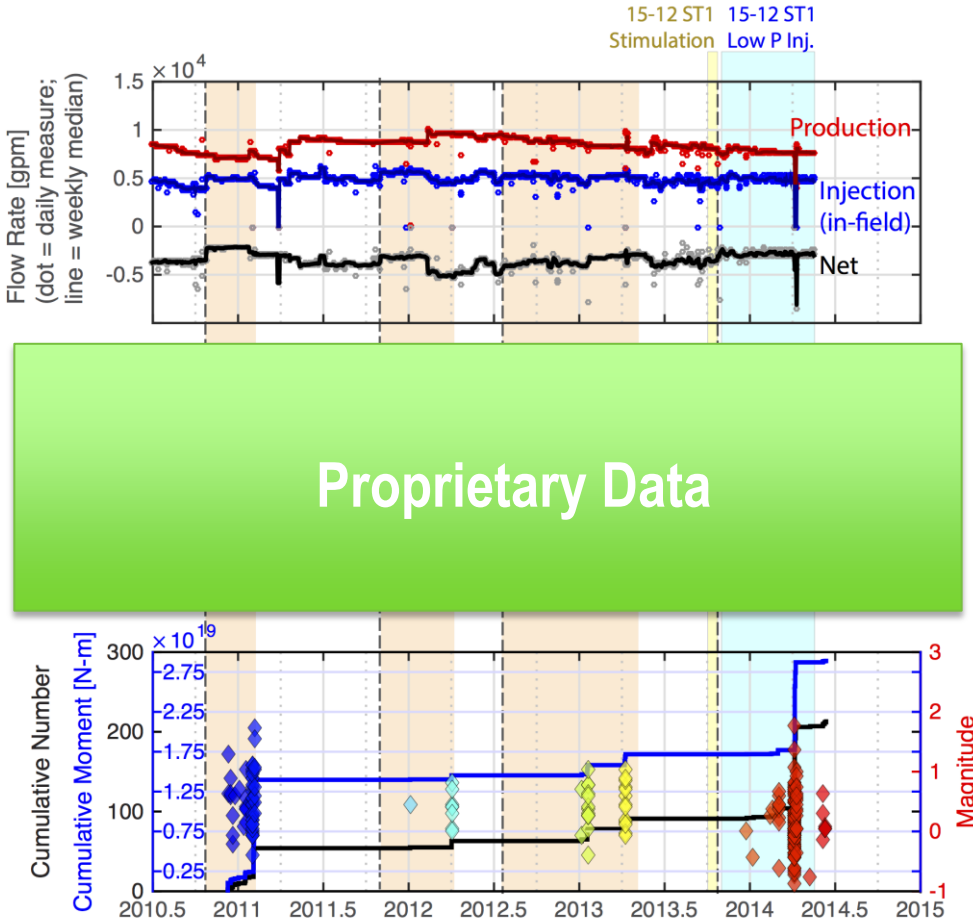


Volume Change

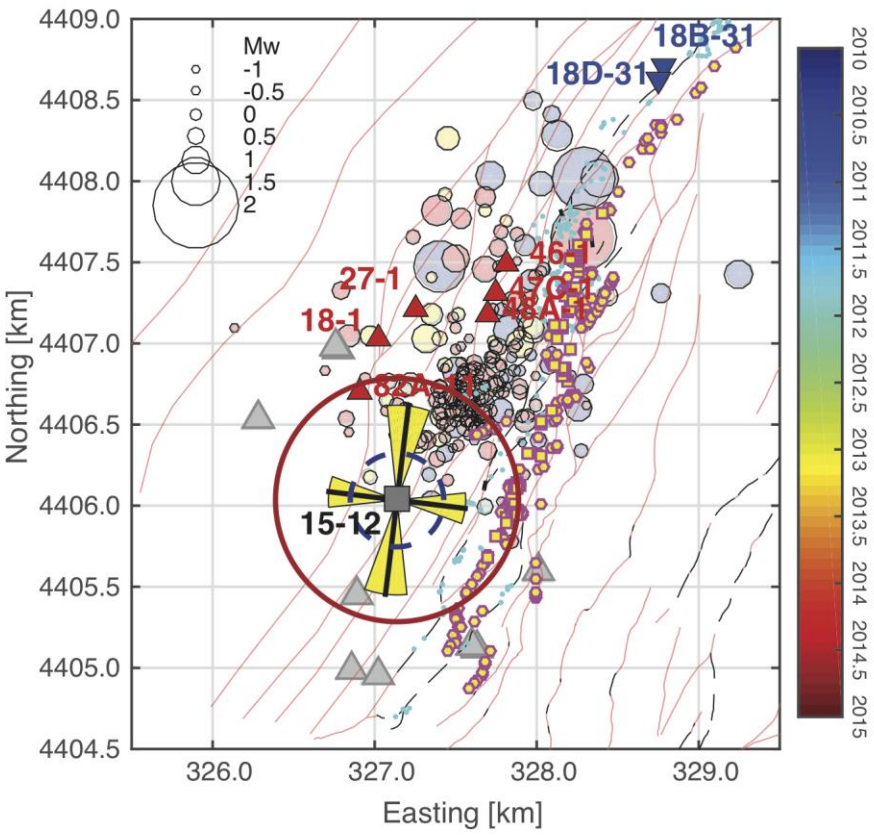
(temporally adjusted)



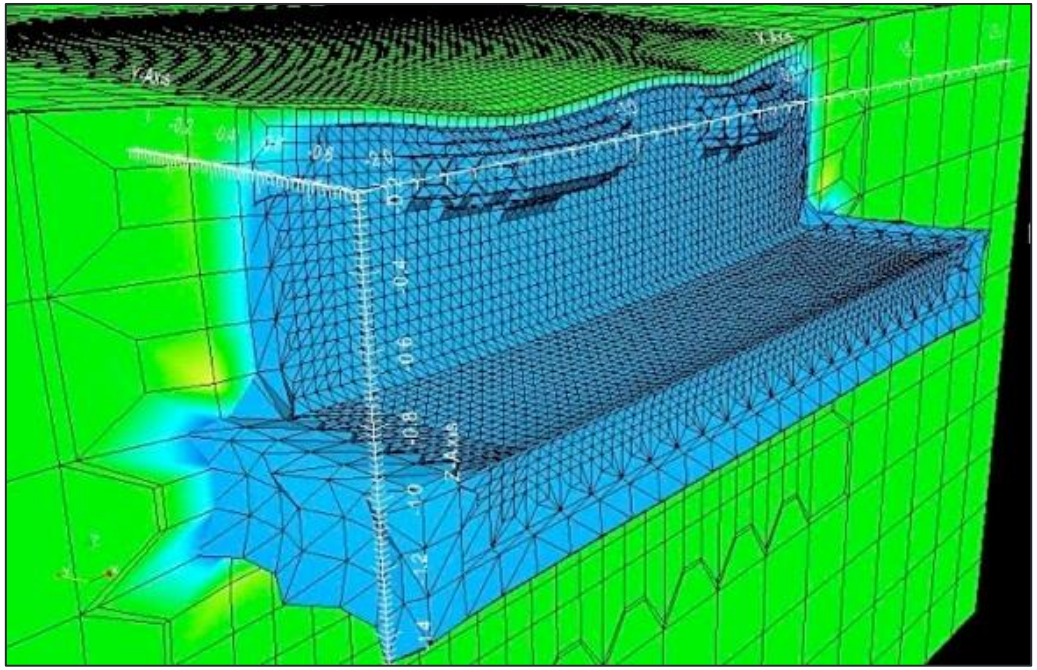
Temporal & Spatial Evolution: Seismicity



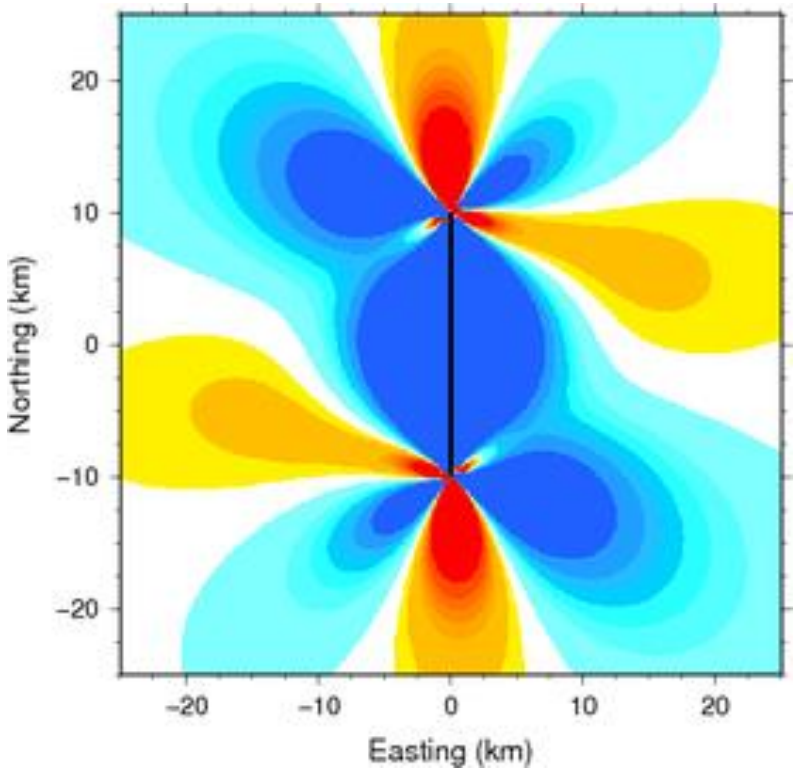
Proprietary Data



Example Simple Poroelastic Reservoir Model Visualization



Example Coulomb Stress Calculation



WORKFLOW: Geomechanical Reservoir analysis:

- Following steps 0-3 of the InSAR analysis:
- **Step 4**: Assemble geological and rock mechanical constraints (Subtask 3.1)
- **Step 5**: Geomechanical (Elastic/Poroelastic/Thermoelastic) modeling (Subtask 3.2)
- **Step 6**: Inverse modeling of SAR data using poroelastic/thermoelastic models (Subtask 3.3 and 3.4).
- **Step 7**: Coulomb stress change calculation/analysis (Subtask 3.5).
- **Step 8**: Integrate surface deformation + MEQ as test
- **Step 9**: Revise as necessary

Future Directions

- The project is on schedule and within budget.
- Phase I is nearly complete and awaiting Stage Gate Review
- Phase II is intended to span 3 Quarters from approval, with a target completion date of December 2015 for all remaining elements (listed below).
- During the wait for Stage Gate result, the project team will continue refinement of data sets, tools including implementation of additional rheologic models, and manuscripts in preparation as allowed by budget.

PHASE I:

Milestone or Go/No-Go	Status & Expected Completion Date
Task 4.0 Stage Gate Report	Drafted, final review (as of submission)
PHASE 1 Go-No-Go Decision Point	Awaiting review

Future Directions

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PHASE II:

Milestone or Go/No-Go	Status & Expected Completion Date
Continue data acquisition: SAR Scenes (Task 1) + MEQ (Task2) + Pumping (Task 3)	• Update surface deformation timeline • Finalize MEQ & Focal mechanism catalog • Finish advanced detection & focal mechanism analyses
Develop Prototype (Task5)	• Finish development of alternate rheologic models in Geomechanical Reservoir Model • Test suite of rheologic models against observed deformations • Test correlation of MEQ/Focal Mechanisms with Geomechanical model of coulomb stress change
Final Reporting (Task 6)	• On Schedule to Submit Final Report • Submit final, non-proprietary data sets to public repositories • Publish papers: Surface deformation manuscript in preparation. Induced seismicity manuscript in preparation.

Mandatory Summary Slide:

- We have successfully met the objectives of Phase I to:
  1. Provide new constraints on the geometry and properties of a geothermal reservoir from seismicity and surface deformation induced by pumping at the Brady Geothermal Field;
  2. Develop a systematic procedure to support determination and updating of these constraints by defining analysis workflows supported by software tools to implement the workflow steps.
- Our approach successfully:
  - Uses multiple mechanisms for monitoring fluid migration, change in stress/pore pressure, and deformation during EGS reservoir management
  - Independently evaluates the relationship between pumping, the volume deforming in response to pumping and MEQ activity
  - Provides an integrated reservoir model with higher temporal and spatial resolution than can be achieved from monitoring well responses or MEQ alone (especially in cases where MEQ are absent or episodic)
  - Benefits from a 20+ year record of reservoir deformation in the shallow subsurface, including pumping records (2004-present), surface deformation (1992-present), seismicity (2010-present), critical supporting data and dedicated feedback from the site operator, ORMAT
- We expanded the project within timeline and budget to address the scientific goals including: (1) Improved seismic velocity; (2) Additional rheologic models; (3) inclusion of GPS to bolster InSAR
- Our project is successfully coordinated with the: (1) Brady EGS project, (2) Brady-Desert Peak Modeling of the near-borehole conditions during stimulation and (3) LBL Induced Seismicity Project and (4) new PoroTomo project as well as (5) transfer of lessons and data from the Desert Peak EGS project.

Additional Information

Technical Metrics Met:

- Compiled and analyzed extensive data sets on surface deformations from InSAR scenes, improved seismic catalog, acquired continuously recorded seismic data, and the supporting reservoir pumping records and geologic properties.
- Existing InSAR data spanning 1992-2014 at Brady have been analyzed using inverse modeling to estimate the rate of volume decrease of the order of ~3 liters/second initially modeled as a dislocation sink buried in an elastic half space.
- GPS data at stations BRDY and BRAD for the time interval from 2009 through 2014 have been collected, archived, and analyzed to yield time series of daily estimates of relative, 3-dimensional position.
- Clearly identify surface deformation and developed physical models that can be used to determine the corresponding geometry of the deforming volume at depth and its hydrologic and mechanical properties.
- A new 1D seismic velocity model (Vp, Vs, and Qs) was derived from ambient noise inversion (useful where seismicity rate is low to improve initial catalog locations prior to inversion). In parallel, a fully 3D seismic tomography model has been derived from the catalog of seismicity.
- Significant improvements in earthquake detection and locations are achieved.
- New long period tremor associated with reservoir management activities has been identified.
- Established a clear correlation between pressure cycling in the reservoir and episodic seismicity.
- These results have led to several testable conceptual models to explain the mechanisms accommodating surface deformation and improved understanding of the intermittent seismicity in this geothermal field.
- Data on pressure, temperature, production, and injection at Brady for the time interval 2004-2014 are being analyzed to distinguish between hydro-mechanical and thermo-elastic models.
- The Reservoir Modeling Task has been expanded to enable a larger suite of physics to be analyzed including poroelasticity, thermoelasticty, and poroplasticity.
- The results have improved the geometric definition of the reservoir and its key physical properties.