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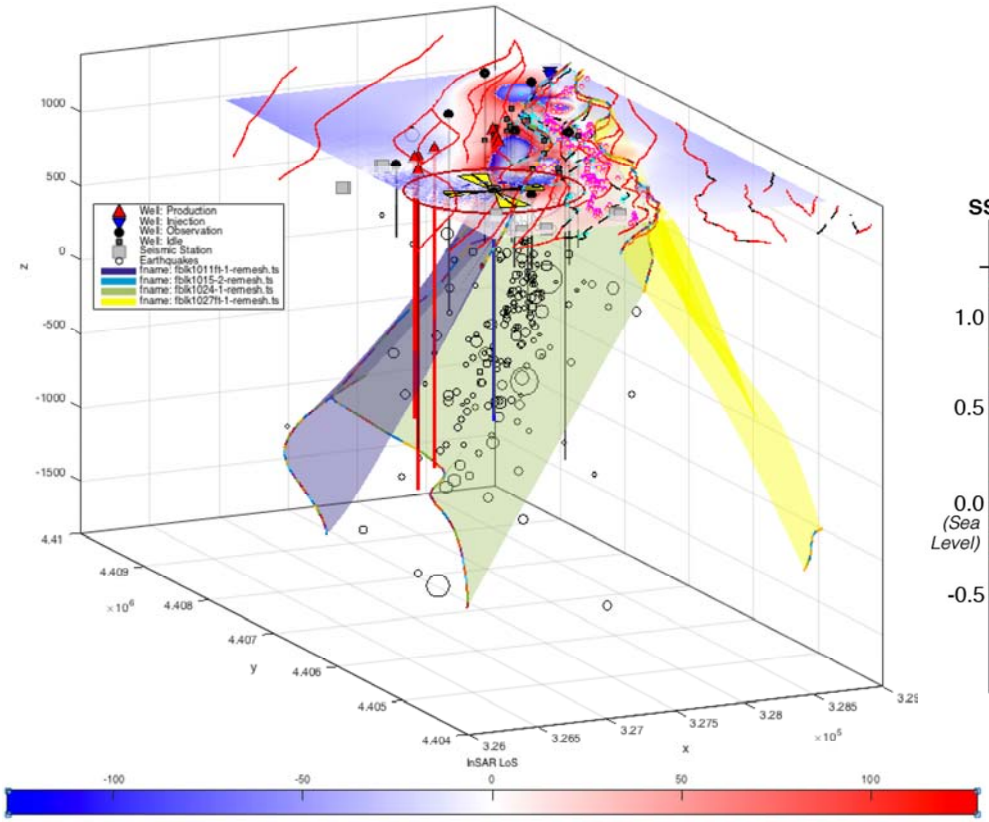
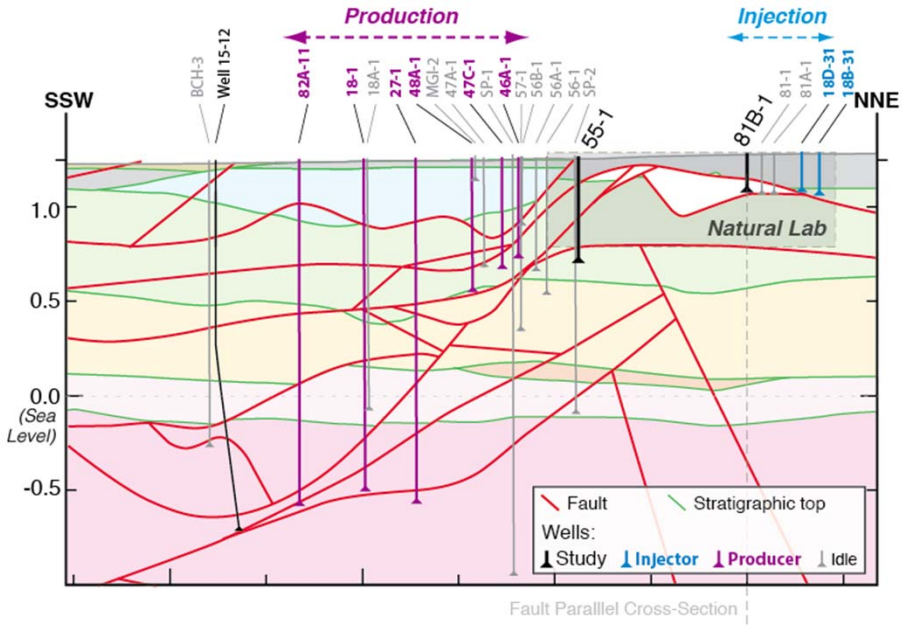




InSAR and MEQ

Project Officer: Lauren Boyd

Total Project Funding: $1,463,000

November xx, 2017

Principal Investigator (always include)
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).

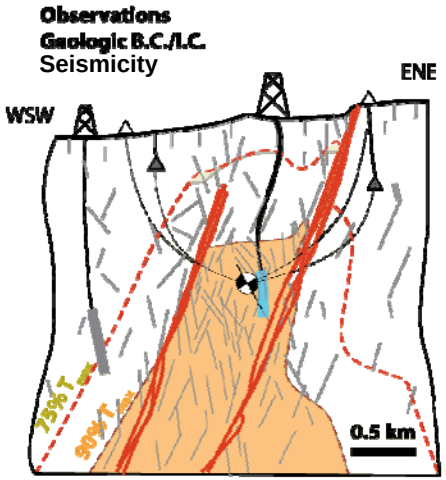
This project is designed to meet the objectives of the GTO by:

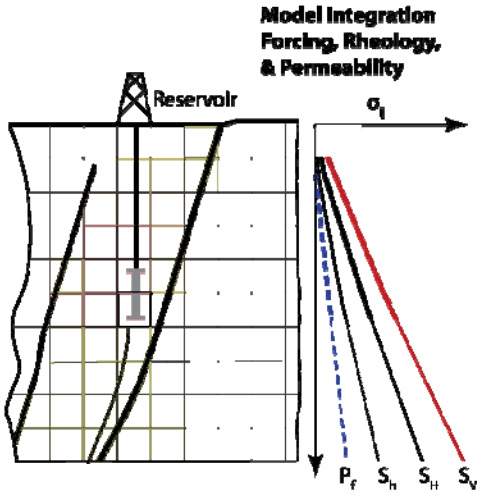
(1) Providing rapid development of technology to monitor and guide stimulation;

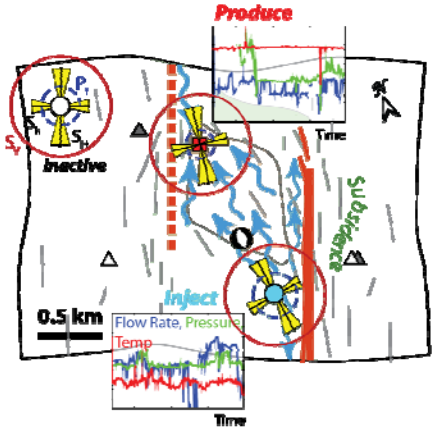
(2) Providing tools to enhance the use of seismicity in monitoring stimulation or production activity;

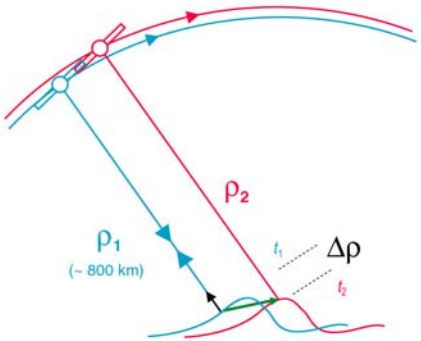
(3) Providing tools to define the geometry of the geothermal reservoir and measure fluid pressure fluctuations correlated to pumping activity;

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

Research Collaboration and Technology Transfer

Partnerships:

- ORMAT ←→ Academic ←→ National Lab (LBNL, LLNL)
- Multi-project:
  Brady EGS ←→ InSAR & MEQ ←→ PoroTomo
- Prototype model implemented on laptop
  - Testing
  - Direct implementation at Brady Geothermal Field (delivered to ORMAT)

Project Team:

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

Technical Accomplishments and Progress: Overview of Tasks

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1: Surface Deformation (InSAR)	Acquired and analyzed 6 years of scenes.	Continuing (joint with PoroTomo)
Task 2: Earthquakes	Developed detailed earthquake catalog + relocation + advanced detection.	Final catalog: 2017/07
Task 3: Reservoir Modeling	SYNEF Note: Task tuned by testing mechanisms consistent with Brady deformation: Elastic, Poroelastic (considered but not modeled Poro-plastic, Thermo-elastic, Geochemical)	2017/10
Task 4: Phase 1 Report	Succesfully passed	Submitted: 2015/08 Passed: 2016/09
Task 5: Prototyping and Documentation	In progress	Incomplete: Due December 30

** Project has coordinated data collection and submission with PoroTomo*

Analysis Workflow

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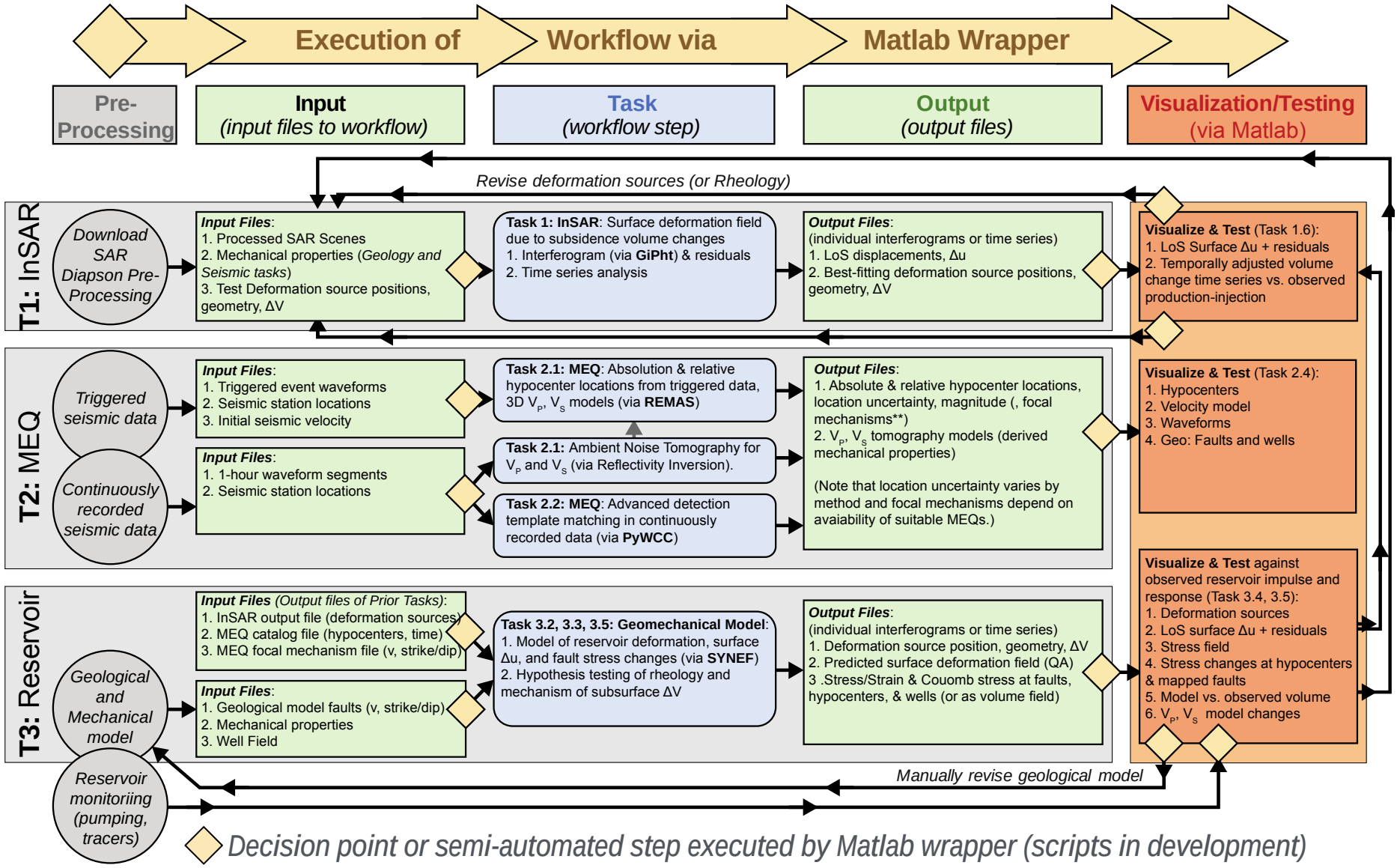

Accomplishments, Results and Progress

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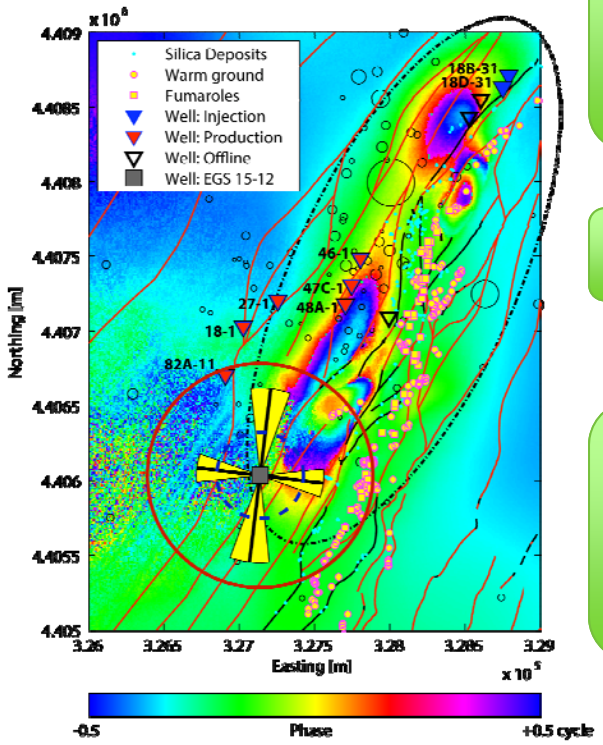
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1 Milestones: SURFACE DEFORMATION		
Obtain Archived and new, recurring SAR Imagery(see Subtasks 1.1 and 1.3)	• Data Set: 96 archived ERS1, ERS2, Envisat, and ALOS retrieved for period from 1992-2010. • Data Set: >125 TSX scenes purchased from 2011-present. • All scenes through processed	Archived: 1992-2008 New: 2011-2016 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 including temporal adjustment • Workflow established to conduct analysis	2015-03-30 2015-03-30

Example Interferogram with Wells, Faults & hydrothermal features



Surface deformation: Ali et al. (2016)

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

WORKFLOW for Surface Deformation from InSAR

Workflow Tasks	Workflow Products
Step 0: Downloading of SAR data (**Subtask 1.1 and 1.3**) *NOTE: (a) Archived data from WinSAR (1.3); (b) New data by scheduled acquisition and purchased which can be accomplished through WinSAR (1.1).*	*DATA/Vis*: Discrete SAR image
Step 1: Processing of SAR data (**Subtask 1.2 and 1.4**)	*DATA*: Initial interferogram showing phase shift or line of site range change spanning a discrete time interval. *Visualization*: Map of surface displacement field.
Step 2: Inverse modeling of SAR data via parameters search using simple superposing analytical models (mechanical from geo/ V_P/V_S+ geometry) (**Subtask 1.5**)	*DATA*: Exploration of deformation source parameterization: position, geometry, and deformation strength (P/V change) with associated uncertainties due to non-uniqueness. → TASK 3 *Visualization*: Map of improved surface disp. field.
Step 3: Time series analysis (**Subtask 1.2 and 1.4**)	*DATA*: Variation in deformation source characteristics through time (e.g., position, geometry, or strength). → TASK 3 *Visualization*: as time series.

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 2 Milestones: Seismicity		
Catalog of event locations with error estimates (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 (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 *Matlab wrappers in development*
Advanced Detection (subtask 3.3)	• PyWCC (python program): detection via template matching	2017-08
Focal mechanisms & Stress drops (subtask 3.4)	• No focal mechanisms achieved, events at Brady are inadequate to solve for these parameters.	N/A

Accomplishments, Results and Progress: MEQ Task

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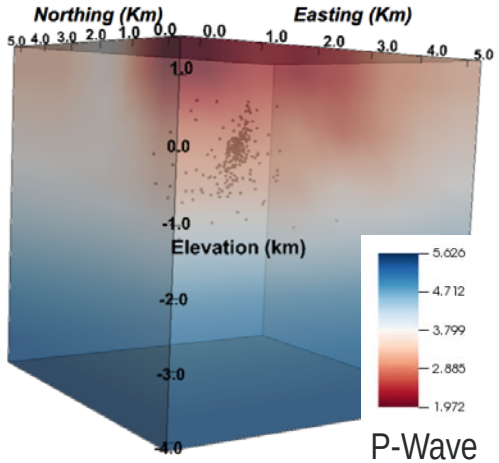
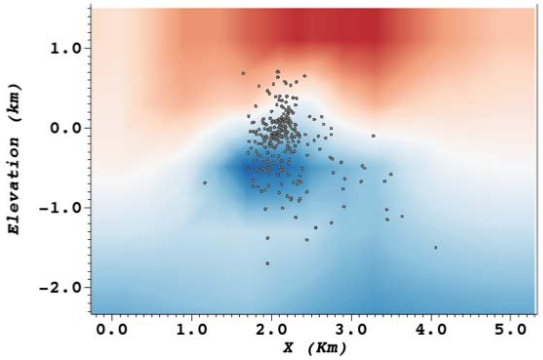
WORKFLOW for Seismicity



P-Wave Velocity



Subtask 2.1; step 1
Acquire data + Data conversion

Triggered waveforms

Continuous waveforms

Subtask 2.2; step 1
Ambient noise tomography

Subtask 2.1; step 2
Advanced event detection
PyWCC

Event waveforms

1D velocity model**

Subtask 2.2; step 2

SimulCR simultaneous inversion

Bayesloc Location**

HypoDD Location**

Subtask 2.2; step 3
SWARM
LPLD event characterization

low frequency tremor discovered (beyond scope)

Data/Vis:
3D velocity model**

Micro-earthquake hypocenters

New Detections Catalog

Data/Vis:
Micro-earthquake catalog:
Locations, magnitude
focal mechanisms**

TASK 3

TASK 3

Accomplishments, Results and Progress

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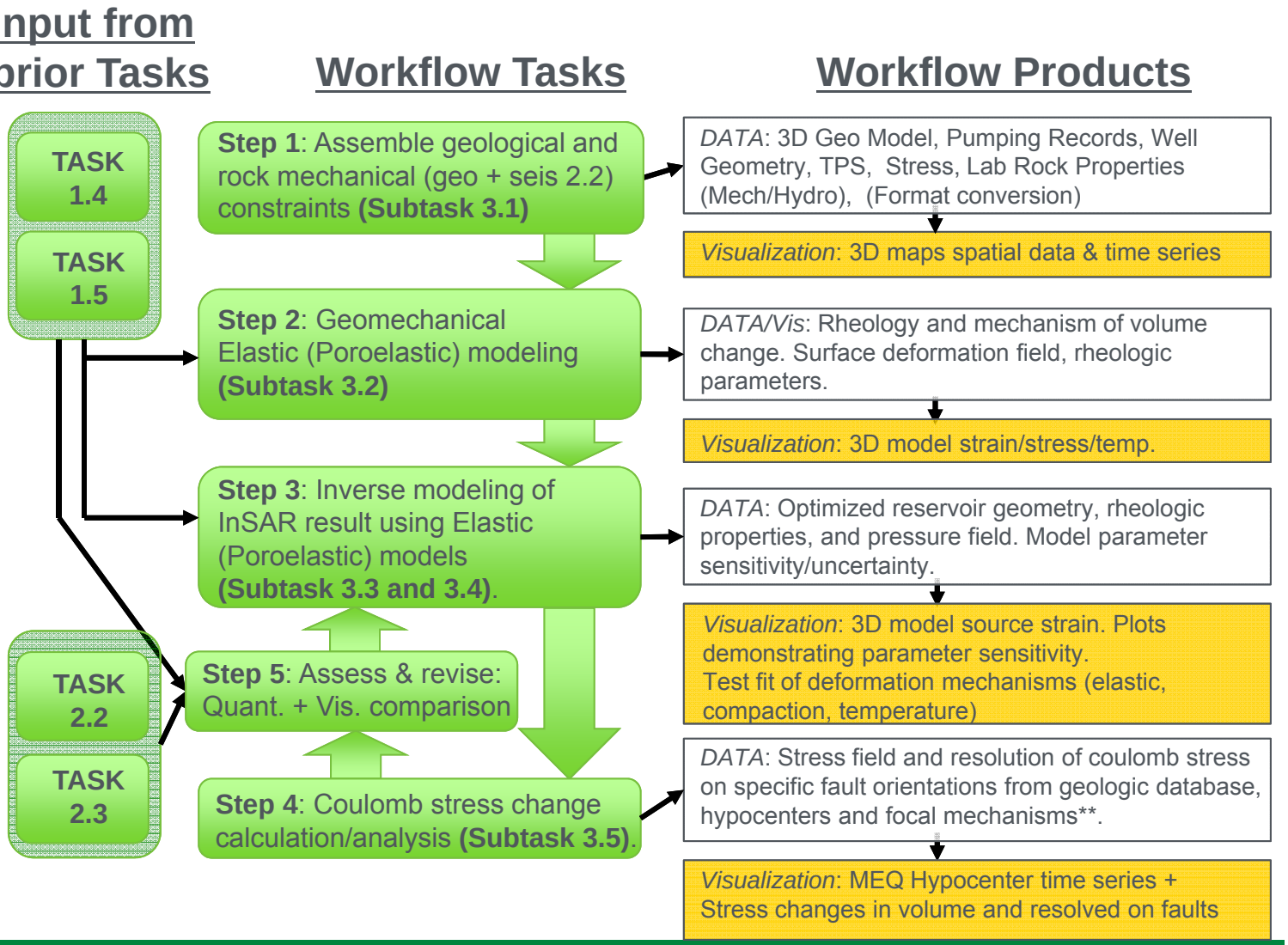
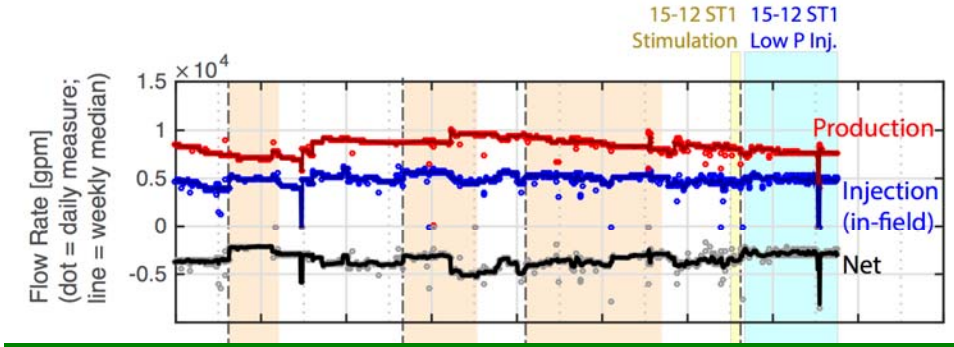
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 3 Milestones: GEOMECHANICAL RESERVOIR MODELING		
Complete Geologic and Reservoir Database (see Subtask 3.1)	• Database assembled including: (1) well locations; (2) rock mechanical properties; (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)	• Builds on volume change inversions from Task 1 InSAR processing using elastic deformation sources • Tools have been developed/implemented to: (1) geomechanical modeling of the reservoir; (2) Rheology: elastic & poroelastic; (3) calculate coulomb stress change • Support includes standard input/output formats for each task • Workflow established to conduct analysis • IP/Licensing of software components	current

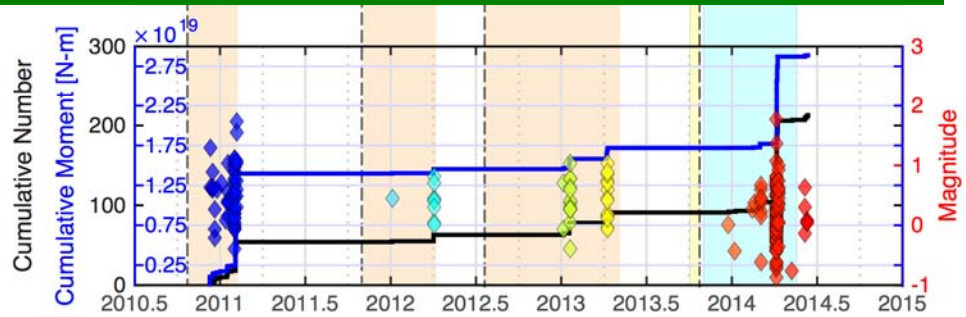
WORKFLOW for Geomechanical modeling



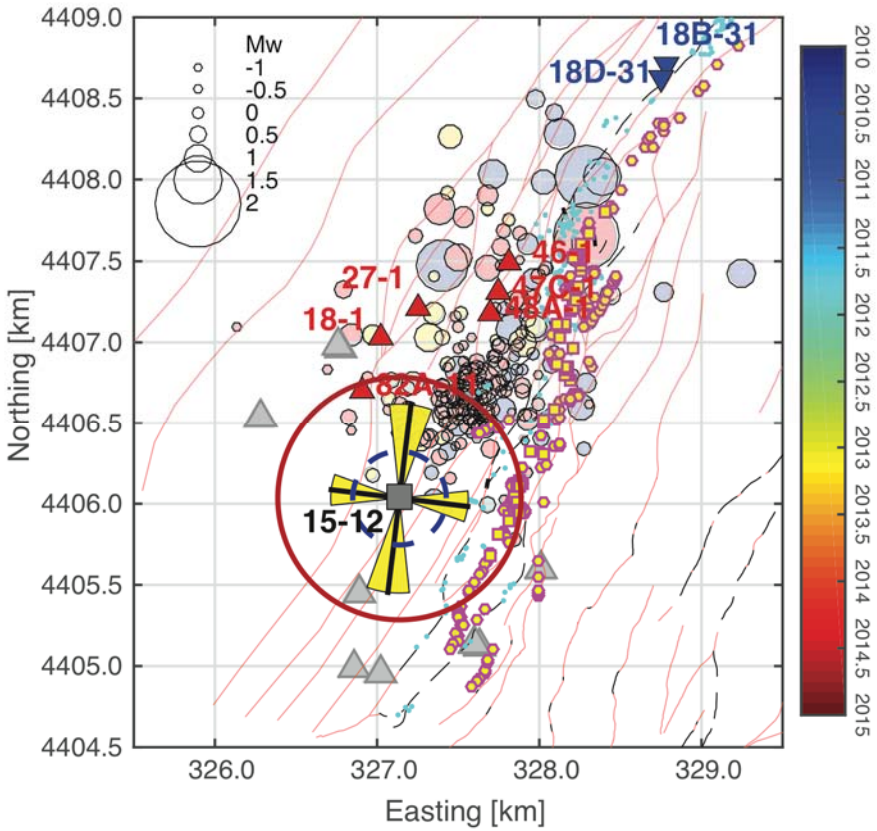
Temporal & Spatial Evolution: Seismicity



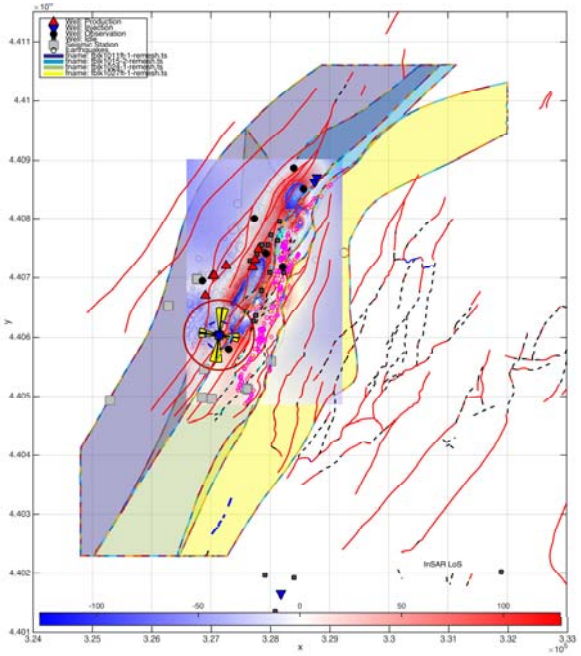
Proprietary Data

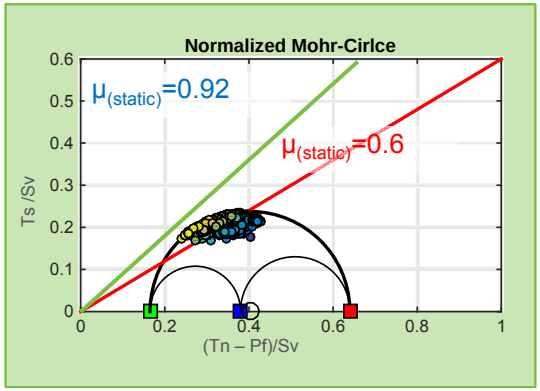


Timeline

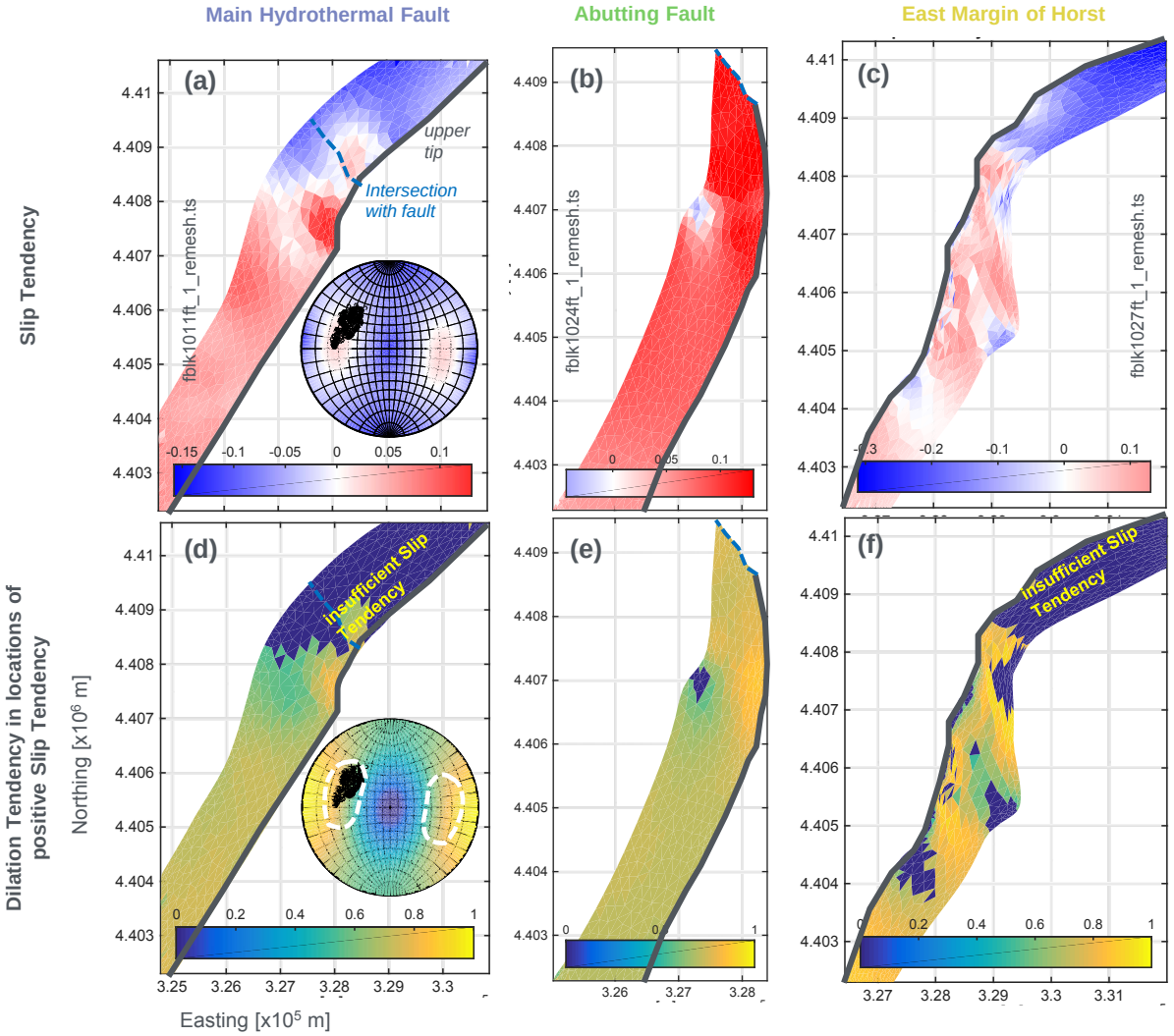


Accomplishments, Results and Progress: SYNEF





Remote stress



Next Step: Superpose loading due to reservoir deformation

Hypothesis Testing: What Rheology best suites modeling Brady Reservoir Behavior?

- The results of InSAR analysis yield a model of volume change at depth
- The mechanism accommodating the volume change
- The volume change is used to assess stress changes in the volume around the reservoir

3 possible end-member interpretations of volumetric strain

Stress on solid framework

$$\Delta\sigma = K\frac{\Delta V}{V}$$

Pressure of a pore fluid

$$\Delta P = H\frac{\Delta V}{V}$$

Change in temperature

$$\Delta T = \frac{1}{\alpha_T}\frac{\Delta V}{V}$$

K	3.0 MPa	bulk modulus
H	3.5 MPa	reciprocal of poroelastic expansion coefficient
α_T	$3\text{x}10^{-5}$/K	Thermal expansion coefficient

Future Directions

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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 • Brady catalog inadequate for focal mechanism analyses • Finished advanced detection
Finalize Prototype (Task5)	• Finish development of alternate rheologic models in Geomechanical Reservoir Model • Test suite of rheologic models against observed deformations – Implement the model needed to (a) fit observations with available constraints, (b) monitor reservoir behavior • Test correlation of MEQ/Focal Mechanisms with Geomechanical model of coulomb stress change • Implement prototype on laptop → transfer to ORMAT
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:

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- 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) Testing the need for additional rheologic models to achieve practical reservoir monitoring; (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) **PoroTomo** project as well as (5) transfer of lessons and data from the **Desert Peak EGS** project.