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Bradys EGS Project

Project Officer: Bill Vandermeer

Total Project Funding: $6.6M

May 12, 2015

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Track 4 EGS2

Relevance/Impact of Research

Project Goals:

- Improve the productivity (or injectivity) of a poorly performing well (15-12 ST1) in the Bradys Hot Springs Geothermal Field as measured by enhancing the hydraulic connection to the more productive areas of the geothermal resource.
- Utilize readily-available commercial technologies and cost-effective methodologies for reservoir stimulation. Optimize these technologies for a geothermal environment based on a careful characterization.

Project Impacts:

- Provide a proven methodology to enhance borehole injectivity/productivity
- Immediately add megawatts by sweeping heat from a currently hot but isolated portion of the system.
- The technology and methodologies will provide a valuable body of best practices that can be incorporated into an EGS “toolbox” and transferred to other similar projects.

Scientific/Technical Approach

- **Ormat**– oversight, organization and scheduling
- **GeothermEx, Schlumberger** – technical management, hydraulic testing, modeling
- **University of Nevada, Reno –** geologic mapping, structural model, 3D geologic model, surface stress indicators
- **USGS & Temple University** – stress field analysis and structural modeling
- **University of Utah EGI** – tracer testing
- **Schlumberger TerraTek** – petrology, stratigraphy, core testing
- **GMI (USGS, Temple)**– image log & failure analysis, stimulation planning
- **LBNL** – seismic monitoring and analysis
- **Hi-Q Geophysics** – surface seismic acquisition and interpretation
- **LANL, NETL** – imaging, characterizing, and modeling of fracture networks in EGS
- **Sandia National Laboratory** – borehole televiewer acquisition and support
- **Temple University** – **In**terferometric **S**ynthetic **A**perture **R**adar and MEQ.

Scientific/Technical Approach

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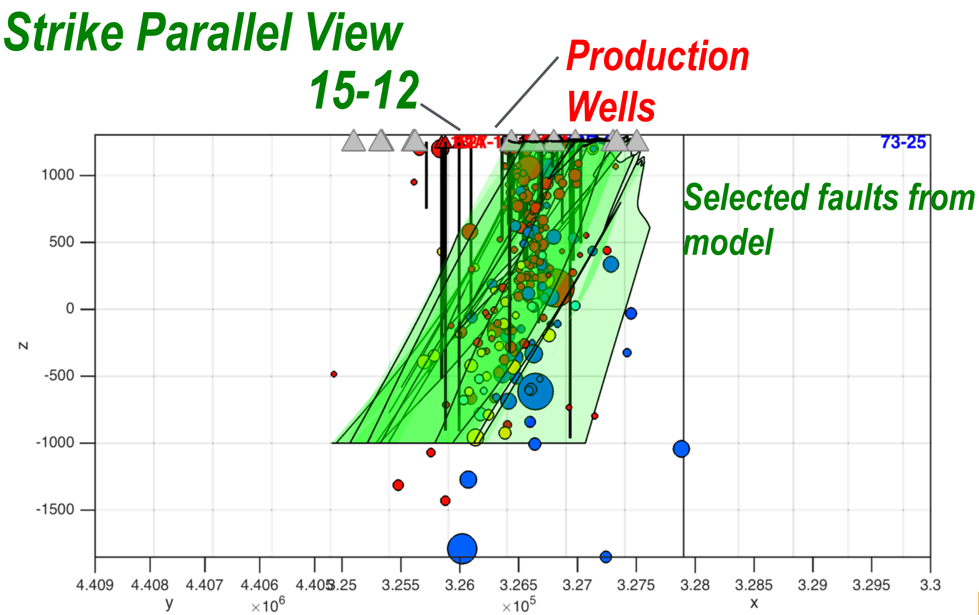
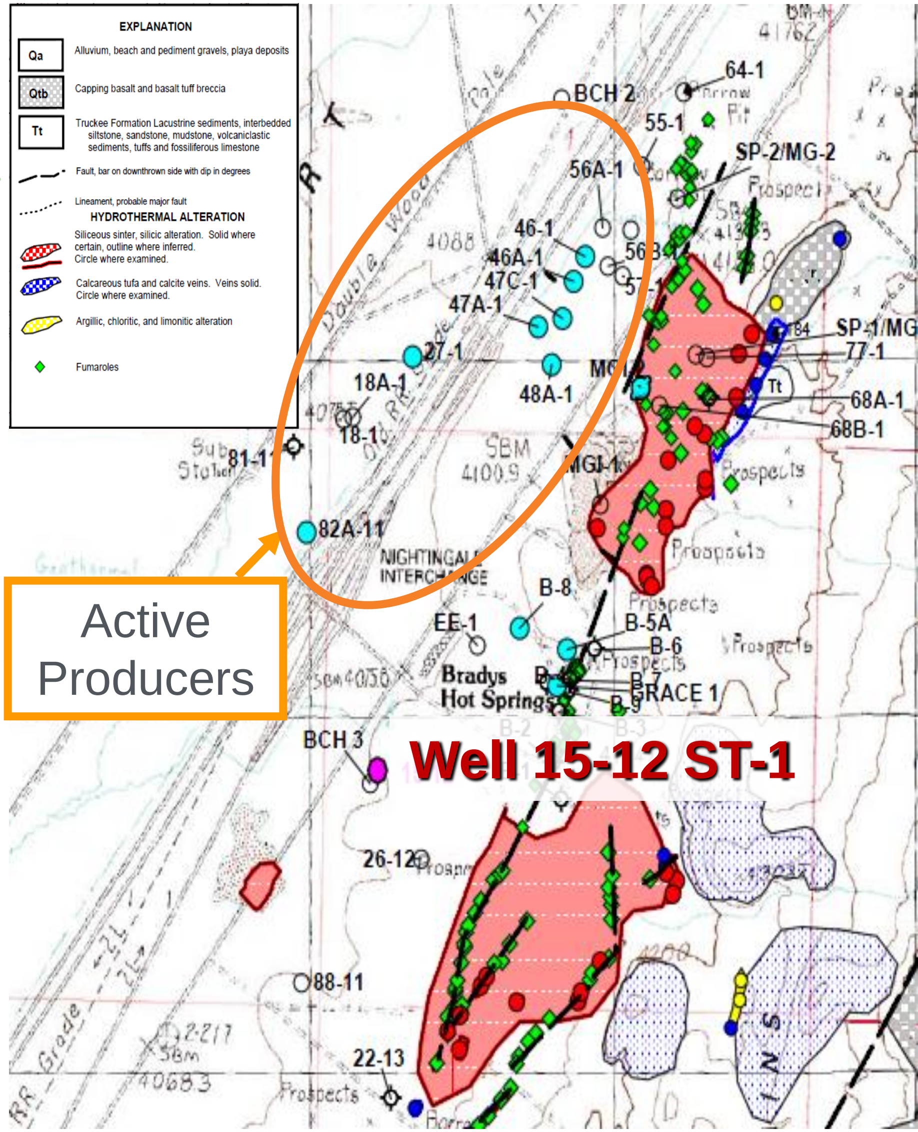
Phase 1: Feasibility Evaluation

- Geologic structural & 3D modeling → define permeability controls and extent of geothermal reservoir
- Petrology & Mineralogy → characterize stimulation target
- Geomechanics/Stress Analysis → failure mode prediction
- Robust seismic monitoring array → real-time stimulation monitoring
- Desert Peak Stimulation Review → Best practices & lessons learned
- Geomechanical Numerical Modeling → Fracture prediction and Stim. management tool
- ~~Downhole Multi-String Geophone detection system → Higher MEQ detection/location~~

Phase 1 Objective: Stimulation Plan

- Shear Stimulation: Injection at $P < S_{hmin}$ for 10 days (Based on LANL modeling)
- Mixed-mode Hydro-shear stimulation: Injection at increasing rates and $P > S_{hmin}$ for 4 – 5 days
- High-rate Pulsed Stimulation: rapid increase in injection rate for 4 days





- Bradys Hot Springs located ~30km Northeast Fernley, NV.
- 15-12 ST-1 encountered low perm. but high temp. (~ 400° F)
- Geology potentially amenable to EGS stimulation
- Adjacent core hole BCH-3 found higher perm.; good core recovery

Scientific/Technical Approach:
Opening Conditions Borehole Characteristics

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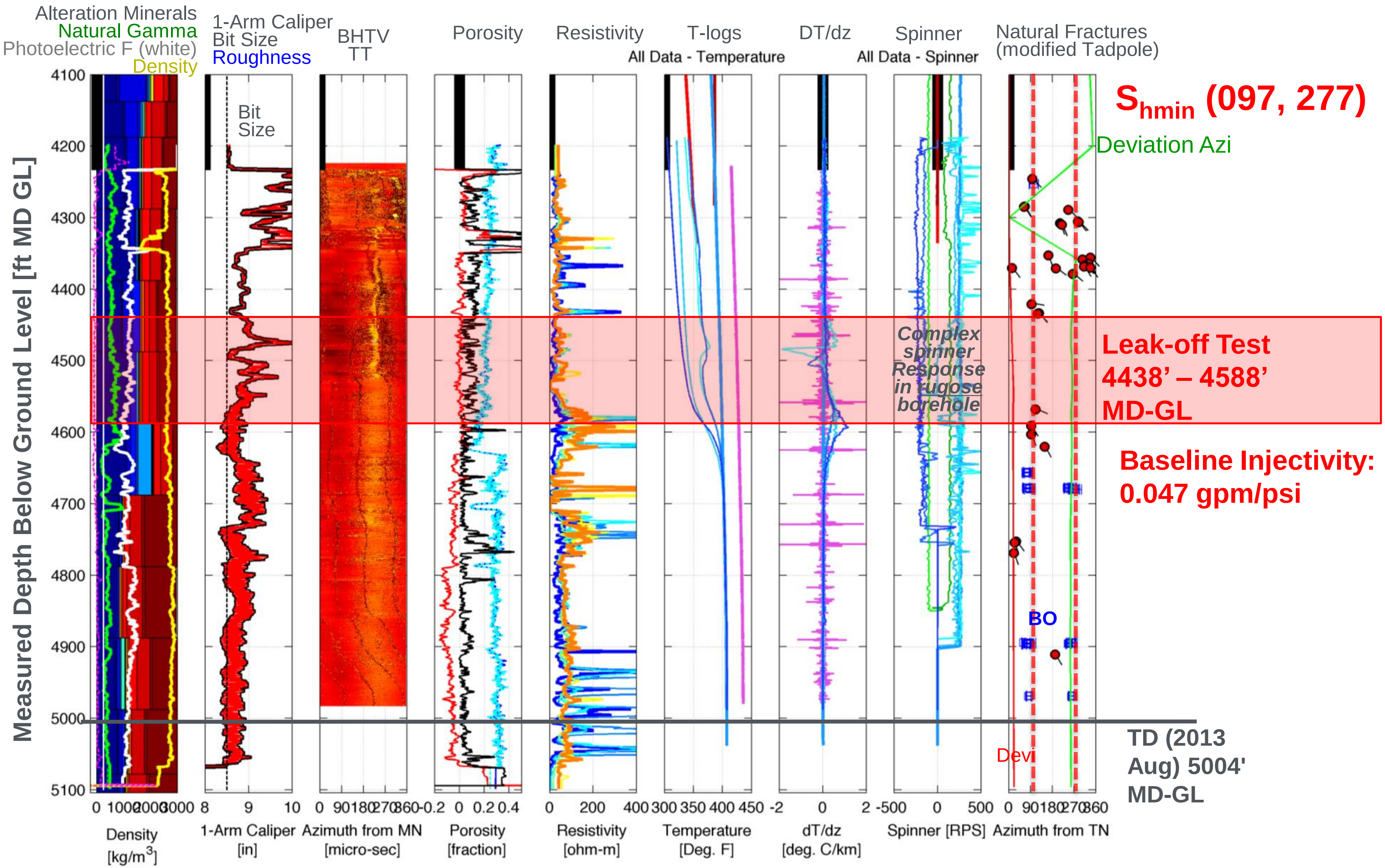
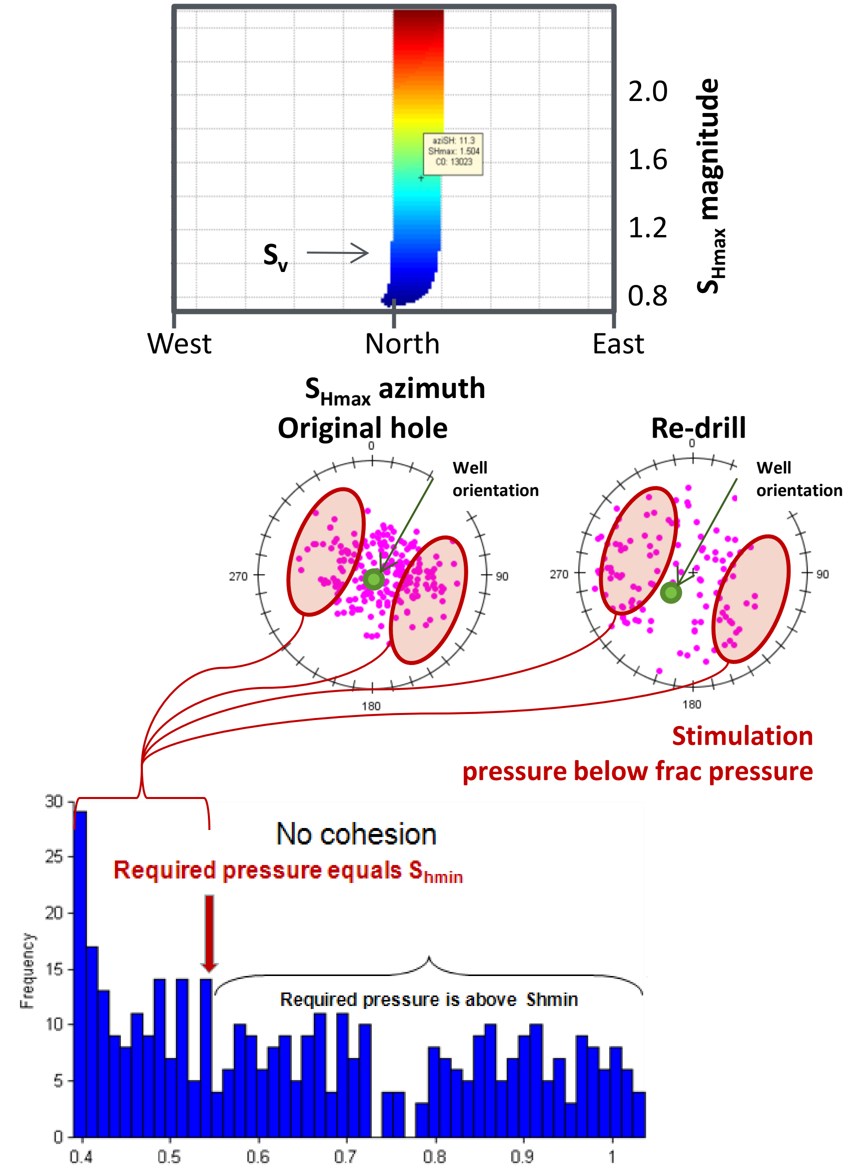


Scientific/Technical Approach:
Stress Model and Natural Fractures

- **Required stress state for observed failures (PTS, RHOB, BO, TC, Leak-off)**
  - S_{hmin} gradient ~ 0.54-0.59 psi/ft
  - S_{Hmax} orientation N7° E±13°
  - S_{Hmax} gradient magnitude > 0.78 psi/ft
  - S_v gradient~ 1.04 psi/ft
  - P_p gradient ~ 0.40 psi/ft

- **Natural fracture orientations (BHTV + FMS)**
  - Dips are near horizontal to more than 80°
  - Wide range of strikes
  - Steeper fractures are under-sampled due to near-vertical hole orientations

- **Critical pressure for shear stimulation** w/o frac'ing depends on fracture strength
  - If cohesion is zero, 30% can be stimulated without creating a hydrofrac
  - Stimulated fractures strike NNE-SSW
  - If cohesion is 500 psi, then <10% of fractures can be stimulated



Scientific/Technical Approach

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Phase 2: Stimulation

- Monitoring
  - (1) a local surface + down-hole seismic network including downhole seismometers with *continuous recording* and *triggered recording*, (2) press-Temp monitoring in nearby wells such as BCH-3, (3) injection of tracer during the stimulation, (4) intermittent TPS logging, step rate testing and pressure fall-off testing.
- Decision tree
  - Established to guide stimulation based on results of monitoring in real time
- Numerical Modeling
  - The stimulation strategy and decision tree were explored via numerical modeling to test the **concept** and **likelihood** and **timeline** for inducing shear failure of natural fractures and related permeability gain as measureable at the wellhead.
  - Pre-conditioning injection provided initial data to benchmark the model and further explore the pre-stimulation conditions in the well.
- Pre-conditioning, Multi-stage stimulation, Long-term injection
  - Key members of the project team were on-site for stimulation to enable real-time decision making based on data from monitoring and stimulation performance.

Scientific/Technical Approach:

Stimulation Plan Decision Tree

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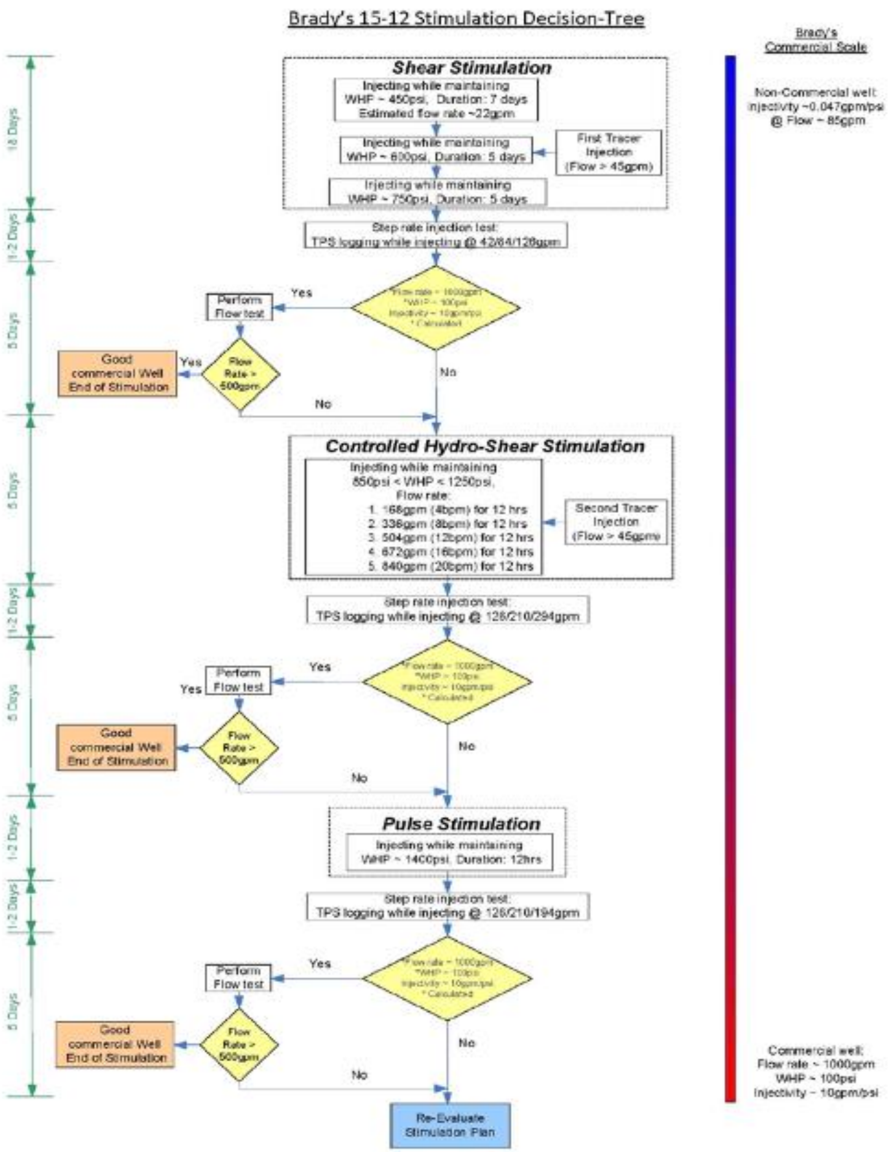

- A decision tree was established to guide stimulation based on results of monitoring in real time.
- The stimulation strategy and decision tree were explored via numerical modeling to test the concept, likelihood, and timeline for inducing shear failure of natural fractures and related permeability gain.
- An injectivity of 10 gpm/psi @ 1000gpm & WHP ~100psi was determine as an indication for a good commercial well, this injectivity represents the existing commercial wells in Bradys field.
- Once this injectivity will be achieved, an attempt to flow the well will be conducted to test the well productivity.

Accomplishments, Results and Progress

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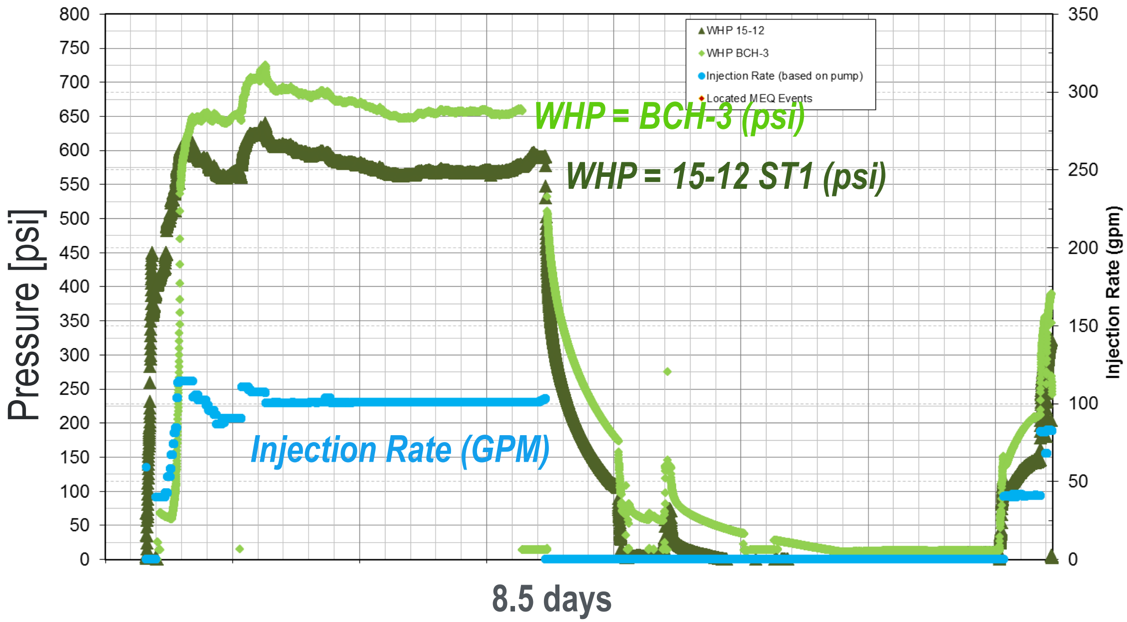
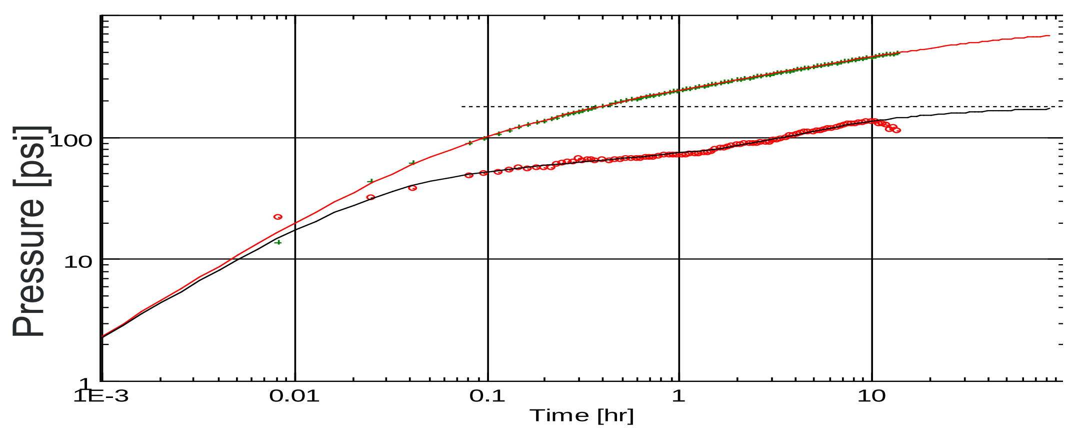
Original Planned Milestone/ Technical Accomplishment	Date Completed
Complete Feasibility Evaluation	Q1 FY2012
Detailed Stimulation Plan	Q2 FY2012
BLM Environmental Assessment	Q1 FY2013
Pre-Condition	Q2 FY2013
Multi-Stage Stimulation	Q4 FY2013
Post-Stimulation Injectivity Test	Q1 FY2014
Long-Term Injection	Q2 FY 2015

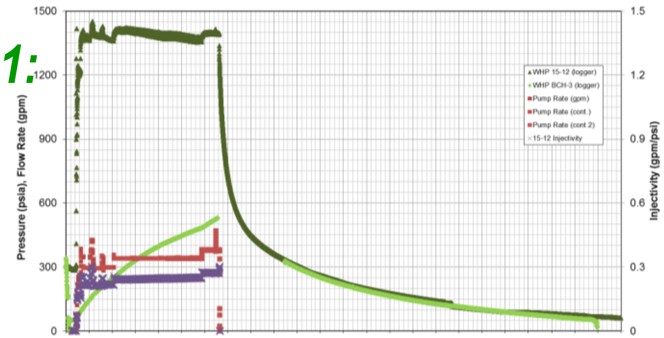
- Pre-conditioning Stage ("Shear Stim")
  - Injection below S_{hmin} per benchmarking LANL model
  - Max. injection rate ~100 gpm
  - Avg. injectivity ~0.3 gpm/psi
  - No MEQs detected
  - Fall-off Analysis:
    - Weak dual-porosity response
    - Finite conductivity fracture response
    - k-h ~ 230 to 300 md-ft





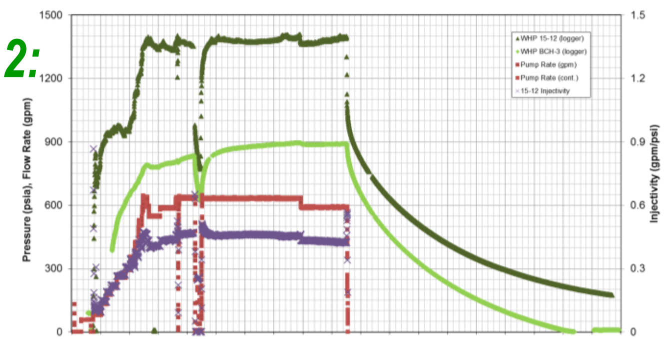
- Stage 1 Stimulation
  - Avg. injection rate ~378 gpm
  - Avg. injectivity ~0.24 gpm/psi
  - No MEQs detected
  - Fall-off Analysis:
    - Closure pressure uncertain (~ 1058psia)
    - Indeterminate flow regime after closure
- Stage 2 Stimulation
  - Max. injection rate ~650 gpm
  - Avg. injectivity ~0.45 gpm/psi
  - No MEQs detected
  - Fall-off Analysis:
    - ISIP ~ 935 psia WHP
    - Indication of pressure-dependent leak-off (natural fractures or dilated fissures)
    - After-closure response suggests radial flow
- Stage 3 Stimulation
  - Max. injection rate ~1,100
  - Avg. injectivity ~0.53 gpm/psi
  - No MEQs detected
  - Fall-off Analysis:
    - Closure pressure ~890 psia WHP (close to S_{hmin} from step-rate test)
    - Indication of pressure-dependent leak-off (natural fractures or dilated fissures)
    - After-closure response suggests radial flow

Stage 1:



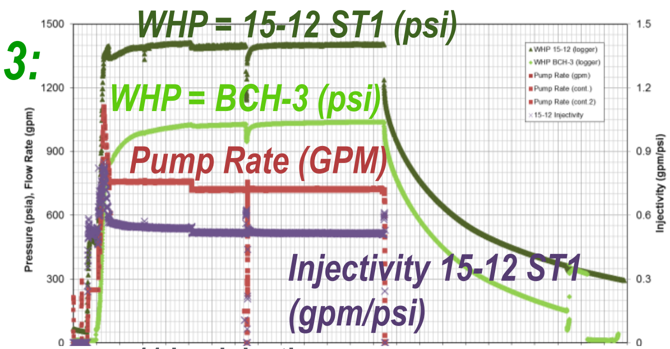
10 hrs injection

Stage 2:



9 hrs injection

Stage 3:



11 hrs injection

Accomplishments, Results and Progress

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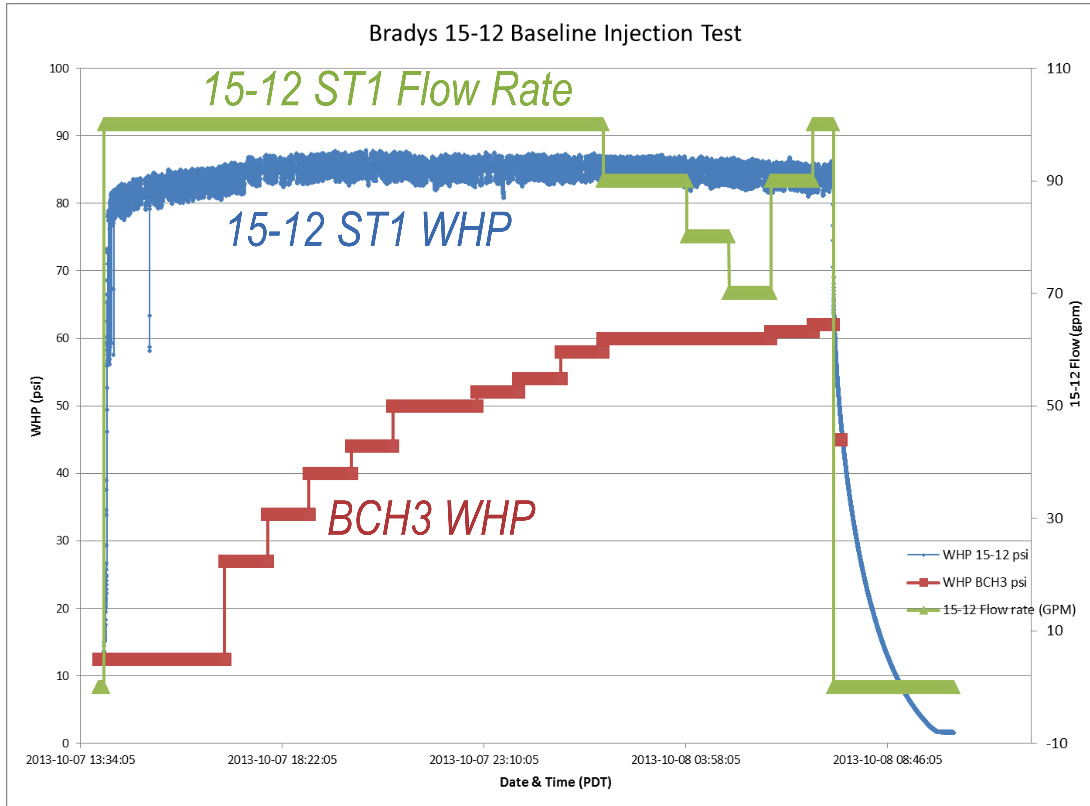
- Post-Stimulation Injectivity Test: October 2013
  - Max. Inj. Rate ~ 100 gpm
  - Injection below S_{hmin}
  - Avg. Injectivity ~ 1.17 gpm/psi
  - No MEQs detected
  - Fall-off Analysis:
    - Stronger dual-porosity response
    - Finite conductivity fracture response
    - k-h ~ 850 md-ft
- Long-Term Injection
  - Allowed increased throughput of produced water power plant
  - Increase from 1.17 gpm/psi to 1.4 gpm/psi



~~*From Stimulation to Injectivity Test:*~~

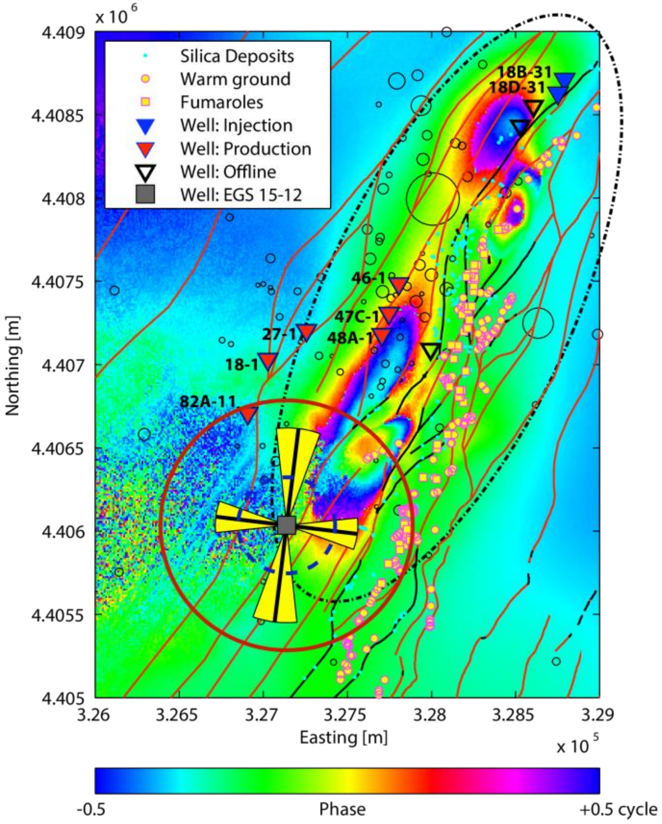
- ~~*3 to 4-fold increase in injectivity*~~
- ~~*~3-fold increase in estimated k-h*~~

From Base-Line Test to Long-Term Test:

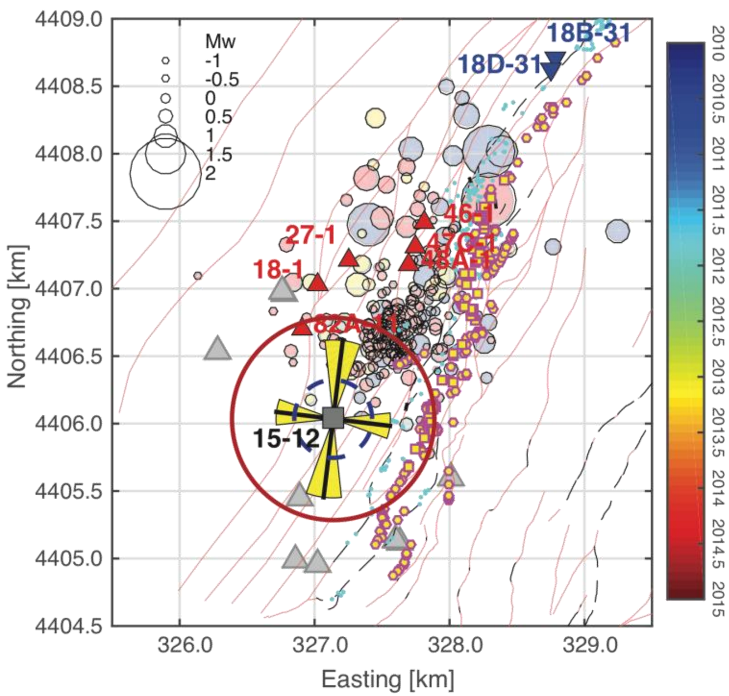
- *30-fold increase in injectivity*

Accomplishments, Results and Progress:
Synergy with InSAR and MEQ; LBL MEQ

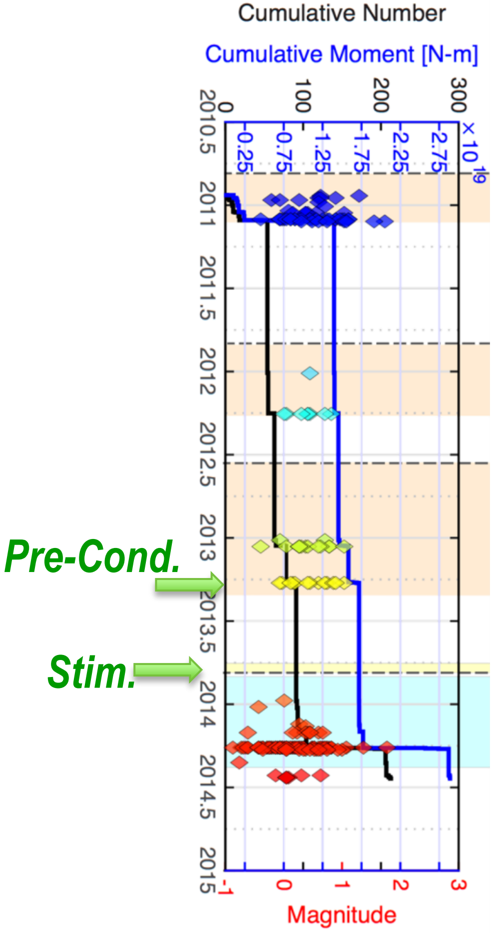
InSAR



Earthquake



Timeline



Future Directions

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- Evaluate long-term injection results
  - MEQ
  - Surface Deformation
  - Injectivity
  - Temperature and Pressure in nearby monitoring wells
    - BCH-3 TPS survey
- Continue coordination with on-going and new projects
  - Stimulation modeling
  - InSAR and MEQ (monitors deformation responses to pumping)
  - PoroTomo (includes adding more pressure monitoring and injection experiments)

Milestone or Go/No-Go	Status & Expected Completion Date
Go/No-Go: Construct Permanent Pipeline	Long term injection continued from late 2013 to March 2015, currently evaluating results

Summary

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- The Bradys EGS Project emphasizes the importance of:
  - Diverse research team plus dedicated field operations partner
  - Integration of tectonics, geology, petrology, rock mechanics and stress
  - Well designed MEQ system that has been deployed early in the project
  - Protocol for monitoring and managing induced seismicity
  - Leveraging successes & lessons learned from Desert Peak experiences
- This project designed and implemented a well-monitored, multi-stage stimulation based on integrated geologic, geomechanical, and well characterization.
- This project is leveraged against several on-going synergistic projects including:
  - The InSAR and MEQ project which is pursuing additional investigations concerning the extent of the reservoir, the geomechanical conditions and controls on seismicity.
  - The PoroTomo project which will characterize reservoir properties at fine-set scale including rock-mechanical properties and porosity structure.