Feasibility of EGS Development at Bradys Hot Springs, Nevada

Project Officer: Bill Vandermeer

Total Project Funding: $6.6M

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Track 3 EGS Demonstrations

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Relevance to Industry Needs and GTO Objectives

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
- Demonstrated the use of cross-industry technology in a geothermal well.
- The technology and methodologies will provide a valuable body of information that will inform future EGS projects.

Methods/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.

Methods/Approach:
Bradys Overview

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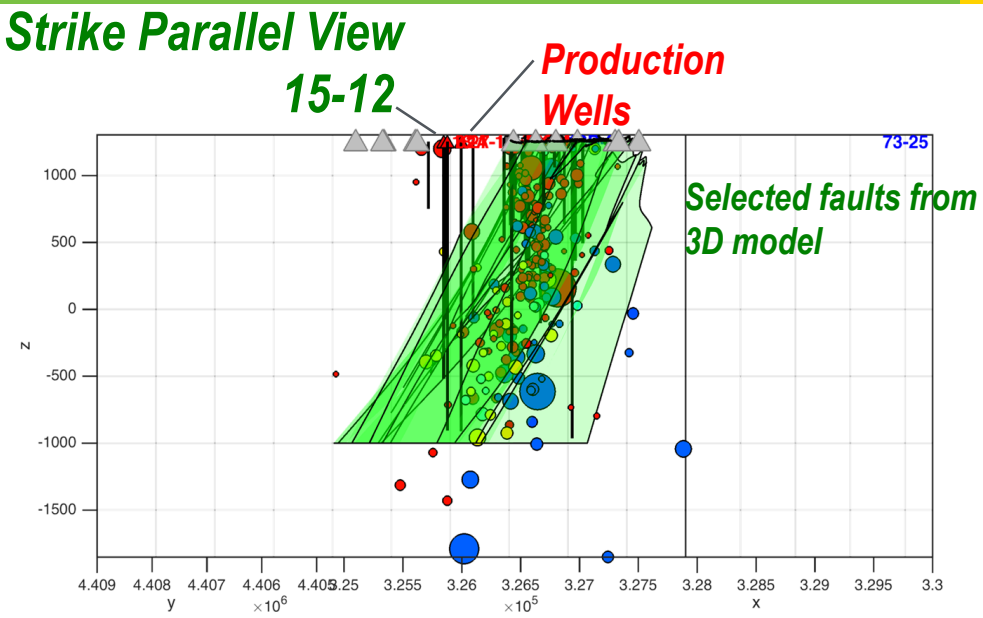
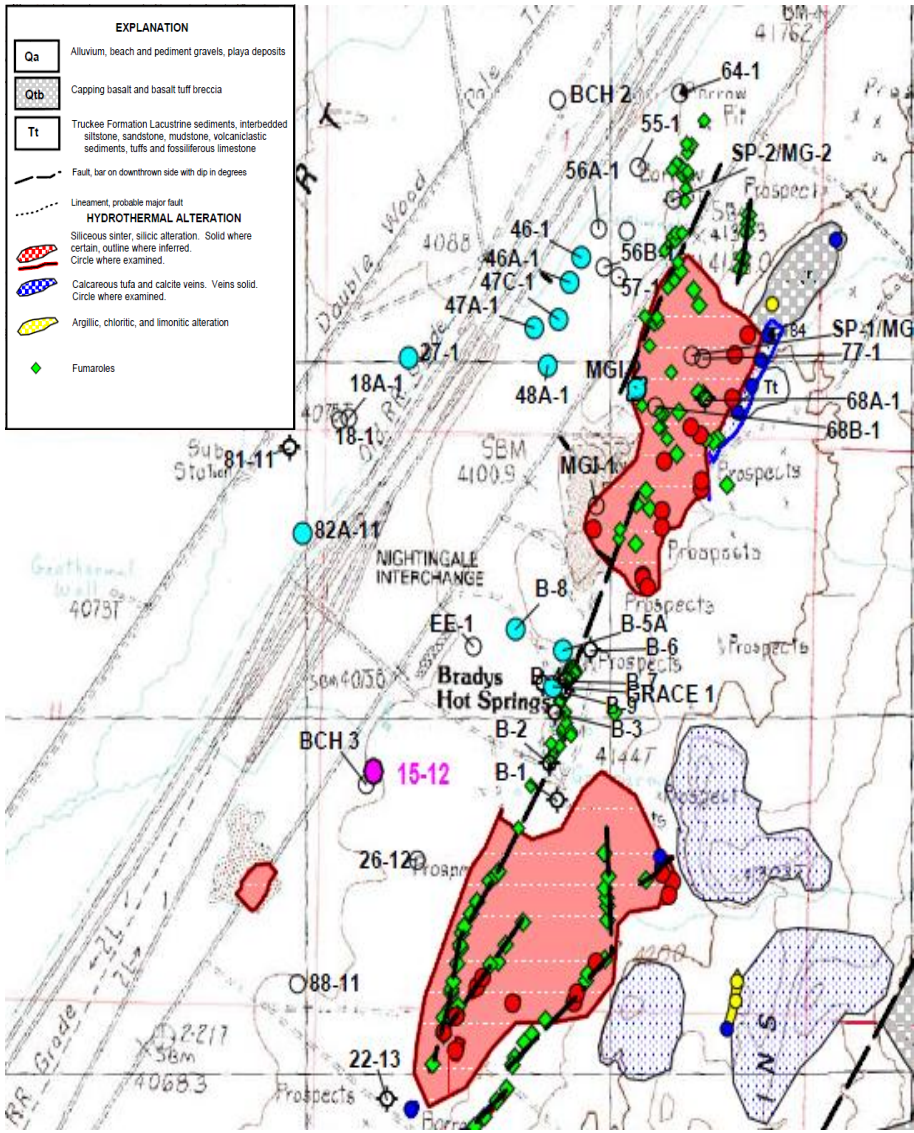


- Bradys Hot Springs located ~30km Northeast Fernley, NV.
- 15-12 ST-1 encountered low perm. but high temp. (~ 400° F)
- Geology potentially amenable to EGS stimulation
- Adjacent core hole BCH-3 found higher perm.; good core recovery



Methods/Approach:
Stress Model and Natural Fractures

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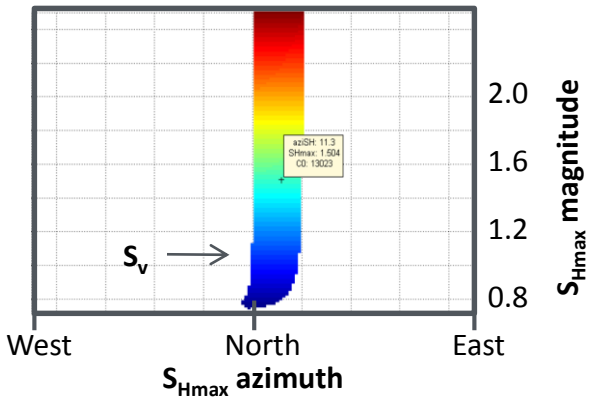
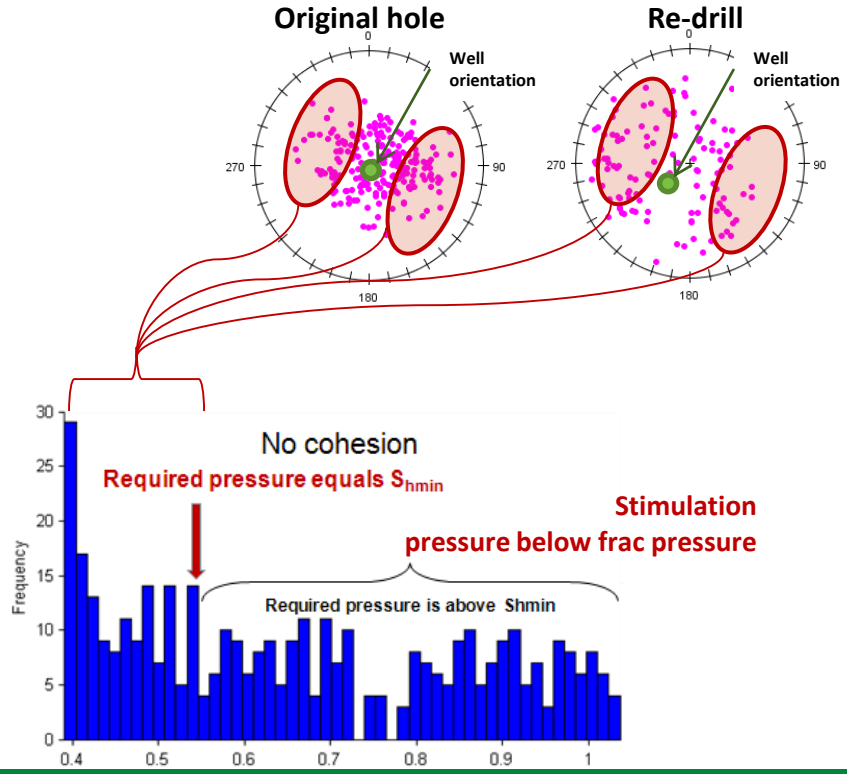
- **Required stress state for observed failures (PTS, RHOB, BO, TC, Leak-off)**
  - S_{hmin} gradient ~ 0.54-0.59 psi/ft
  - S_{Hmax} orientation N7° E±13°
  - S_{Hmax} gradient magnitude > 0.78 psi/ft
  - S_v gradient ~ 1.04 psi/ft
  - P_p gradient ~ 0.40 psi/ft

- **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





Methods/Approach:
Interpreting Opening Borhole Conditions

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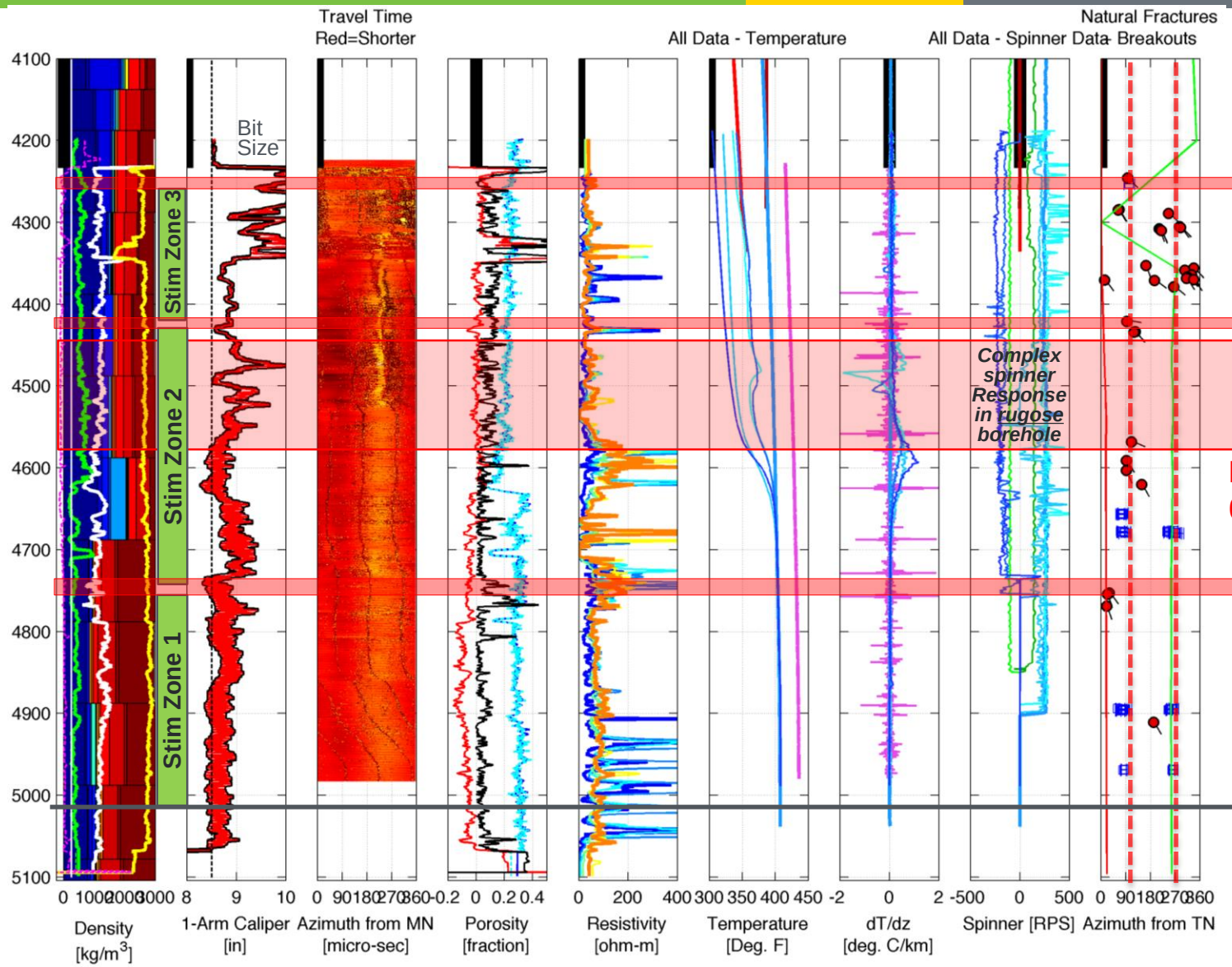


Packer Placements, to top of 11' seal (MD-GL)

4255'
(guard packer)

4412'

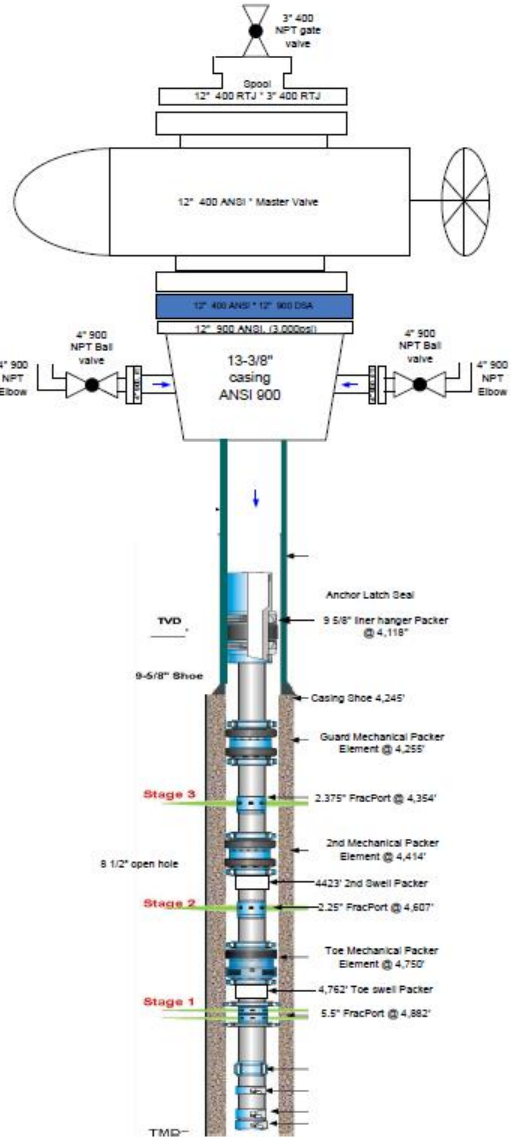
Mini-frac
4438' – 4588'
MD-GL

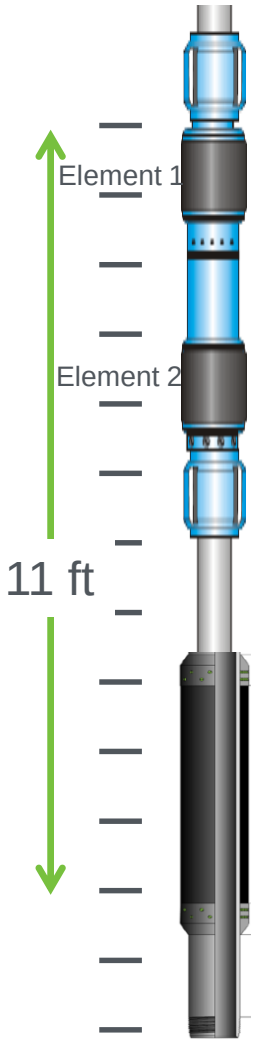
Baseline Injectivity:
0.047 gpm/psi

4750'

TD (2013 Aug)
5004' MD-GL

Methods/Approach:
Zonal Isolation





Packers Plus 9-5/8" x 5-1/2" RockSEAL II Viton 10K Centralized Hydraulic Set Open Hole Packer:

- **Two, 12"-long sealing elements, 7.75" OD**
- **6' x 5-1/2" 17# L-80 BT&C Pup joint on top and bottom**

SwellRight Packer, 5-1/2"

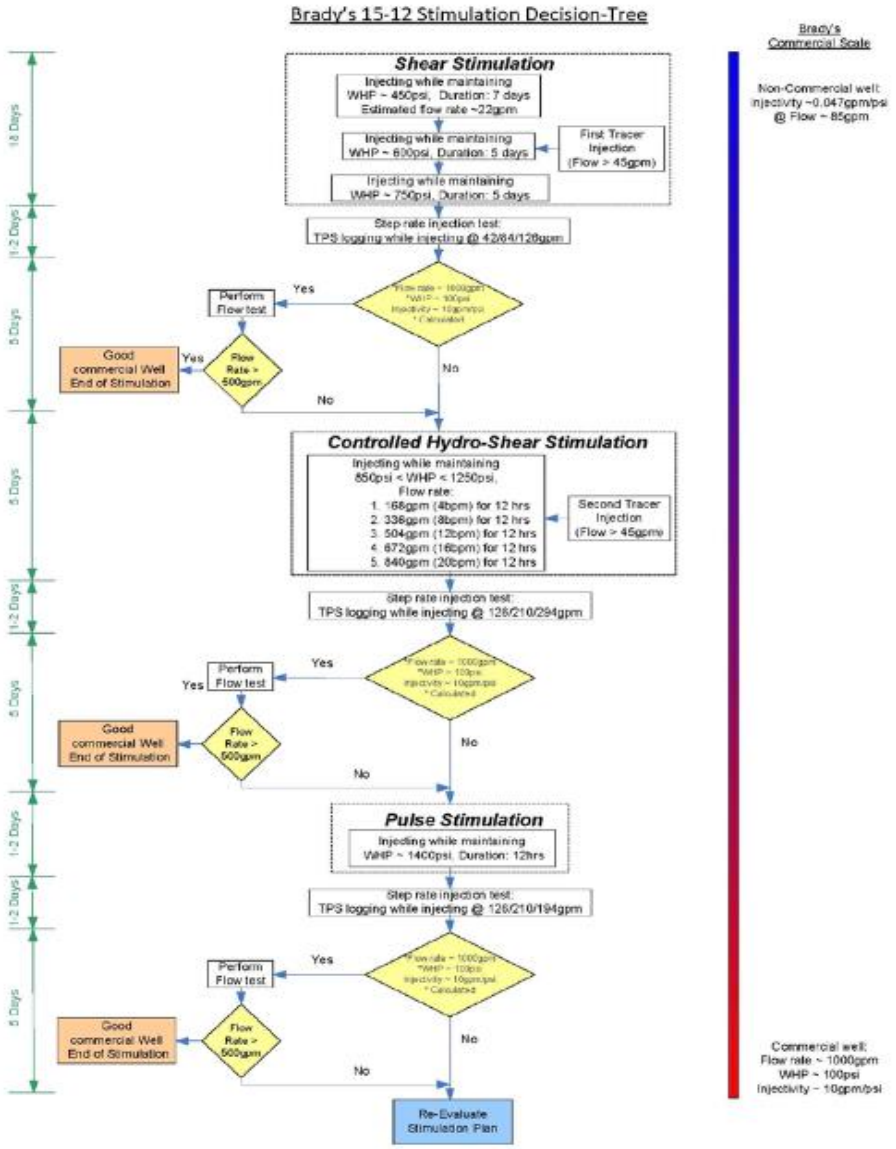
- Packers divide the well into three intervals for stimulation .
- Depths were correlated from the drilling logs, SLB geophysical logs, and the two BHTV logs.
- Intervals chosen to isolate like lithologies/physical properties as much as possible, while also containing identified natural fractures (preferably well oriented).

Methods/Approach

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, (5) Long term monitoring injection and InSAR.
- 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/zone 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.

Methods/Approach:
Stimulation Plan Decision Tree



- 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.

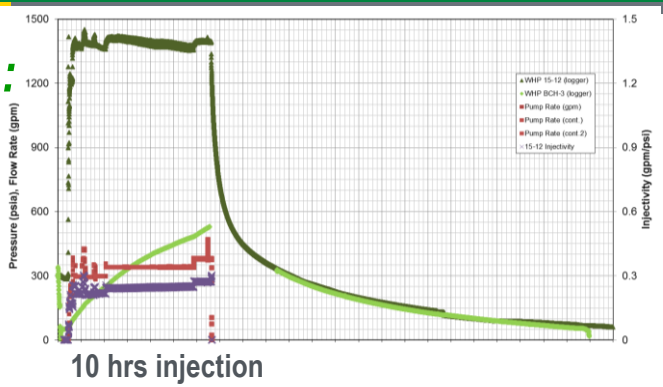
Technical Accomplishments and Progress

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

Technical Accomplishments and Progress

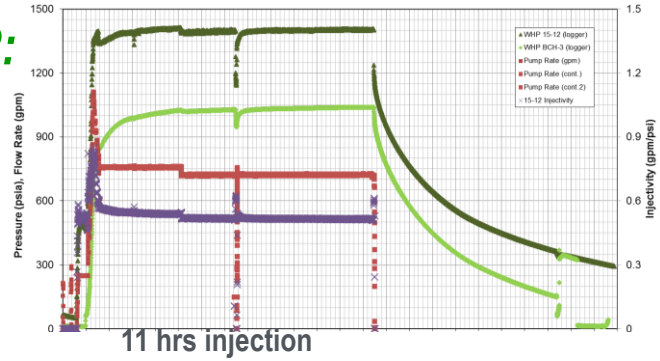
- Zone 1 Stimulation
  - Avg. injection rate ~378 gpm
  - Avg. injectivity ~0.24 gpm/psi
  - No MEQs detected
  - Fall-off Analysis:
    - Closure pressure uncertain (~ 1058psia)
    - Indeterminate flow regime after closure
- Zone 2 Stimulation
  - Max. injection rate ~1,100
  - Avg. injectivity ~0.53 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
- Zone 3 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

Zone 1:



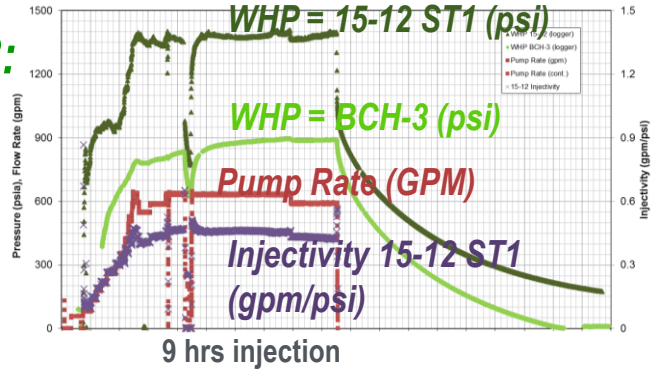
10 hrs injection

Zone 2:



11 hrs injection

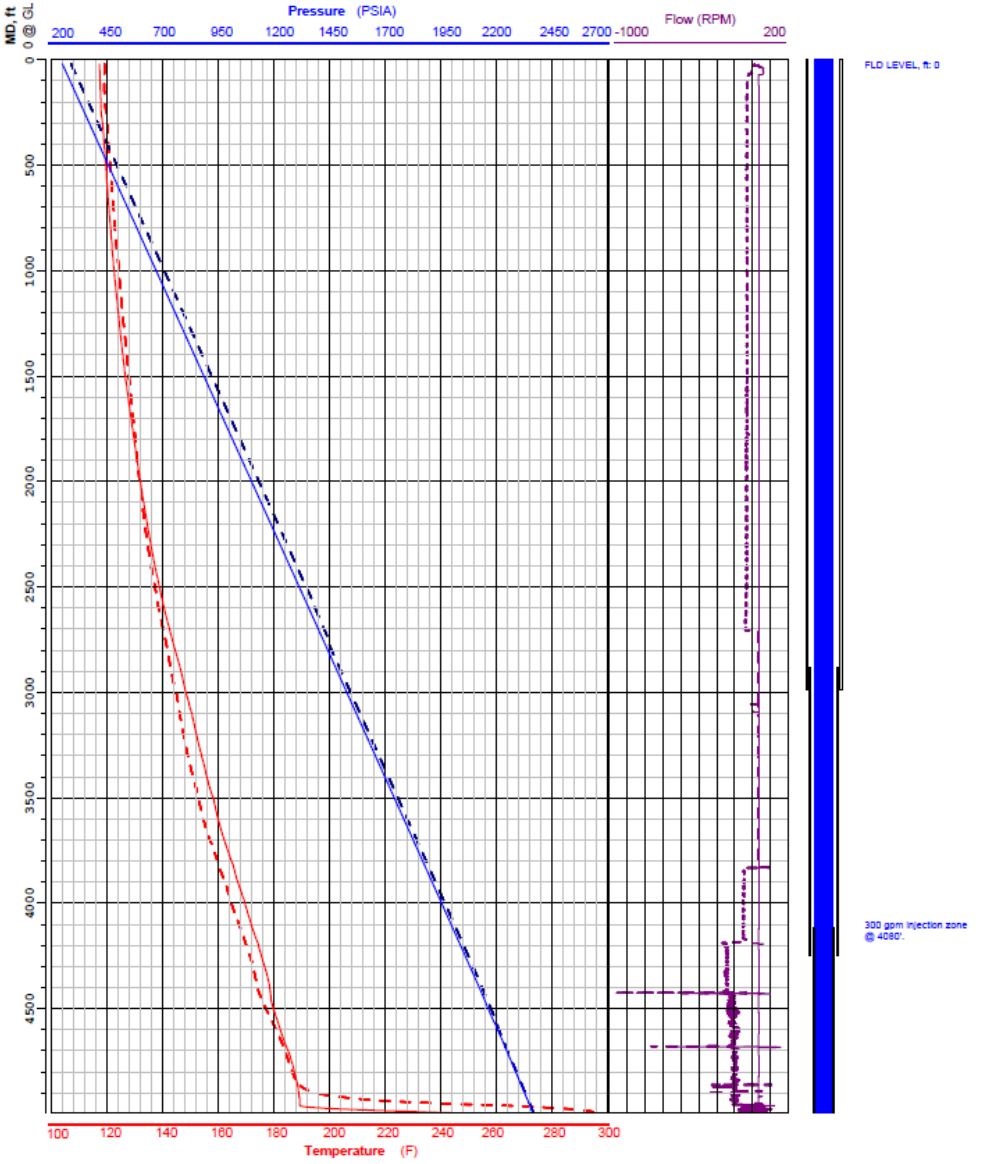
Zone 3:



9 hrs injection

Technical Accomplishments and Progress

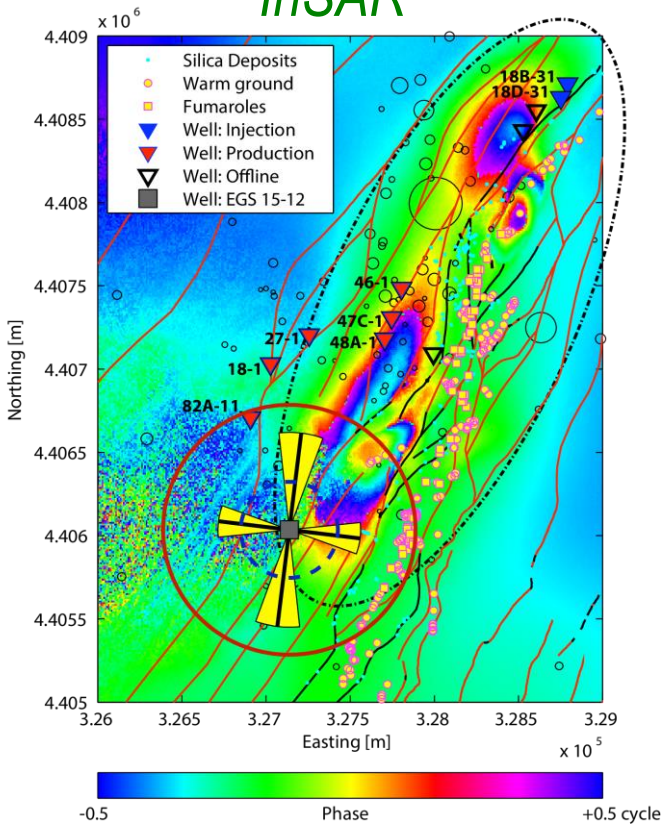
- Surveys were run on June 2, 2016 when the well was taking 150-300gpm.
- The temperature survey shows that the maximum temperature was 407 ° F.
- The spinner surveys indicate that injection is leaving the well near 4300 ft. and 4700 ft. (near zones 2 and 3).



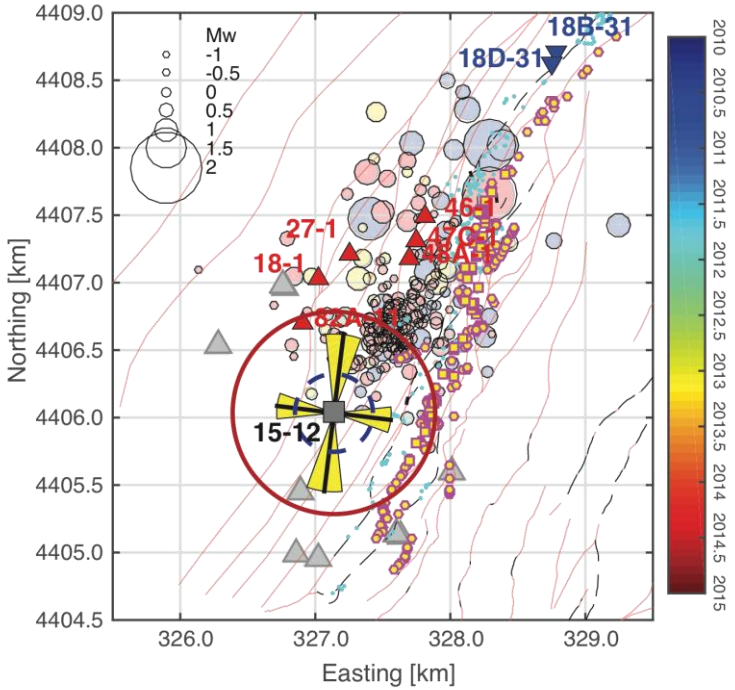
Research Collaboration and Technology Transfer

- This project is leveraged against several on-going synergistic projects including the InSAR and MEQ project and the PoroTomo project.
- Geomechanical analysis from this project has provided a regional analog to the FORGE project at Fallon, NV

InSAR



Earthquake



Future Directions

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- Ongoing work for this project includes a comprehensive report on the enhanced geothermal stimulation (EGS) activities that occurred in 2013. This project will include review of the decisions and documentation from the Phase 1 and Phase 2 of the Bradys EGS project. These tasks include:
  - Data Compilation and Initial Review
  - Interview Key Project Participants
  - Analysis of the EGS Stimulation Planning Process
  - Analysis of the Bradys EGS Stimulation in Well 15-12 ST1
  - Reporting, including lessons learned and suggestions for future EGS projects
- Continue coordination with on-going and new projects
  - InSAR and MEQ (monitors deformation responses to pumping and provides earthquake relocation)
  - PoroTomo (includes adding more pressure monitoring and injection experiments)
  - FORGE (lessons learned from the Bradys EGS stimulation)

Milestone or Go/No-Go	Status & Expected Completion Date
Stimulation Analysis Report	December 2017

Summary

- 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, multi-zone stimulation based on integrated geologic, geomechanical, and well characterization.
- The current work underway to fully analyze the stimulation will provide insights into the outcome of the 2013 activities and help guide future work at the FORGE site.