Geothermal Technologies Office 2015 Peer Review

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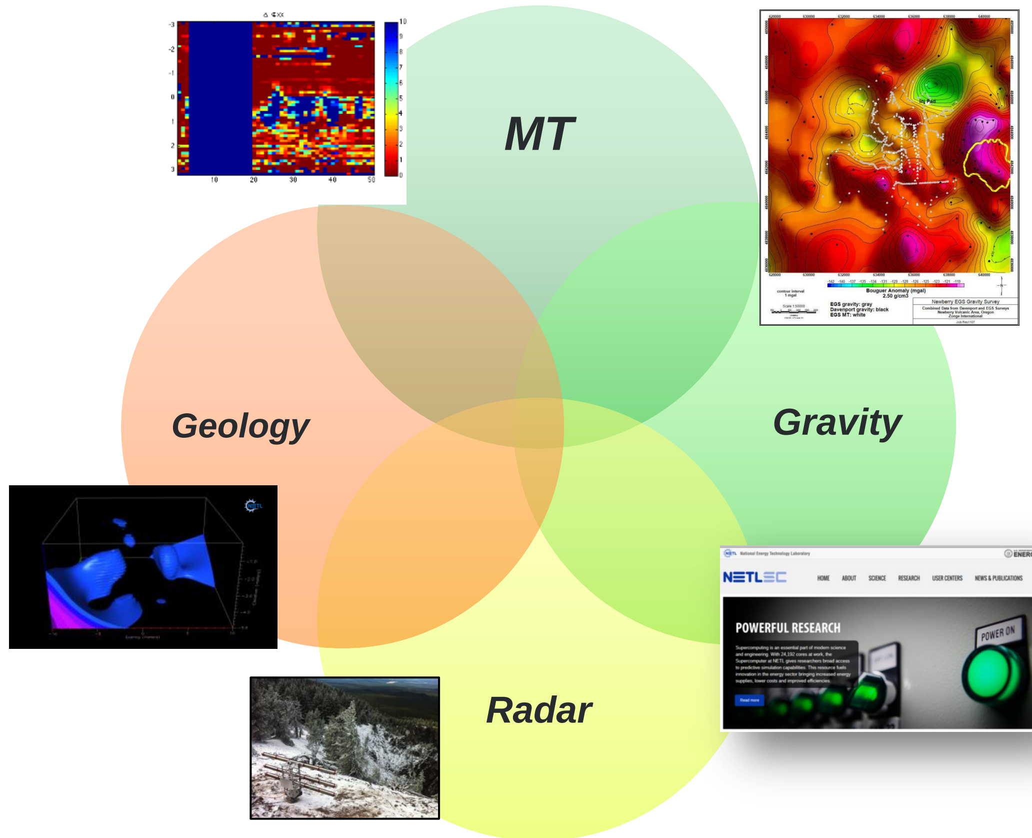

Novel use of 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems

Project Officer: Lauren Boyd   Total Project Funding: $2146512

May 2015

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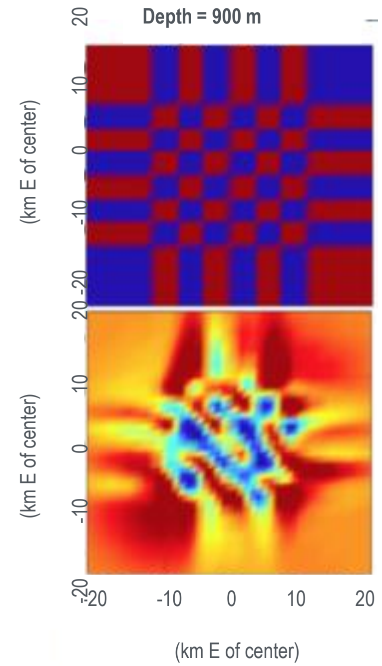
Track 3 EGS1

Novel use of 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems

- Unlock potential of an EGS play by improving knowledge of the temporal-spatial variation in temperature, crack volume, and their effects on porosity and permeability.
- During the lifetime of an EGS resource, these factors can be strongly influenced by the balance between extraction and recharge.
- To maximize production and longevity of the resource, it is desirable to monitor the temporal spatial changes in these conditions as accurately as possible, at minimal expense.
- This project seeks to improve low-cost monitoring capabilities through the novel integration of newly emerging, surface-based techniques.



Project Participants & Goal

U.S. Department of Energy's National Technology Laboratory (NETL)

- Kelly Rose
- Mackenzie Mark-Moser
- Benjamin Heath

Oregon State University

- Adam Schultz
- Paul Vincent

Zonge International

- Scott Urquhart
- Les Beard

Overarching project goal: Provide new information that is necessary to ensure reservoir longevity and optimal production.

The methodology is designed to be transferrable to other EGS reservoirs.

External collaborator:

- Alta Rock Energy

Scientific/Technical Approach Phase 1

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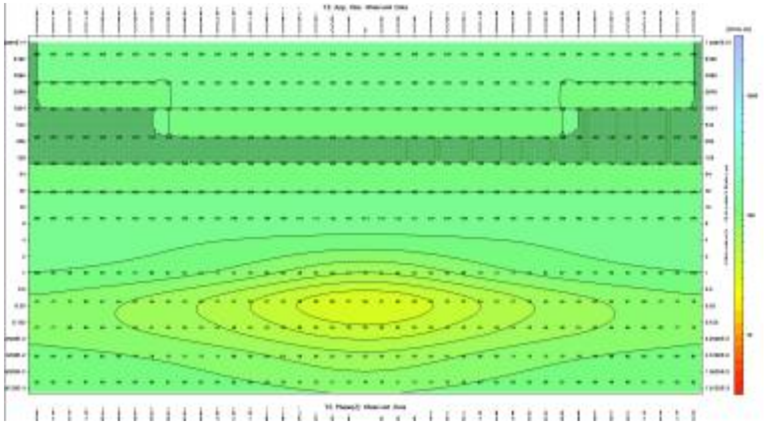
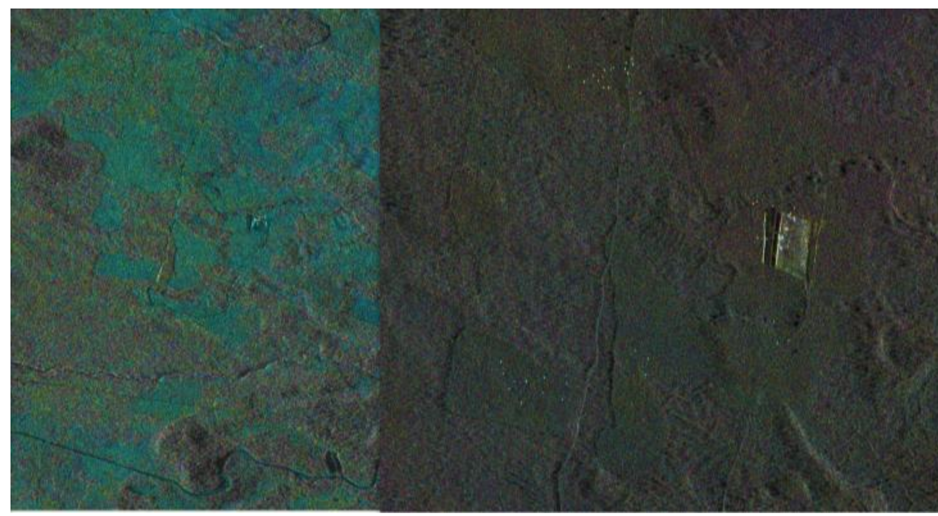
Phase 1 Tasks – All completed

- Acquisition of radar and MT equipment
- Permitting for MT/CSEM, Gravity, Radar
- Numerical and laboratory-based feasibility assessment of the proposed EM and radar systems.
- Produced predictive models and simulations based on the phase 1 field/lab tests.
- Developed a plan for Phase 2 efforts, in coordination with AltaRock and their partners



Technical Approach – Portable Radar/Satellite Radar– Phase 2

- Combination of portable and satellite Radar Interferometers
- No detectible deformation (>0.5 cm) apparent in either satellite data set
- Results consistent with LBNL modeling of injected volume
- Processing ongoing of portable, Radarsat-2, and TerraSAR-X data



Radarsat-2 (left)and TerraSAR-X(right) differential interferograms prior to geocoding for period of stimulation

Technical Approach – Magnetotellurics/CSAMT – Phase 2

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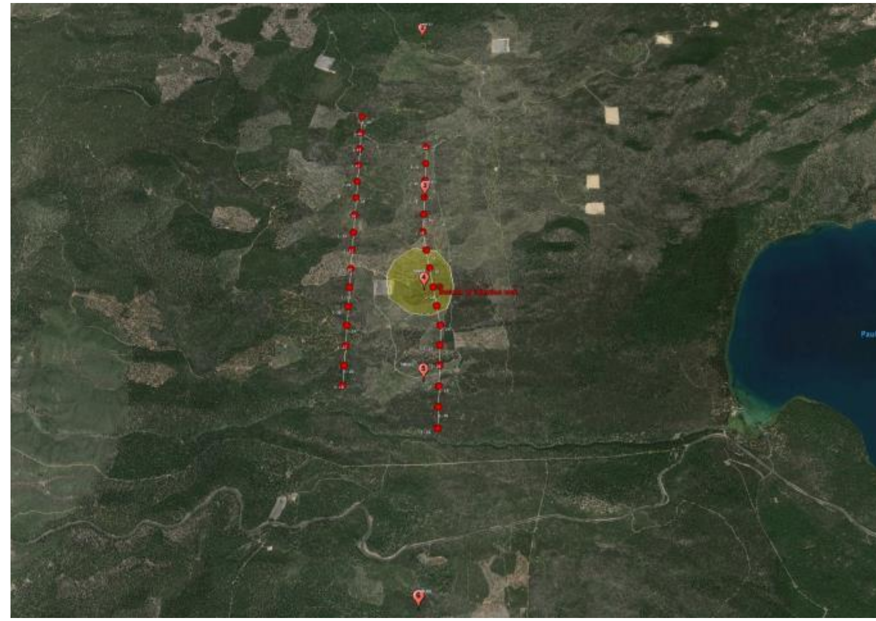
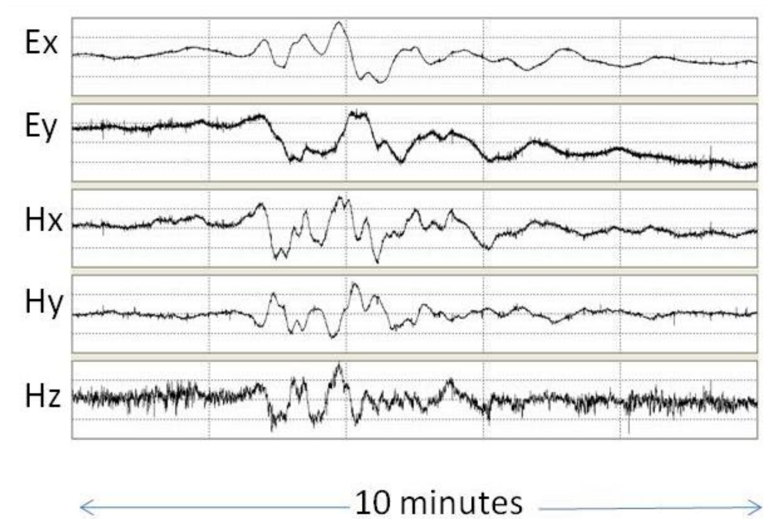
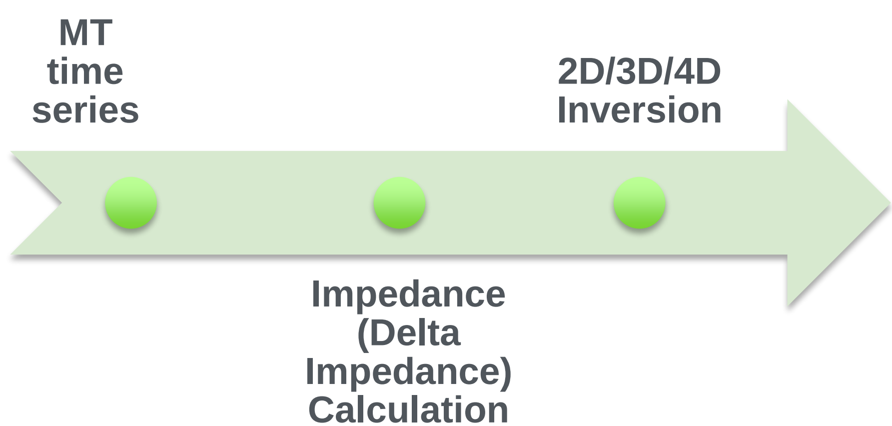


2014 MT Survey Design

- Two modes of deployment
  - Long Period Installations with episodic servicing (6 Tensor stations)
  - High Density installations with daily servicing (12 channels for Electric Fields and Magnetic Fields)
  - Similar Instruments





Technical Approach – Magnetotellurics/CSAMT – Phase 2

Detecting the subtle time derivative in electrical properties due to fluid flow and mineral reaction processes at depth

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yz} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} + \mathbf{U}$$

$$H_z = \begin{bmatrix} T_{x,z} \\ T_{y,z} \end{bmatrix} \begin{bmatrix} H_x & H_y \end{bmatrix} + \mathbf{U}$$

The impedance (a complex-valued 2 x 2 frequency dependent tensor) and tipper (a complex-valued 1 x 2 frequency dependent vector) are usually assumed to be stationary, i.e. time-invariant.

We allow for variability from one daily sample window to the next to determine the delta impedance and delta tippers

1. We sample for 12 hours/day during the dusk-to-dawn period, using a sample rate that varies from 256 Hz to 4096 Hz, with a precision of 32 bits

1. We calculate $Z(f,t_1)$ and $T(f,t_1)$ for 2 adjoining days of data; then we move 1 day and calculate $Z(f,t_2)$ and $T(f,t_2)$ for the next 2 adjoining days, and so on, building up a set of $Z(f,t_i)$ and $T(f,t_i)$ each centered on a different 2 day window

1. We calculate the first difference $\delta Z(f,t_i) = Z(f,t_i) - Z(f,t_0)$ each day, where t_i is the ith day, and t_0 is a period starting two days before the start of stimulation, which was when we obtained our pre-stimulation baseline conductivity reference structure.

1. We also calculate the time derivative in the tipper $\delta T(f,t_i) = T(f,t_i) - T(f,t_0)$

Technical Approach – Magnetotellurics/CSAMT – Phase 2

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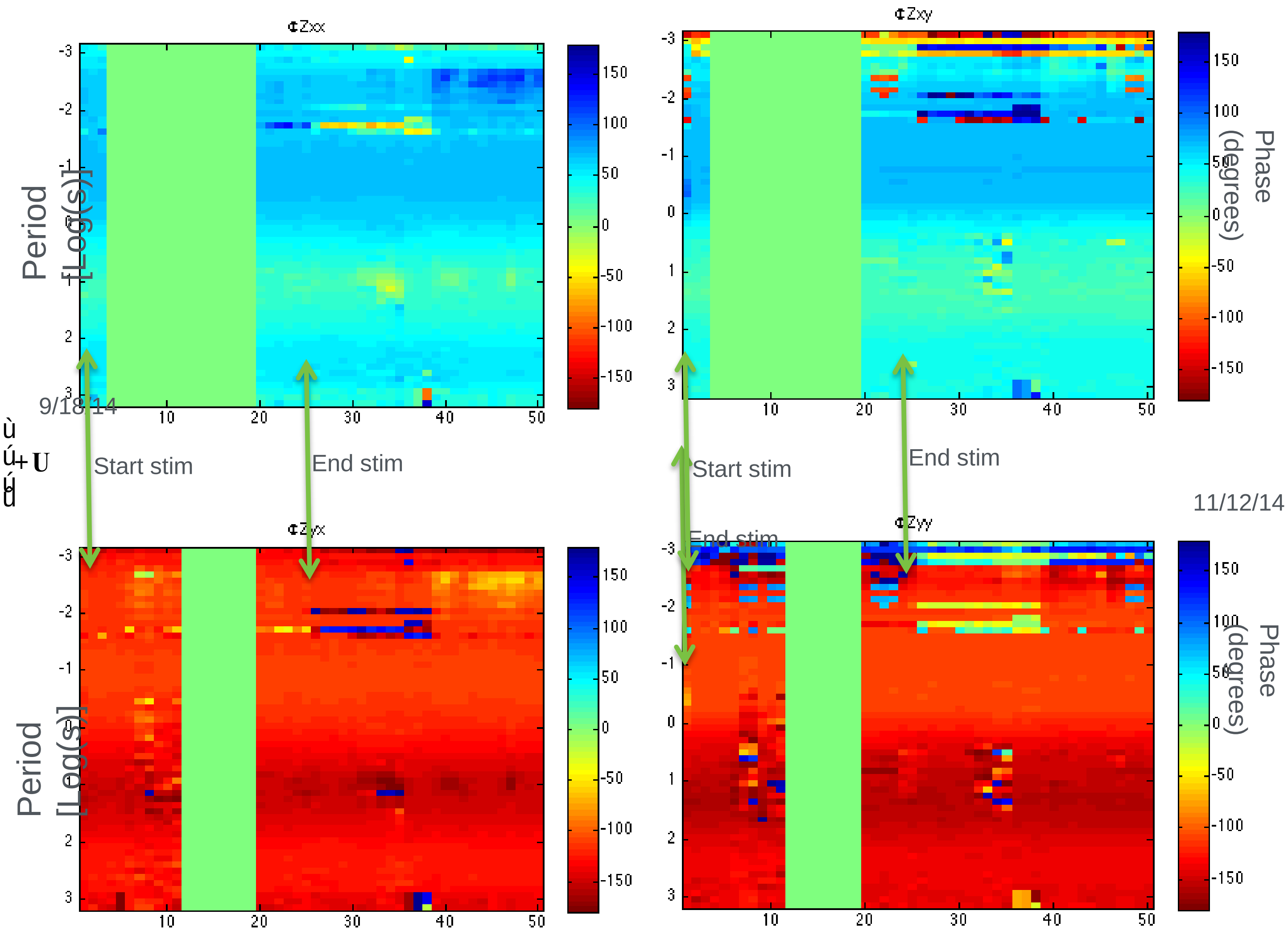
Phase of Z at NBL04 9/18/14-11/12/14

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yz} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} + \mathbf{U}$$

$$phase = \arg(Z)$$



Technical Approach – Magnetotellurics/CSAMT – Phase 2

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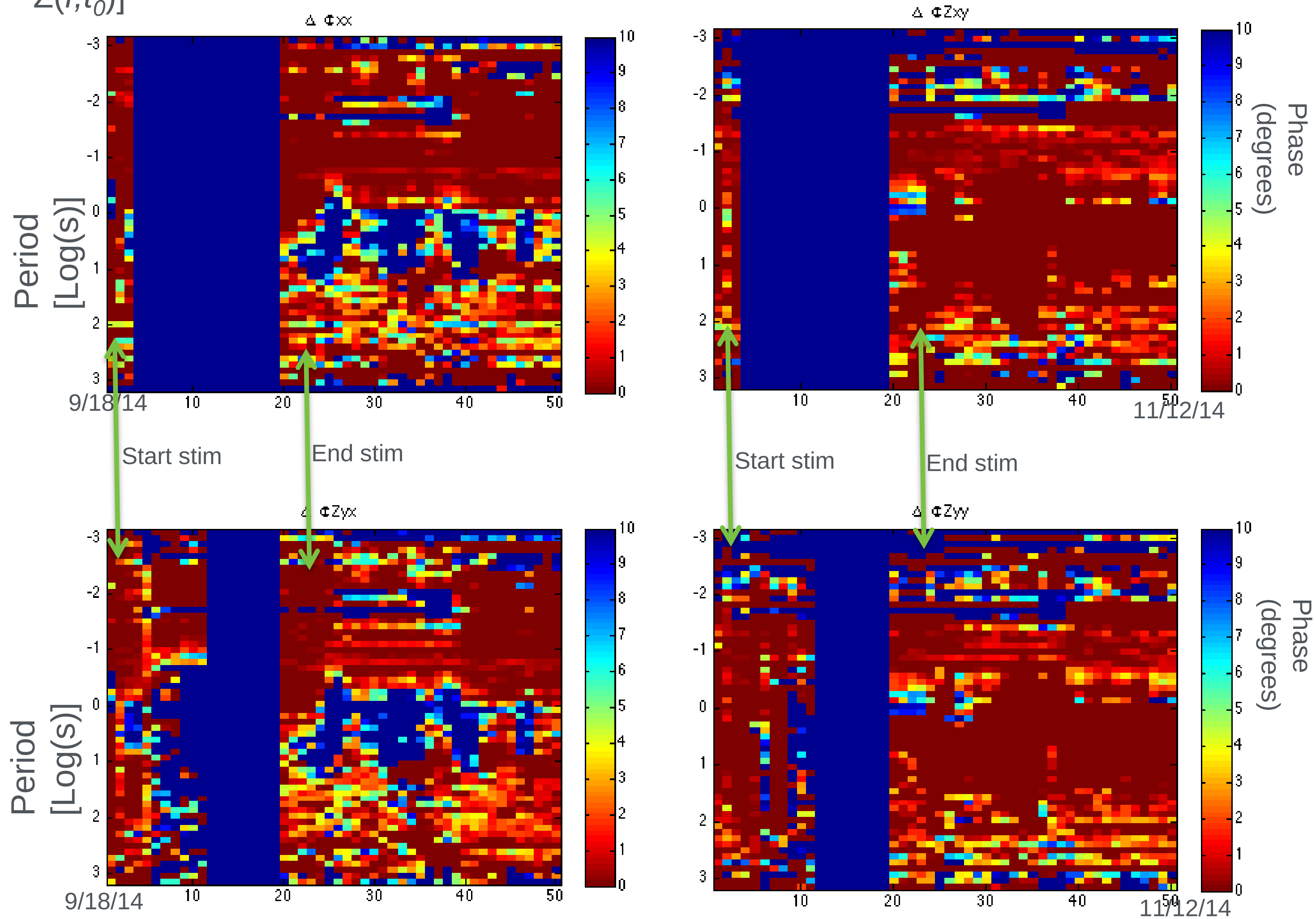
$\delta\arg[Z(f,t_i)] = \delta\arg[Z(f,t_i) - Z(f,t_0)]$

δPhase of Z at NBL04

9/18/14-11/12/14

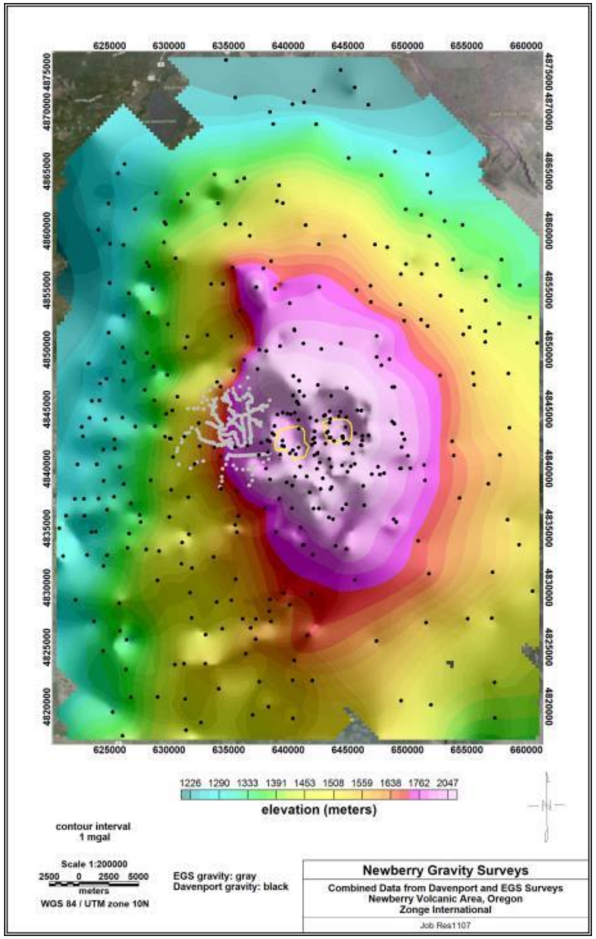
$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yz} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} + \mathbf{U}$$

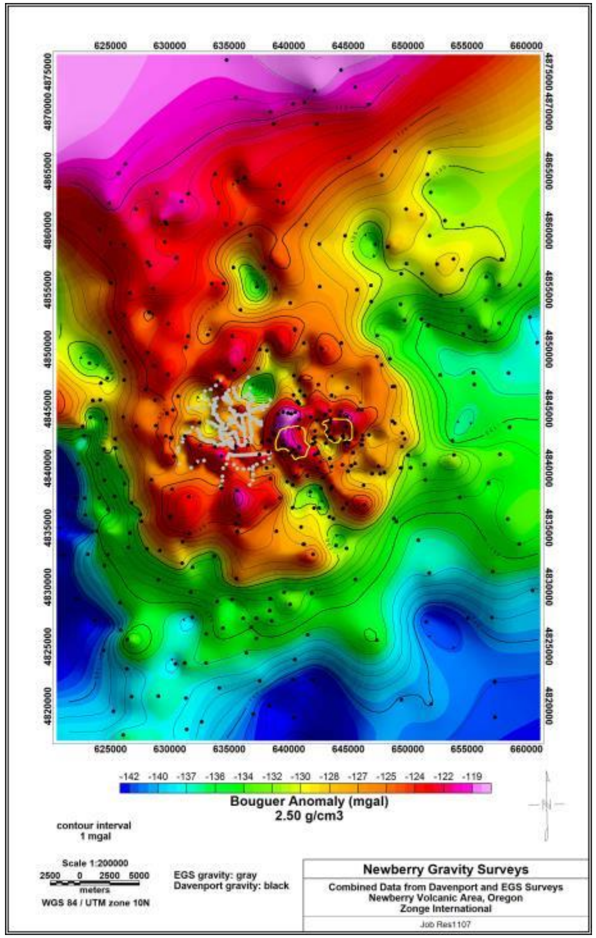
$$phase = \arg(Z)$$

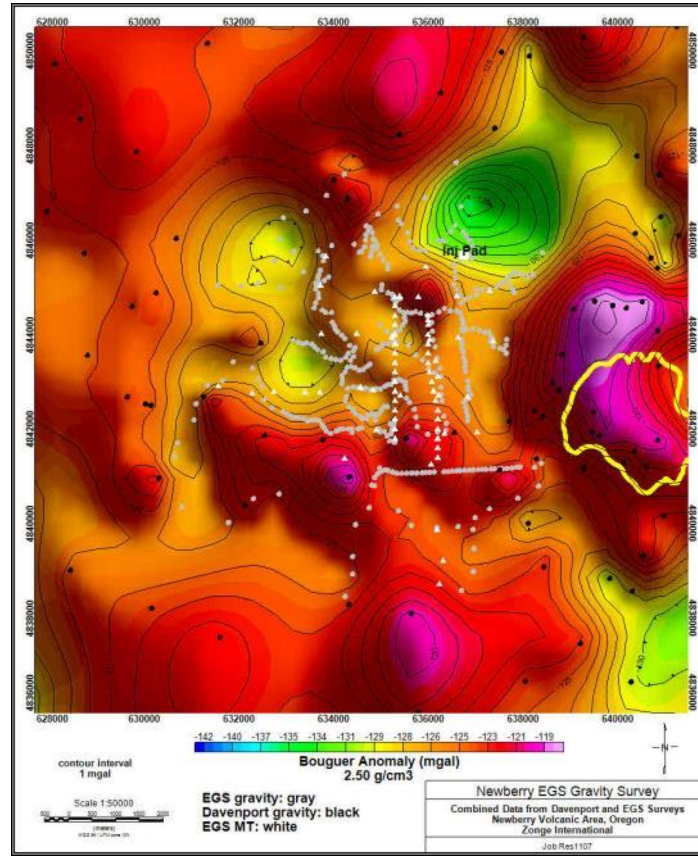


Technical Approach - Gravity

2012 microgravity data will be combined with both large-scale and stimzone MT survey data to constrain permeability changes







Technical Approach - Geologic Model Development, Newberry

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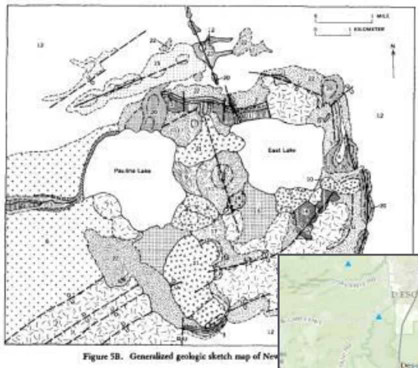
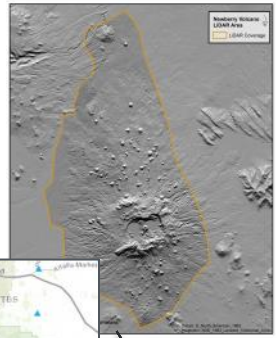
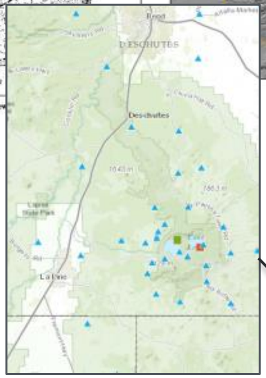
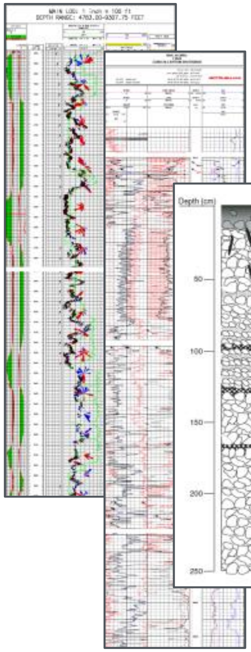
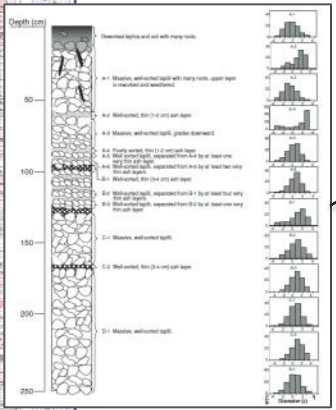
- Leveraging available data and knowledge of the Newberry subsurface to inform a 3D geologic model
- Utilizing a comprehensive approach by employing surface geologic maps, stratigraphic columns, LIDAR, well log, seismic, gravity, and magnetotelluric data
- The geologic model will support data interpretation and decision-making by reducing uncertainty of the Newberry geothermal area
- Supporting exploration and installation of the EGS

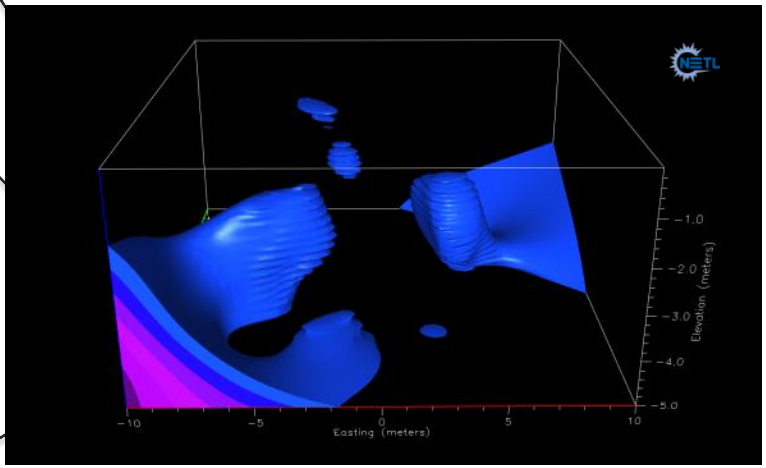


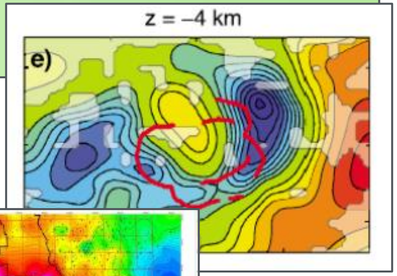


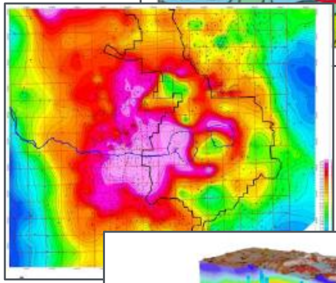


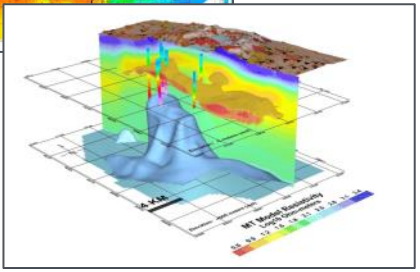


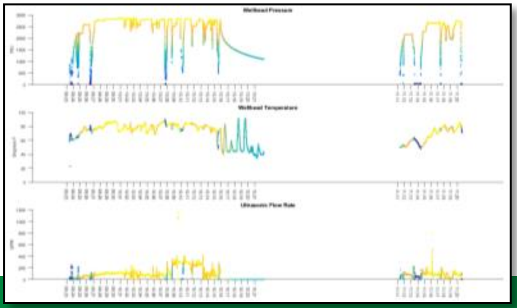












Well 55-29 pressure, temperature, & flow rate records for fall 2014

- 3D subsurface modeling
- Framework to support geophysical interpretations
- Flexible in adding new data as it becomes available

Accomplishments, Results and Progress

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- Completed Phase 1 tasks see slide 4 above, and original Phase 2* activities including:
  - Deployed integrated surface geophysical tools (portable radar, MT, gravity) during initial hydro-shearing at Newberry EGS site in coordination with Alta Rock.
  - Deployed integrated surface geophysical tools during subsequent injection and production periods/testing at Newberry EGS site in coordination with Alta Rock

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Phase 1 **go/no-go decision point**	Phase 1 presentation & **report** submitted	9/2012
Collect geophysical monitoring per Phase 1 plan at Newberry EGS stimulation	Completed field data acquisition, some difficulties due to weather & lower stimulation volumes	12/2012

*This project aligned to the separately funded field/stimulation activities of the Altarock Newberry project. The project team benefitted from good coordination with the Altrarock team, but original milestones, deliverables and schedule were impacted by the realities of field work and challenges experienced by the Altarock project at Newberry. This is also what led to the augmentation of Phase 2 from the original proposal with the Phase 2b scope to cover the re-stimulation of well 55-29 in the fall of 2014 by Altarock.

Accomplishments, Results and Progress

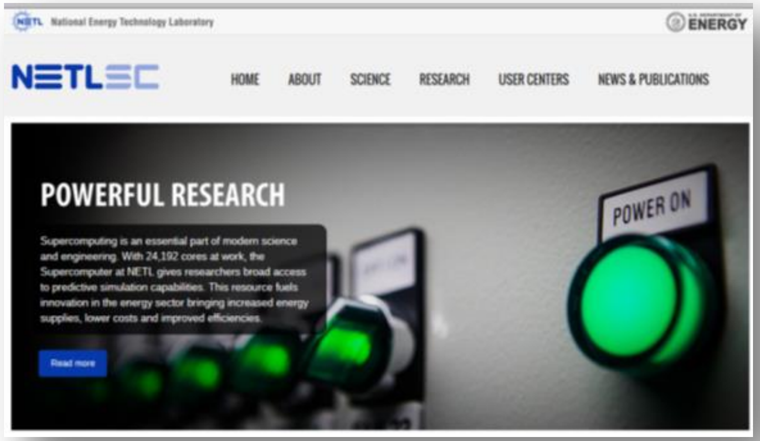
- Phase 2b*
  - Deployed integrated surface geophysical tools (portable radar, MT) during second phase of hydro-shearing at Newberry EGS site in coordination with Alta Rock utilizing modified survey design based on experience from first campaign.
  - Deployed integrated surface geophysical tools during subsequent injection and production periods/testing at Newberry EGS site in coordination with Alta Rock

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Phase 2b proposal for monitoring of 2nd Newberry stimulation	Submitted to GTO (actually funded ~1/2014)	9/2013
Collect geophysical monitoring per Phase 1 plan at Newberry EGS stimulation	Completed field data acquisition, some difficulties due to weather & lower stimulation volumes	11/2014

*This project aligned to the separately funded field/stimulation activities of the Altarock Newberry project. The project team benefitted from good coordination with the Altrarock team, but original milestones, deliverables and schedule were impacted by the realities of field work and challenges experienced by the Altarock project at Newberry. This is also what led to the augmentation of Phase 2 from the original proposal with the Phase 2b scope to cover the re-stimulation of well 55-29 in the fall of 2014 by Altarock.

Future Directions

- Expedite Processing
  - Volume of data collected from the stimulation phase alone is larger than anticipated and distinctive
  - Significant improvements underway in signal analysis software
  - Team is leveraging NETL's supercomputing facility to assist with processing and expedite analysis
- Inversion of gravity data for density structure
- Develop Inversion for 3D/4D Electrical Resistivity Structure
  - Repose inverse problem with new data kernels (d,m) where d = delta impedance and model = delta

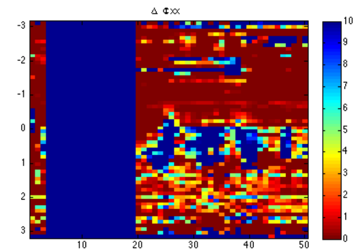


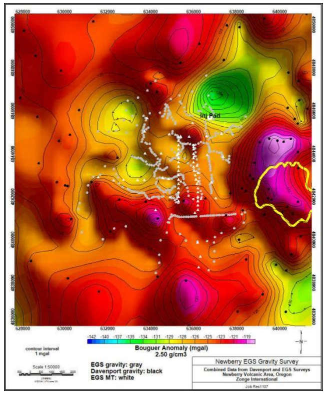
- Joint Interpretation of geophysical to assess changes over time to the EGS reservoir.
  - MT Inversion constrained by:
    - Produced water analyses
    - Subsurface geology ← Integration with Geologic model to refine interpretations
    - Gravity/Radar
- Leveraging of results and products to support future FORGE and Altarock efforts at Newberry

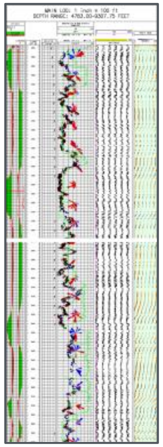
Milestone or Go/No-Go	Status & Expected Completion Date
Inversion & analysis of MT and gravity datasets	~9/2015
Geospatial Integration/Interpretation of Monitoring & Newberry EGS Datasets	11/2015, Newberry Geologic Model v. 1 In development
Final Report	Q2 FY16

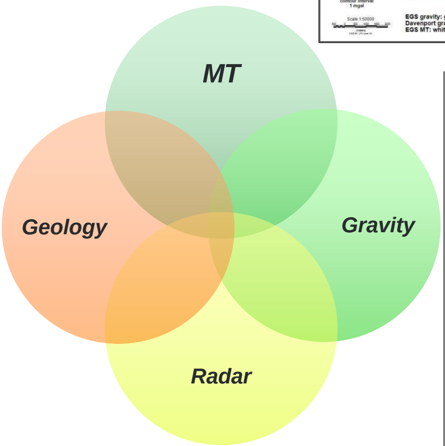
Mandatory Summary Slide

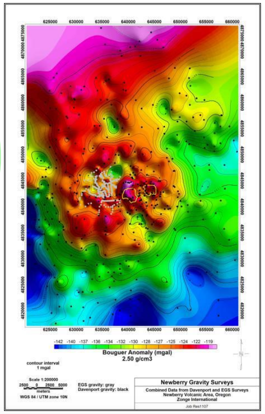
- Completed all Phase 1 Milestones
- Successfully completed all field operations in Phase 2 & Phase 2b
- Processing of MT and Radar data underway
- Initial MT processing reveals time-varying changes in electrical impedance
- Geologic framework model development underway for integration with subsurface seismic records
- Anticipated completion, Q2 FY16

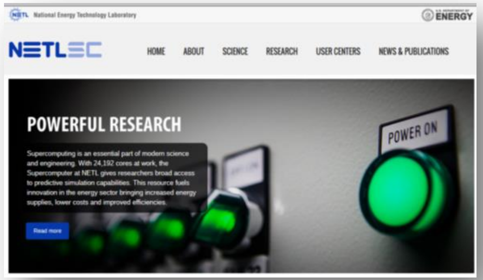












Additional Information

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- Project is affiliated with other projects in the Office
  - Newberry Volcano EGS Demonstration (AltaRock) - EE0002777
  - Validation of Innovative Exploration Technologies for Newberry Volcano
  - (Davenport) - EE0002833
  - Integrated Approach to Use Natural Chemical and Isotopic Tracers to Estimate Fracture Spacing and Surface Area in EGS (LBNL) - 1202
  - Optimizing Parameters for Predicting the Geochemical Behavior and Performance of Discrete Fracture Networks in Geothermal Systems (NETL)
- Coordination with industry & stakeholders
  - Alta Rock Energy
  - FORGE Newberry site
- Select Project Presentations to Date:
  - Schultz, A., Vincent, P., Rose, K., Hakala, A., Lopano, C., Shroeder, K., Urquhart, S., Hare, J., and Beard, L., 2012, Novel use of 4D monitoring techniques to improve reservoir longevity and productivity in enhanced geothermal systems, Alta Rock Newberry EGS coordination meeting, Palo Alto, CA February 2012.
  - Schultz, A., Vincent, P., Rose, K., Hakala, A., Lopano, C., Schroeder, K., Urquhart, S., Hare, J., and Beard, L., 2012, Newberry Volcano, Novel Use of 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems, GeoPRISMS Cascadia Conference, Portland, Oregon.
  - Schultz, A., Vincent, P., Rose, K., Hakala, A., Lopano, C., Schroeder, K., Urquhart, S., Hare, J., and Beard, L., 2012, 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems, International Workshop of Deep Geothermal Systems, WuHan, China, June 2012.
- Select Project Publications to Date:
  - Rose, K., Schultz, A., Vincent, P., Hakala, A., Lopano, C., Schroeder, K., Urquhart, S., Hare, J., and Beard, L., 2012, Novel Use of 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems, EERE Geothermal Program Phase 1 Report.
  - Schultz, A., Vincent, P., Rose, K., Hakala, A., Lopano, C., Schroeder, K., Urquhart, S., Hare, J., and Beard, L., 2012, 4D monitoring techniques to improve reservoir longevity and productivity in Enhanced Geothermal Systems, International Workshop of Deep Geothermal Systems Proceedings, 7 pgs.