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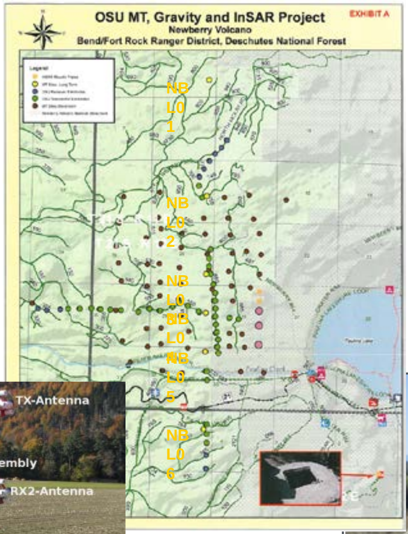
NETL

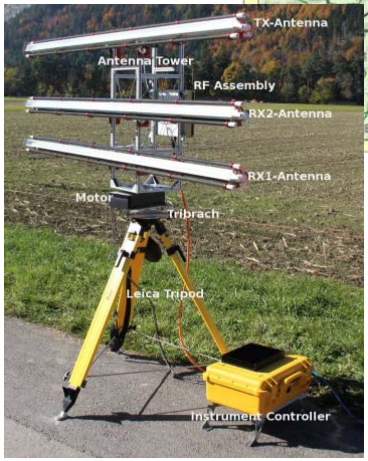
CEOAS College of Earth, Ocean, and Atmospheric Sciences

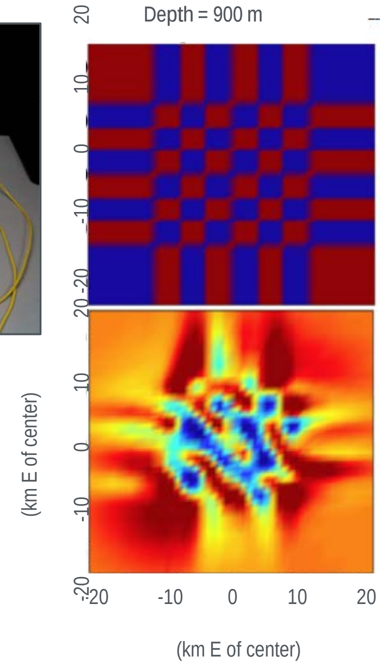
NGF National Geoelectromagnetic Facility

OSU Oregon State University

Zonge







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

Project Officer: Lauren Boyd Total Project Funding: $2146512

April, 2013

Kelly Rose & Adam Schultz

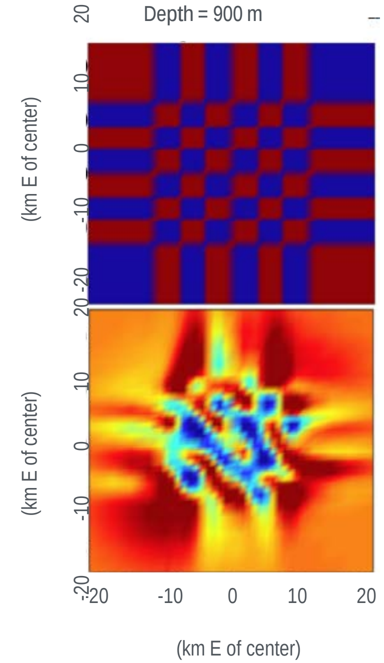
National Energy Technology Laboratory

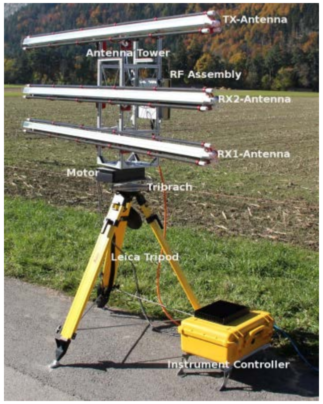
NETL 0522-1611 Track 1

Relevance/Impact of Research

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), Office of Research and Development

- Kelly Rose
- Alexandra Hakala (Phase 2 only)
- Christina Lopano (Phase 2 only)
- Karl Schroeder (Phase 2 only)

Oregon State University

- Adam Schultz
- Paul Vincent

Zonge International

- Scott Urquhart
- Jennifer Hare
- 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 collaborators:

- Alta Rock Energy
- Davenport Newberry Holdings, LLC

Organizational & Project Structure

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National Energy Technology Laboratory
Office of Research and Development

Kelly Rose(PI)
Project Coordination

Kelly Rose
Conceptual Geologic Model*
Geospatial Data Integration*

Ale Hakala; Christina Lopano; Karl Schroeder
Fluid chemistry interpretation & analysis*

Oregon State University
College of Earth, Ocean & Atmospheric Sciences

Paul Vincent
GPRI Analysis, Calibration, Acquisition*, Modeling, & Interpretation*

Adam Schultz
3D MT/CSEM/Gravity Permitting, Calibration, Acquisition*, Modeling, & Inversion*

Adam Schultz
Geospatial Interpretation of Monitoring Datasets*

Zonge International

Scott Urquhart
Conceptual Geologic Model*

Jennifer Hare; Les Beard; Scott Urquhart
3D MT/CSEM /Gravity Acquisition*, Modeling , Inversion*

Scott Urquhart
Thermal Modeling & Software Commercialization*

* = phase 2 activities dependent on EERE approval & support to execute

Scientific/Technical Approach

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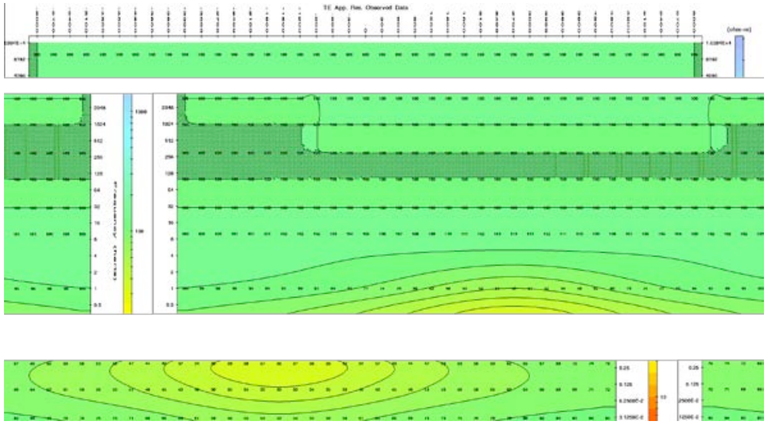
Phase 1 Tasks – All completed

- 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 Interferometric Radar

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Allows detection of sub-centimeter ground surface deformations:

- Similar to InSAR but the portable system provides much higher spatial and temporal resolution imagery
- Crack opening and closure, and the movement of fluids within the system can be inferred by the volume change detected at the surface
- Portable real-aperture radar complements microseism work

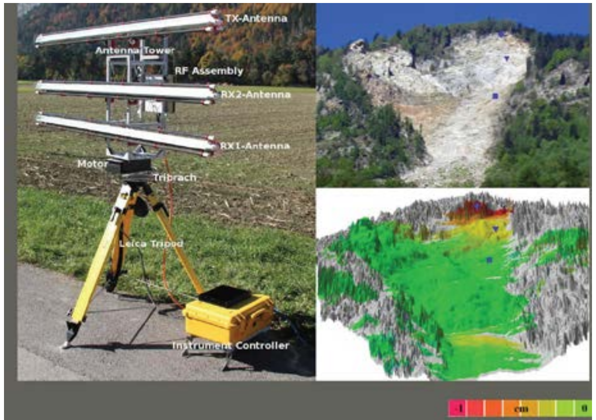
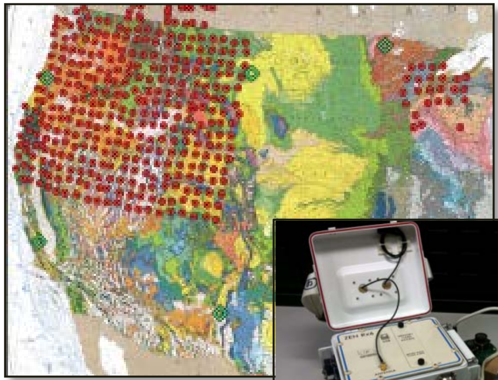


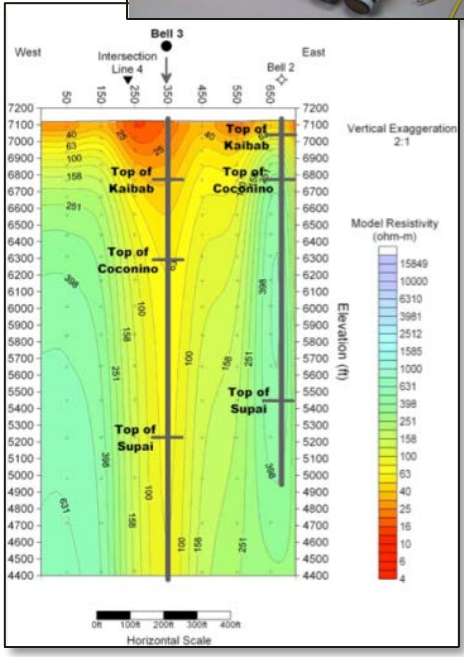
Figure 1. Left: GAMMA® Portable Radar Interferometer. Upper Right: Example of deformation from rock slide area in Switzerland between May 18 – June 3, 2010 with locations of measurement points used in time-series plot shown at right. [From Wiesmann and Gruner, 2011].

- Frequency range: 17.1 - 17.3 GHz
- Operational range: 50 m - 10 km
- Transmit power: <100 mW
- Pixel resolution: 1 m x 8 m (range x azimuth)
- Azimuth scan time: 10 deg/sec

Technical Approach – Magnetotellurics/CSMAT

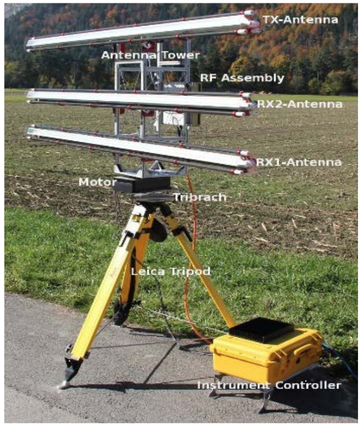
- Electrical resistivity within a reservoir is a primary indicator of:
  - The presence or absence of fluids
  - Fluid and rock composition
  - Temperature variations within the reservoir,
  - Porosity/fluid saturation
  - The degree of interconnection between fluid pockets and hence, the hydraulic conductivity/permeability
- A 2D grid of MT surface stations is used to determine the 3D resistivity structure.
- Combined MT and CSEM can achieve deep penetration and finer scale resolution of fluid and structural pathways.

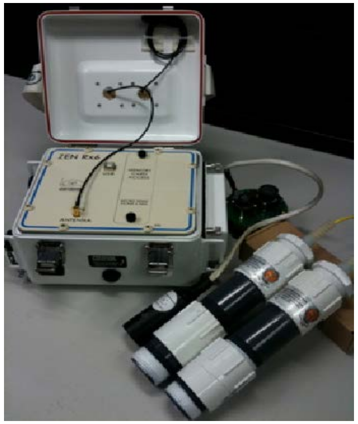




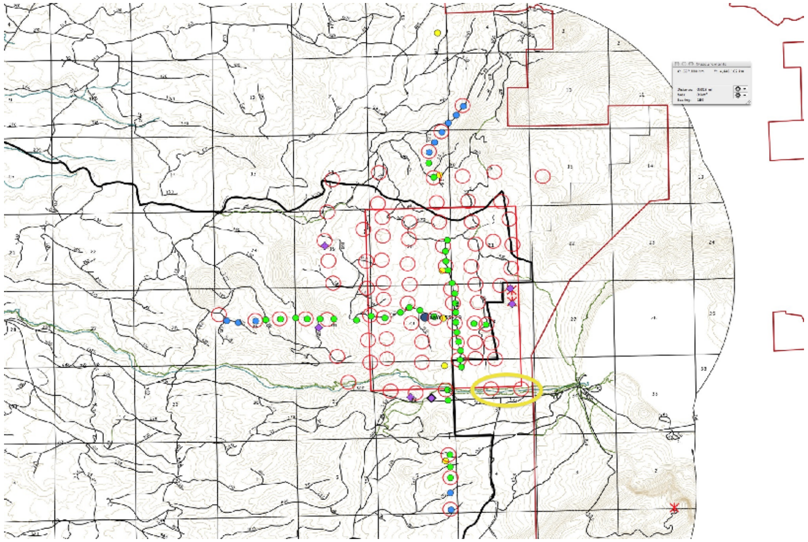
Technical Approach - Gravity

- Gravitational acceleration measured
  - Indicator of the density of the column of rocks below and surrounding the measurement point
- The density is related to rock composition, mineral structure, and porosity of the rock.
  - Anticipate changes with EGS stimulation



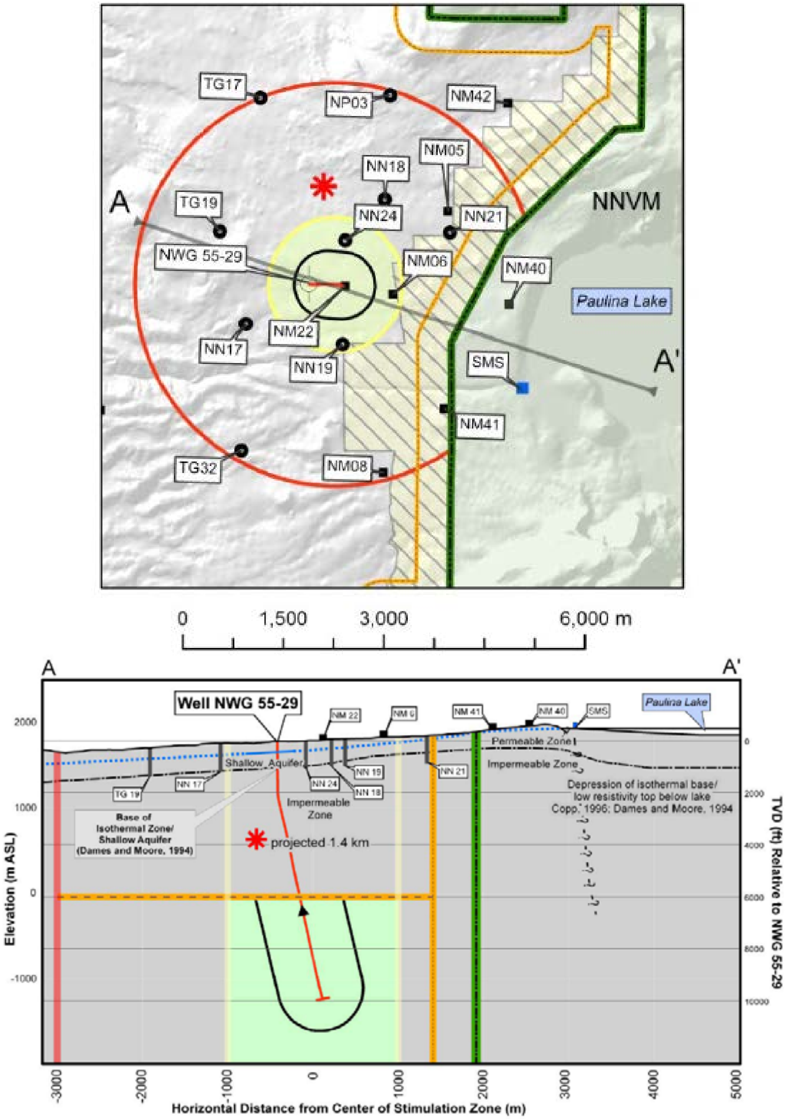


The permitted MT/CSEM, Gravity array.



Phase 1 "proof of concept" results of lab-scale 4D EGS equipment tests and numerical simulations, including:

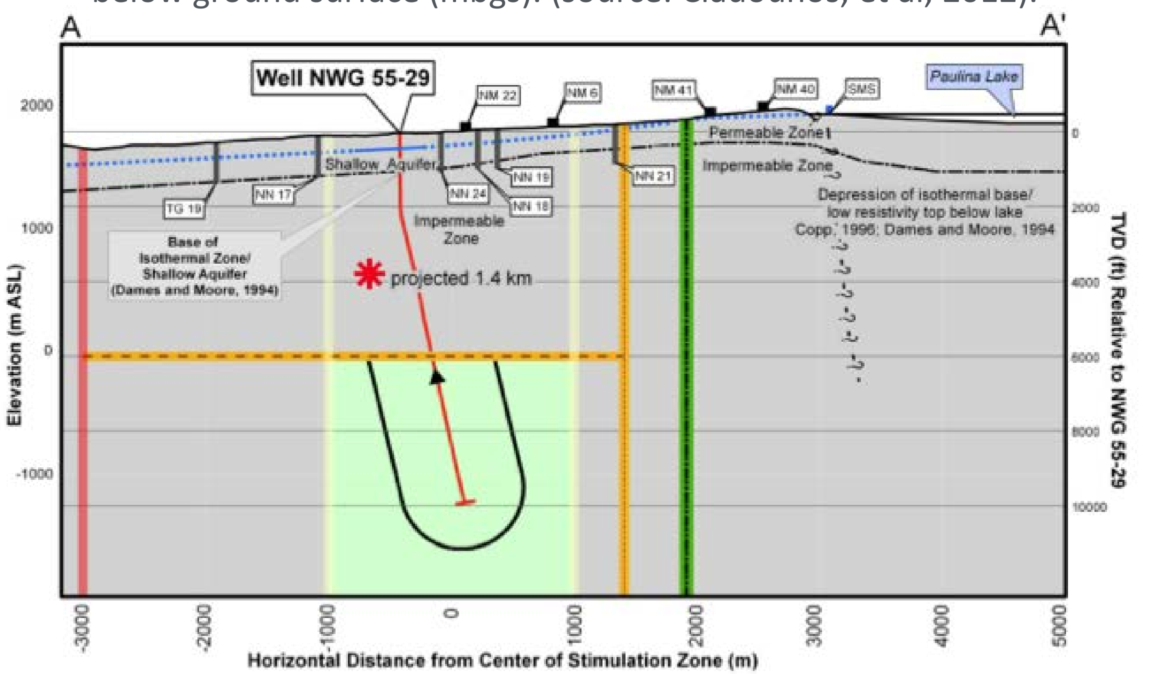
- Sensitivity and Noise Analysis for the GAMMA®, GPRI
- GPRI Instrument- Acquisition and Operational Training
- Laboratory Testing GPRI instrument Performance
- 3D MT/CSEM Model Sensitivity Study of Hypothesized Resistivity Variations Due To Extraction and Ejection
- Acquisition of wideband MT/CSEM receiver systems
- Permitting study for MT and/or MT+CSEM stations

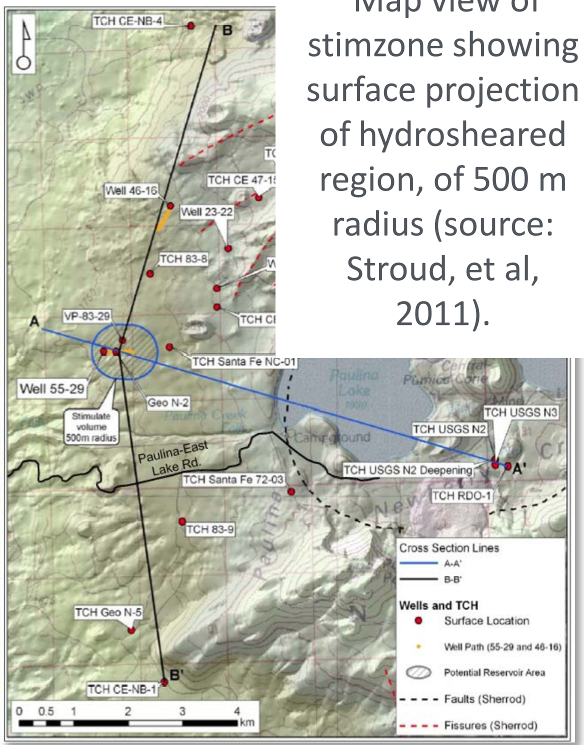


3D MT/CSEM Model of Hypothesized Resistivity Variations Due To Extraction and Ejection

- Phase 1 - This task evaluated sensitivity of wideband passive & active MG/CSEM in presence/absence of fluid pathways
  - Ultimate goal, evaluate appropriate means for deploying CSEM/MT for 4D field monitoring of EGS stimulation
  - Focused on Newberry EGS stimzone as proposed Phase 2 test site

Shallow aquifer hydraulically isolated by impermeable formations from the top of Newberry EGS stimzone, which is located 2000 m below ground surface (mbgs). (source: Cladouhos, et al, 2012).





Map view of stimzone showing surface projection of hydrosheared region, of 500 m radius (source: Stroud, et al, 2011).

3D MT/CSEM Model of Hypothesized Resistivity Variations Due To Extraction and Ejection

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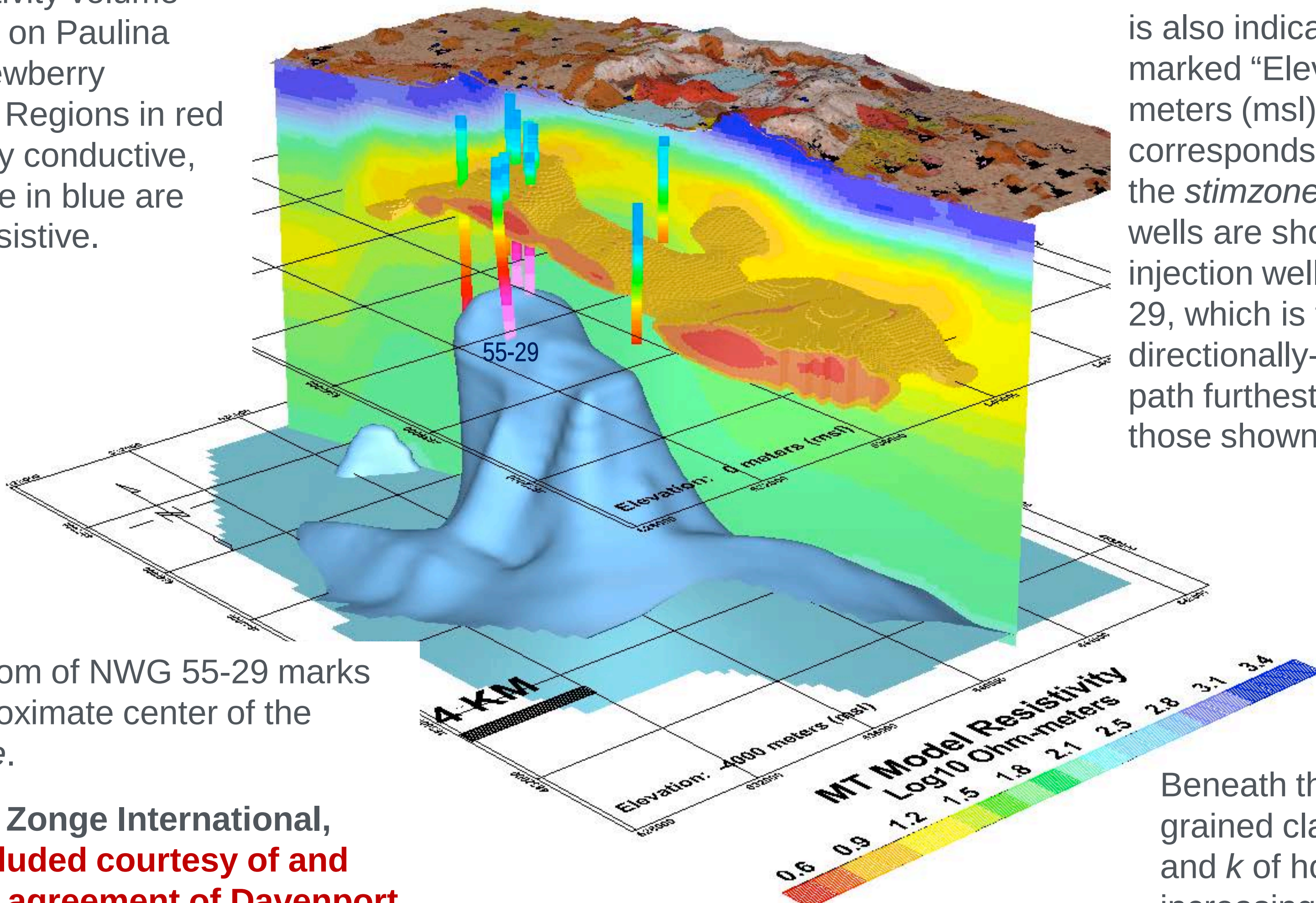
3D resistivity volume centered on Paulina Lake, Newberry Caldera. Regions in red are highly conductive, and those in blue are highly resistive.



A 100 ohm-m isosurface is also indicated. The grid marked "Elevation: 0 meters (msl)" corresponds to the top of the *stimzone*. Existing wells are shown including injection well NWG 55-29, which is the directionally-drilled well path furthest west of those shown.

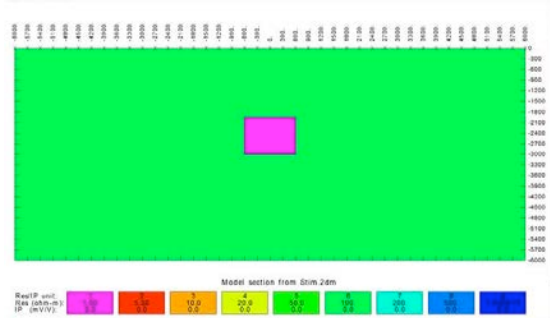
The bottom of NWG 55-29 marks the approximate center of the *stimzone*.

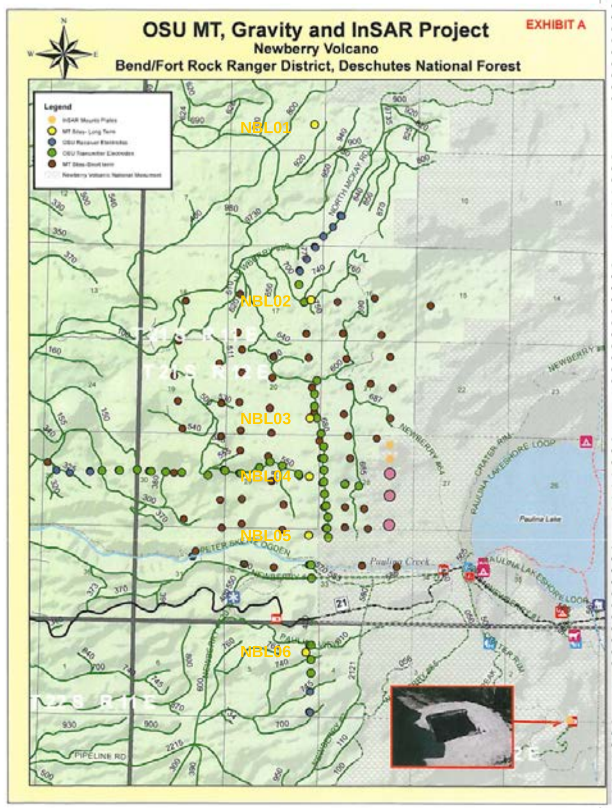
Source: Zonge International, Inc., included courtesy of and with the agreement of Davenport Newberry Holdings, LLC

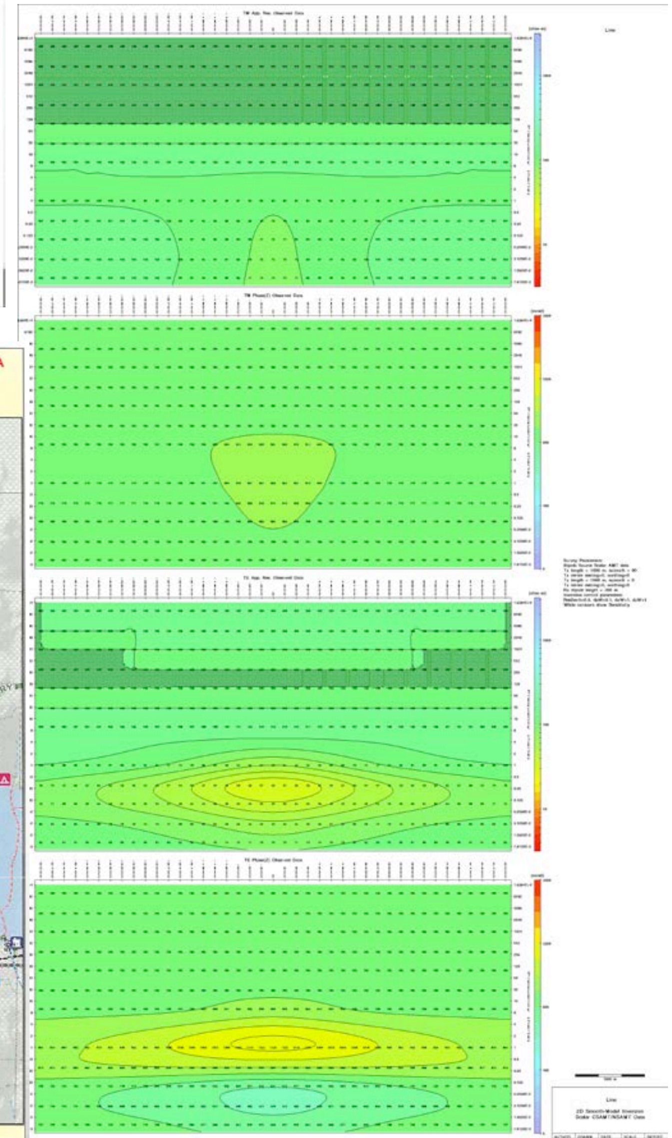
Beneath the caldera fine grained clays reduce ϕ and k of host rock, increasing resistivity at depths of 700 mbgs

3D MT/CSEM Model of Hypothesized Resistivity Variations Due To Extraction and Ejection

- MT/CSEM station spacing was designed to optimize resolution imaging of resistivity changes within the survey area
- 2 components of the MT/CSEM array design.
  - 6 long-duration MT/CSEM receivers for continuous monitoring, 9km long
  - 75 temporary MT stations designed to provide high-resolution 3D image snapshots prior, during and following stimulation

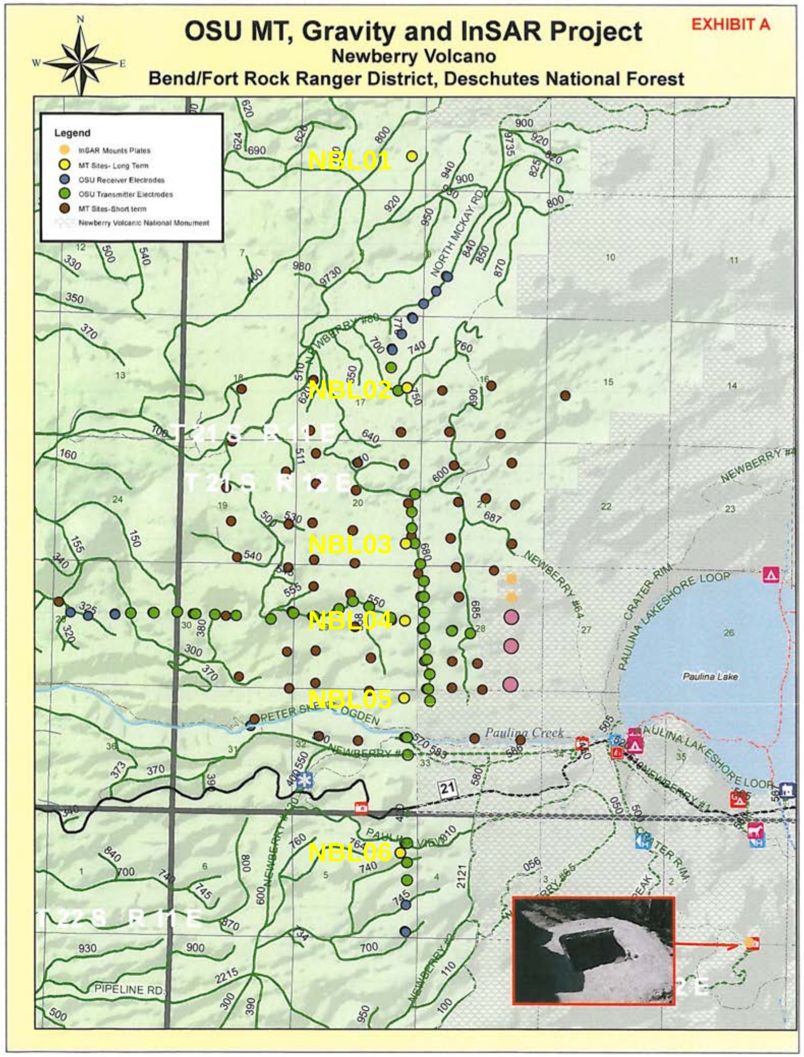






Additional Phase 1 Updates

- Acquisition of wideband MT/CSEM receiver systems
  - Completed
  - 2 of the 6 “permanent” MT sensors were installed in July by this project at the Newberry EGS site ahead of phase end
- Permitting study for MT and/or MT+CSEM stations –
  - Completed
  - Section in Phase 1 final report summarizing results of the permitting study; including if appropriate copies of the permits.
- NDA between NETL and Davenport was signed
  - Provided this project with access to subsurface geophysical surveys, data and interpretations relevant to the Newberry EGS site
- Coordination with AltaRock - ongoing throughout
  - AltraRock provided key information in relation to the geology, operational plans and schedules that were utilized in the Phase 1 site selection and preliminary modeling efforts.
- Additional cost share for Phase 2 identified



Phase 2 Progress

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Newberry Volcano Enhanced Geothermal System
4D Imaging of Fluid Migration by combined MT/CSAMT, Gravity, Interferometric Radar, Microseismicity

- Initiated Phase 2 - 9/2012
- Goal – to monitor fluid injection, changes in permeability, porosity and mineral reaction products during a controlled enhanced geothermal system stimulation event
- Method – reduce ambiguity by overlaying complementary data sets:
- 6 continuously-operating wideband Zonge Zen Rx6 MT stations – continuous recording for high-resolution temporal variations in resistivity
- 75 wideband MT/CSAMT Zonge Zen Rx6 or GDP24 MT stations deployed before, during and after “stimulation”
- 400 gravity stations deployed before, during and after stimulation
- 100 radar corner reflectors + ground-based interferometric radar monument; multiple satellite InSAR radar images (tasked TerraSAR-X acquisitions).
- Periodic chemical sampling

Phase 2 Progress

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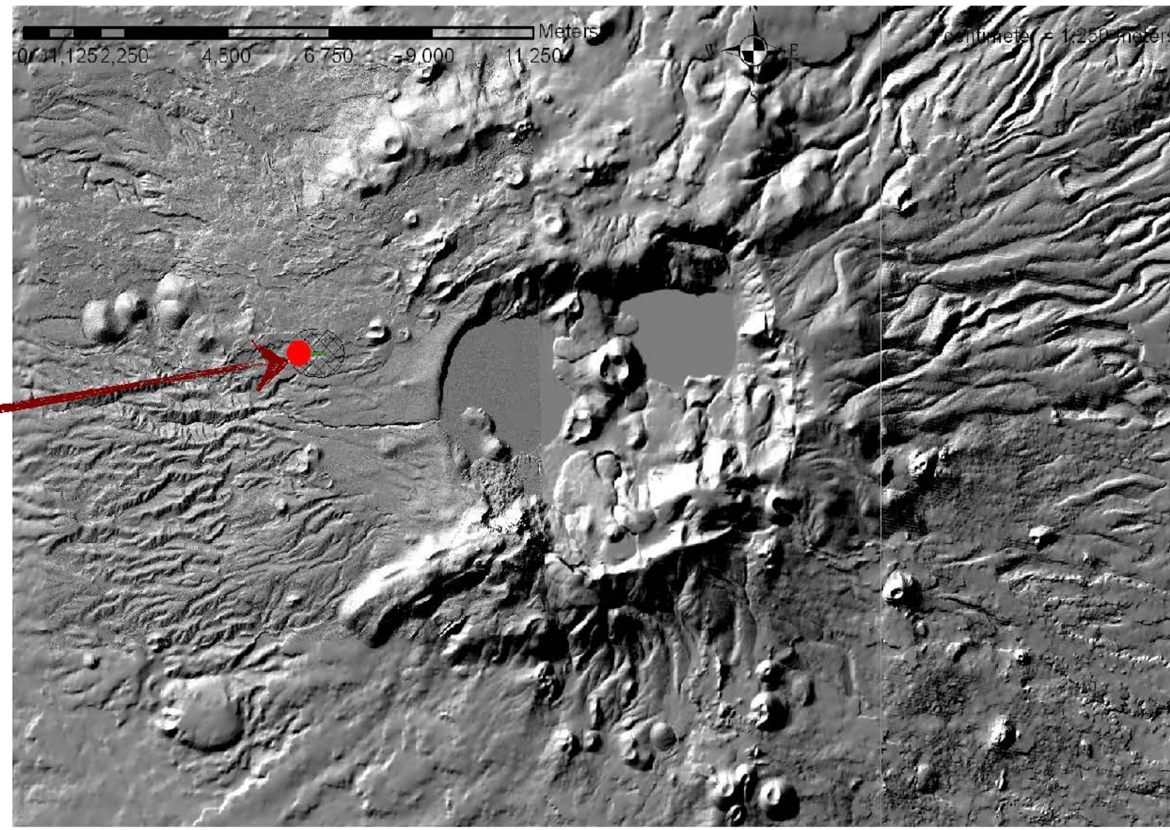
Newberry Volcano Enhanced Geothermal System
4D Imaging of Fluid Migration by combined MT/CSAMT, Gravity, Interferometric Radar, Microseismicity



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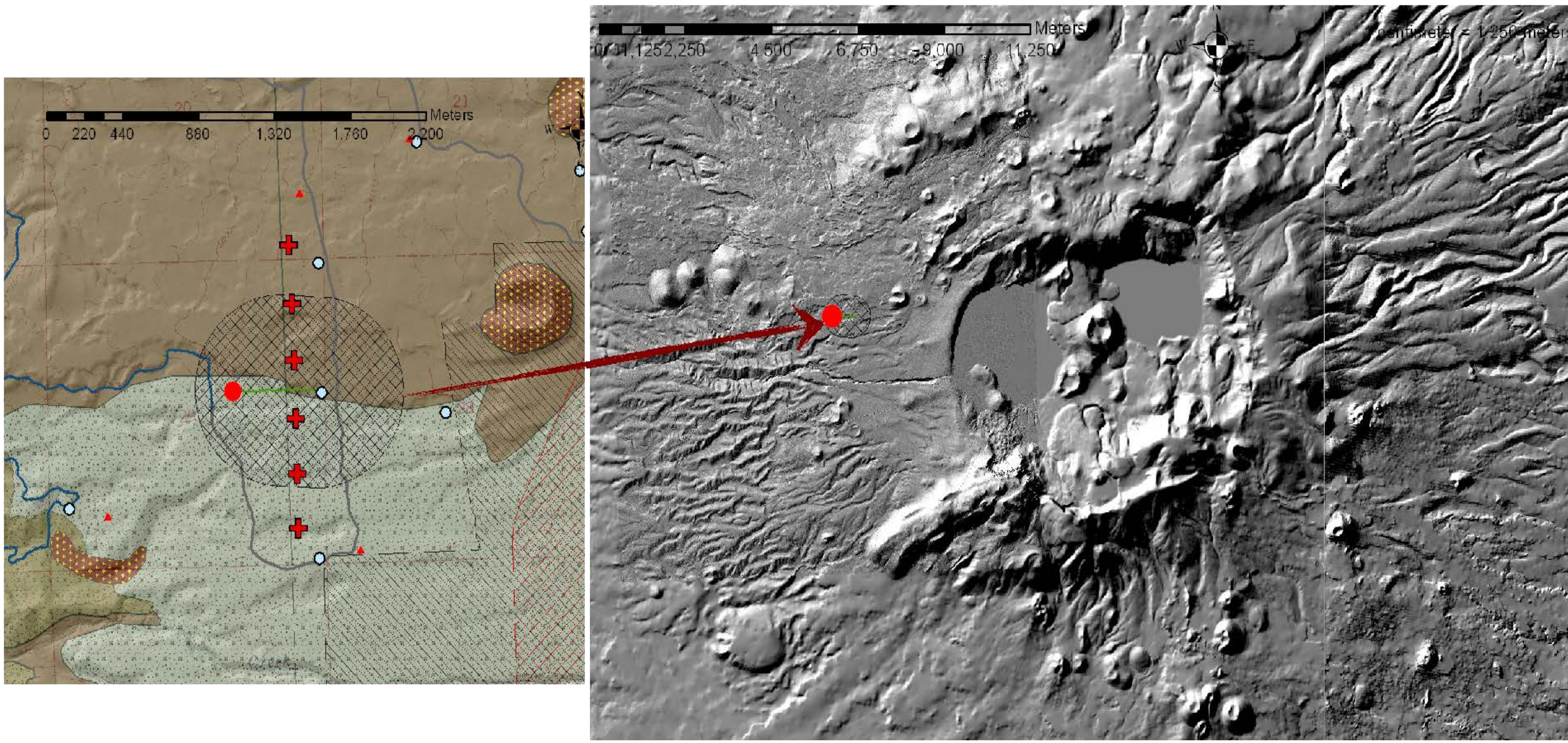
Newberry Volcano Enhanced Geothermal System 4D Imaging of Fluid Migration by combined MT/CSAMT, Gravity, Interferometric Radar, Microseismicity



Phase 2 Progress

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- Stimulation was delayed from originally planned start in July 2012 to late October 2012 (first stim attributed microseism detected on 10/29/2012)
- Injection fluid samples obtained during stimulation
- Microseisms tended to break shallower than predicted by AltaRock, with more northerly trend
- Well shut in 12/8/2012
- Approximately 10.4 M gallons (est) of water was injected, which is approximately half of the amount planned at the onset of stimulation, and around 10% of the total amount permitted
- No flowback achieved as of 12/18/2012. Well shut in and flowback efforts ended; no fluid samples obtained. Solid phase (mineral) samples will be made available.

Phase 2 Progress

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- Field operations were adapted to the modified AltaRock stimulation schedule and in response to microseismic monitoring - Ground Deformation

Late Summer, 2012

100 Radar Reflectors Installed in Stim Zone

Ground Radar Deployment on Paulina Peak

Mid-Fall, 2012

GPRI2 Radar Image (only 5 deg. grazing angle looking at forest!)

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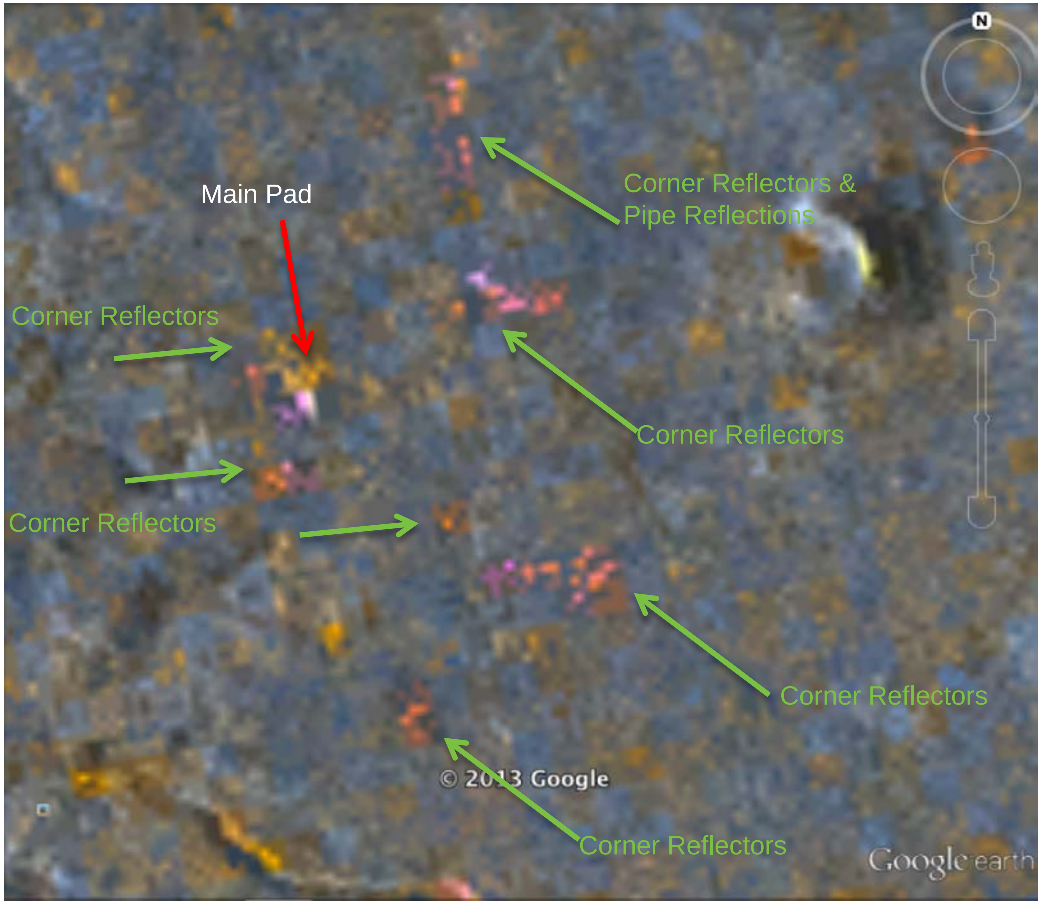
Phase 2 Progress

Field operations were adapted to the modified AltaRock stimulation schedule and in response to microseismic monitoring - Ground Deformation

Radar Corner Reflectors can be seen in TerraSAR-X Satellite Data

Radar corner reflectors (distributed), water pipes (along road), and pad structures detected in TerraSAR-X Satellite data make excellent (short-term) stable targets for ground deformation measurements (small orange squares). [Note: these represent ascending orbit track only visible targets. Approx. the same number of different targets visible in descending orbit track data.]



TerraSAR-X Data Georeferenced Image

Phase 2 Progress

- **Field operations were adapted to the modified stimulation schedule and in response to microseismic monitoring – Gravity**
  - Pre-stim gravity data were obtained over a 400 joint absolute/relative gravity station survey grid
  - Field conditions led to decision not to proceed with syn-stim and post-stim absolute gravity work

Trimble Networked RTK-GPS with 3 Bases

CG-5 Gravity Meter

A-10 Absolute Gravity Meter

Phase 2 Progress

- **Field operations were adapted to the modified stimulation schedule and in response to microseismic monitoring – Wideband MT/CSEM Arrays**
  - Pre-stim array AMT data were obtained over a 75 station survey grid
  - Controlled source EM data were also obtained at these sites
  - Syn-stim MT data were obtained over 29 of the original station survey grid.
  - Continuous MT profiling data were obtained during the pre-stim and stim periods.
    - Severe winter weather impacted the operation of some solar panel arrays
    - The fuel cell systems achieved their goal of providing continuous power

Accomplishments, Results and Progress

- Completed Phase 1 tasks see slide 13 above, and initiated 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

Future Directions

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Through 10/31/2014:

- **Integrate field geophysical datasets with produced water analyses and subsurface geology to model and assess changes over time to the EGS reservoir.**
- **Port a signal analysis code appropriate to the new Zen wideband MT instruments from a PC environment to a high performance Linux environment, in order to efficiently process the approximately 1/3 TB of raw binary MT time series from the continuous monitoring MT profile**
  - **Volume of data collected from the stimulation phase alone is larger than anticipated and distinctive**
- **Evaluating alternatives, geochemical modeling etc., given no water was produced back during the stimulation upon which to conduct analyses to assist with resistivity/MT calibrations.**
  - **Seeking coordination with LBNL geochemists in support of this effort.**
- **Post-injection geophysical monitoring activities**
- **Inversion for 3D/4D Electrical Resistivity Structure**
- **Inversion of gravity data for density structure**
- **Geospatial Integration/Interpretation of Monitoring & Newberry EGS Datasets**
- **Final report**

Summary Slide

- **Overarching project goal:** Provide new method & technique to ensure EGS reservoir longevity and optimal production.
- While the project is focused on coordination with external collaborators at Newberry Field, the methodology is designed to be transferrable to other EGS reservoirs.

External collaborators:

- Alta Rock Energy
- Davenport Newberry Holdings, LLC

NETL-RUA Regional University Alliance

Kelly Rose(PI)
Project Coordination

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Conceptual Geologic Model
Geospatial Data Integration*

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Thermal Modeling & Software Commercialization*

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
Phase 1 - 10/2011	Phase 1 – 11/2012	**11/2011**	**09/2012**
Phase 2 – 11/2012	**Phase 2 – 12/2014**	**09/2012**	**10/2014**

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
Phase 1 $770,000	$2323	$ 772,323	$772,323	$802,323	$30,000
Phase 2 $1,099,130	$275,059	$1,374,189	~$600,000	~$600,000	

- **How is this project integrated 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
  - Davenport Newberry Holdings, LLC
- **If your project is behind schedule, please tell us here.**
  - **Project is on schedule.**