A novel approach to map permeability using passive seismic emission tomography constrained by joint inversion of active seismic and EM data

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U.S. Geothermal Inc.

Project Officer: Michael Weathers   Total Project Funding – Fed: $1,497,017, USG: $449,378

This presentation does not contain any proprietary confidential, or otherwise restricted information.
Project Team

Erika Gasperikova, LBNL – electromagnetics
Satish Pullammanappullil, independent consultant – seismic
Ian Warren (PI) – U.S. Geothermal Inc.

Data Collection Contractors

Microseismic Inc. – passive seismic
Quantec - electromagnetics
Relevance to Industry Needs

Project Objectives

• Despite continual advancements, we are still unable to adequately or consistently image permeability in geothermal systems.
• This project will test permeability mapping techniques used by unconventional O&G, i.e., passive seismic emission tomography (PSET) derived from very dense geophone arrays (~58/km²).
• PSET will be augmented with 3-D resistivity generated from EM data optimized by joint inversion with seismic data
• We are not aware of any similarly robust test of PSET for mapping geothermal permeability.
• If successful, the techniques will improve drilling success rates in fracture-controlled geothermal reservoirs. Drilling amounts to $10s of millions in development budgets, so any costs savings have a direct, positive impact on project economics.
• The techniques potentially contribute to better management of geothermal reservoirs
Relevance to GTO Objectives

- Project objectives directly address multiple GTO goals
  - Improving processes of identifying, accessing, and developing geothermal resources
  - Overcoming technical obstacles and mitigating risk
  - Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
  - Supporting early-stage research and development (R&D) to strengthen the body of knowledge upon which industry can accelerate the development and deployment of innovative geothermal energy technologies

- Opportunities to inform EGS challenges
  - Monitoring of induced and natural fracture creation
  - Assessment of fracture/reservoir volumes
O&G use PSET to monitor behavior of induced and natural fractures during fracking and to create permeability fairway maps to aid drill planning
  - Can the same technique map fracture-controlled geothermal permeability?

MT and seismic data have been directed toward mapping of geothermal permeability with mixed results
  - Can we enhance the details mapped by MT data related to geothermal permeability?
  - Can the hydrology signals of MT, geologic structure and contact information from seismic, and seismic energy mapped with PSET be combined to create a robust 3D map of geothermal permeability?
• Methodology evaluates “off-the-shelf” solutions and innovative inversion techniques to enhance and refine signals related to geothermal permeability
  – PSET data collection completed by O&G vendor; however, application to geothermal permeability is novel.
  – EM data collection completed by O&G, minerals, and geothermal vendor with project team expertise informing survey design and data collection.
  – PSET will benefit from refined velmod developed with innovative joint inversion techniques. Hoping to gain additional insight from the vendor team who are interested in new applications of their technology.
  – EM will benefit from joint inversion that aims to refine the 3-D resistivity volume.
  – Gravity, magnetics, drilling, and other datasets will constrain and test results.
Two locations test the applicability of the techniques across the spectrum of geothermal projects from grassroots to production

- **San Emidio site** is well constrained by drilling, historic DOE-supported active seismic and innovative exploration work, and proximity to the producing San Emidio power plant
  - Historic active seismic profiles combined with newly collected MT data will guide joint inversion development
  - Drilling from 2011-2017 provide data within the project AOI, including newly discovered 320F+ resource
  - Gravity, magnetics, PSInSAR

- **Crescent Valley** has a much less well constrained subsurface and no proven commercial reservoir (yet)
  - 80s era seismic, gravity, magnetics, limited CSAMT, shallow TG (100<500’), one geothermal well (2746’)
  - Top prospective location identified by UNR PFA
Methods/Approach continued

USG Data
Gravity
Magnetics
Active seismic
PSInSAR
TG, Observation, and Geothermal drilling
Power plant and wellfield monitoring
Methods/Approach continued

- USG Data
- Gravity/gravity gradient
- Magnetics
- Historic Seismic
- Historic CSAMT
- Minerals drilling
- TG drilling
- Geothermal drilling
- Hot springs geochemistry

UNR Play Fairway
- Gravity
- Seismic interpretation
- Geologic and structural mapping
## Technical Accomplishments and Progress

<table>
<thead>
<tr>
<th>Original Planned Milestone/Technical Accomplishment</th>
<th>Actual Milestone/Technical Accomplishment</th>
<th>Date Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Project Management Plan</td>
<td>Quarterly reporting; team meetings</td>
<td>ongoing</td>
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<tr>
<td>1. Kickoff Meeting</td>
<td></td>
<td>9/30/2016</td>
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<tr>
<td>2. Evaluation and preparation of historical dataset</td>
<td>Ongoing with new data; modeling of grav/mag</td>
<td>ongoing</td>
</tr>
<tr>
<td>3.1. Final designs for new passive seismic data collection</td>
<td>New contractor; traded downhole-shot-derived velmod for active weight-drop source</td>
<td>10/1/2016</td>
</tr>
<tr>
<td>3.2. Completion of new passive seismic data collection</td>
<td>PSET delivered 4/1/2017 with shot/vendor-generated velmod; MEQ events for SE</td>
<td>12/18/2016*</td>
</tr>
<tr>
<td>4.1. Final designs for new passive EM data collections</td>
<td>Delayed design at CV to learn from SE survey; rabbits and low natural signal</td>
<td>10/28/16(SE), 6/30/17 (CV)</td>
</tr>
<tr>
<td>4.2. Completion of new passive EM data collections</td>
<td>CV data and final SE (3rd attempt) data received</td>
<td>10/10/17</td>
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</table>
### Technical Accomplishments and Progress continued

<table>
<thead>
<tr>
<th>Original Planned Milestone/Technical Accomplishment</th>
<th>Actual Milestone/Technical Accomplishment</th>
<th>Tentative new completion date</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Processing, joint inversion, and analysis of newly acquired datasets</td>
<td>To begin 11/17 when EM processing complete</td>
<td>3/31/2018</td>
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<tr>
<td>6. Final velocity model completed</td>
<td></td>
<td>3/31/2018</td>
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<tr>
<td>7. Semblance volume completed with final velocity models</td>
<td></td>
<td>4/30/2018</td>
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</tbody>
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**Primary schedule impacts:**
- MT delays
  - Contractor scheduling
  - Rabbits and low natural signals affected crucial SE sites
  - Overall delay to project ~4-5 months, but not impacting costs
- On budget
  - Changes to passive seismic saved more money than spent for MT delays and resurveys
  - I. Warren time, primarily grav modeling, will contribute more to USG cost share than planned
San Emidio

Preliminary resistivity volume and PSET from shot-generated velmod (simple layer cake model)
San Emidio Preliminary Results

- PSET and low resistivity anomalies correlate with new 320F+ resource defined by 2016-2017 drilling
- Geology-constrained “gravity basement” ~correlative with top of reservoir rocks
Technical Accomplishments and Progress continued

Crescent Valley

- Best constrained subsurface geology is the Crescent Valley Fault
- PSET identifies subparallel, basinward fractures and SW projection of right-hand step-over
At Crescent Valley we are working closely with the UNR PFA team to coordinate efforts and share data.

Our test of “off-the-shelf” PSET will allow anyone to order the same from Microseismic Inc.

- Microseismic is continuing to participate with help related to specific data requests and manipulations as well as re-processing with a refined velmod.
- Preliminary results to be presented at a Microseismic user conference in February 2018.
- Investigating potential for seismic interferometry.
## Future Directions

<table>
<thead>
<tr>
<th>Milestone or Go/No-Go</th>
<th>Status &amp; Expected Completion Date</th>
</tr>
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<tbody>
<tr>
<td>5. Processing, joint inversion, and analysis of newly acquired datasets</td>
<td>Beginning October 2017; 3/31/2018*</td>
</tr>
<tr>
<td>6. Final velocity model completed</td>
<td>3/31/2018</td>
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<tr>
<td>7. Semblance volume completed with final velocity models</td>
<td>Work ongoing with simple velmod PSET volume; 4/30/2018</td>
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<tr>
<td>8. Integration of new and historic datasets into complete 3D model</td>
<td>5/31/2018</td>
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<tr>
<td>8.2. Drill targeting</td>
<td>5/31/2018</td>
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<tr>
<td>8.3. Finalize drill targets GO/NO-GO</td>
<td>5/31/2018</td>
</tr>
<tr>
<td>9. Permit drilling locations</td>
<td>BLM has all data necessary and an EA covering the entire SE project area is in progress. CV targets on BLM land could take 60+ days to permit; 8/31/2018</td>
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<tr>
<td>10. Drill and test wells</td>
<td>12/31/2018</td>
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<tr>
<td>11. Final report</td>
<td>1/31/2019</td>
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*proposed schedule changes due to MT delays (schedule update not official as of 10/9/2017)
Data collections have been successfully completed.
On budget but behind schedule in order to include best quality MT data.
Preliminary results are encouraging.
Interpretation of data volumes is greatly enhanced where structurally and geologically important surfaces are well constrained and intersect the data volumes:
- Revisiting gravity, magnetics, and 2/3D modeling of those data.
- Evolving understanding of geology and structure with latest drill results at San Emidio.
- Integrating UNR PFA data at Crescent Valley.