

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

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

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Track 2 SubTER

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Project Team

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electromagnetics

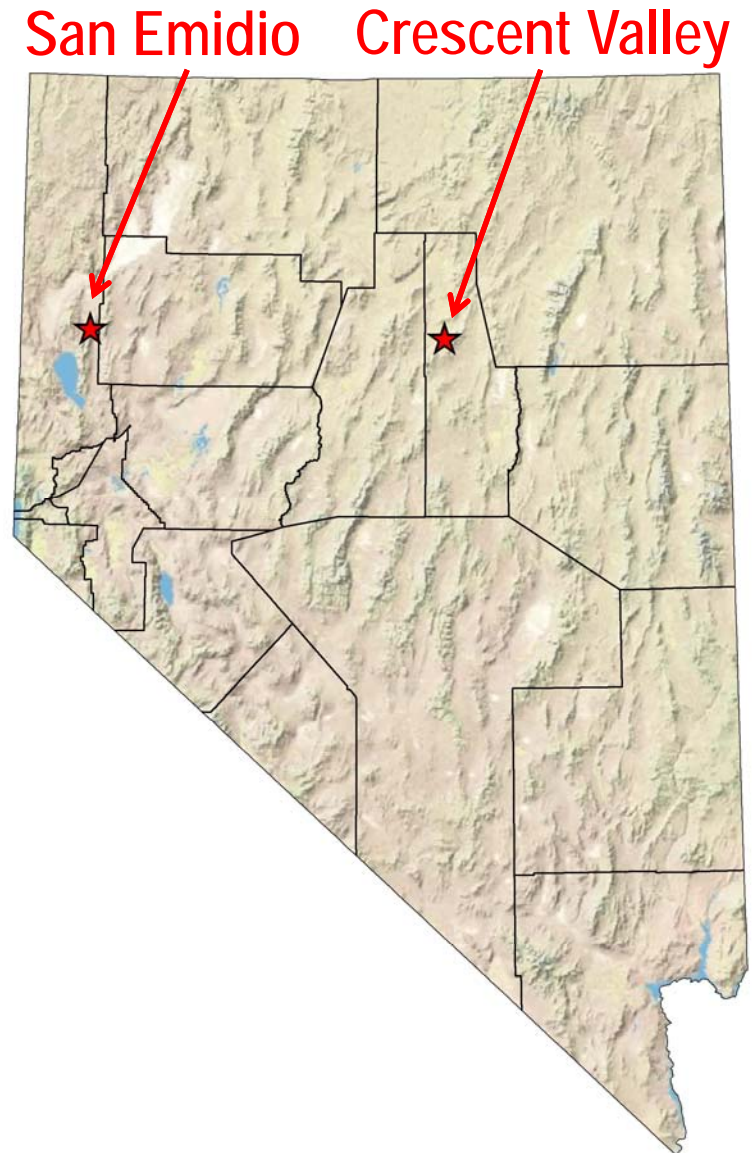
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Data Collection Contractors

Microseismic Inc. – passive seismic

Quantec - electromagnetics



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

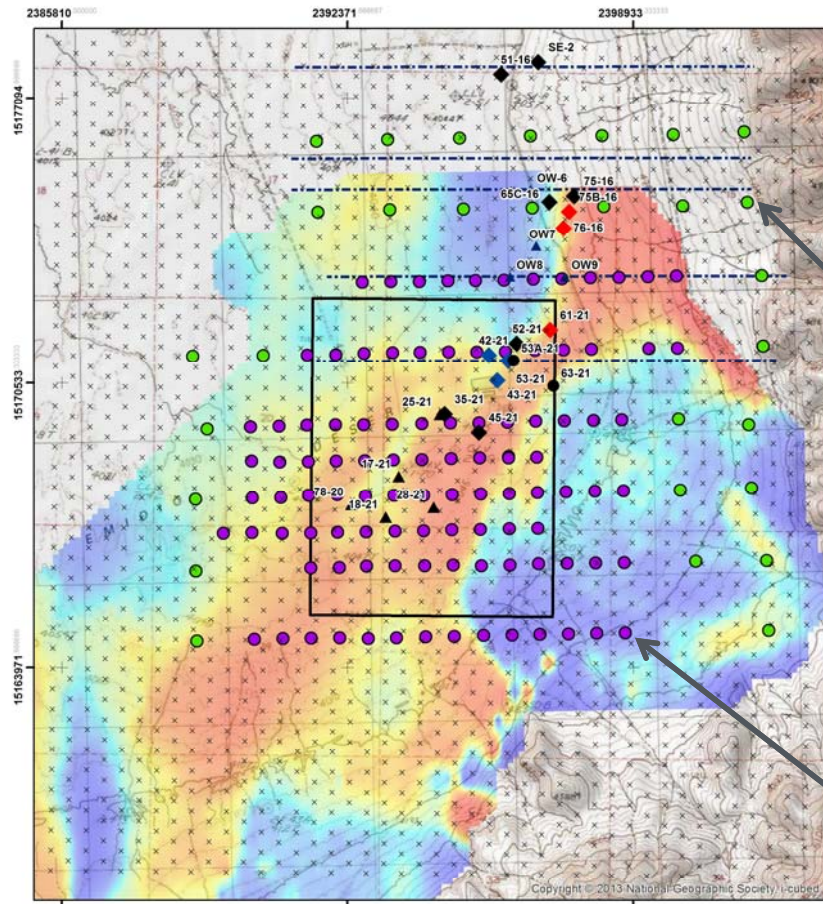
- Project objectives directly address multiple GTO goals
 - Improving processes of identifying, accessing, and developing geothermal resources
 - Overcoming technical obstacles and mitigating risk
 - Identifying and accelerating near term conventional and/or blind hydrothermal resource growth
 - Supporting 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

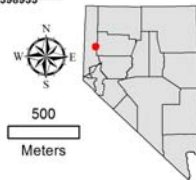
- San Emidio site is well constrained by drilling, historic DOE-supported active seismic and innovative exploration work, and proximity to the producing San Emidio power plant
 - Historic active seismic profiles combined with newly collected MT data will guide joint inversion development
 - Drilling 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



San Emidio SubTER Project Area

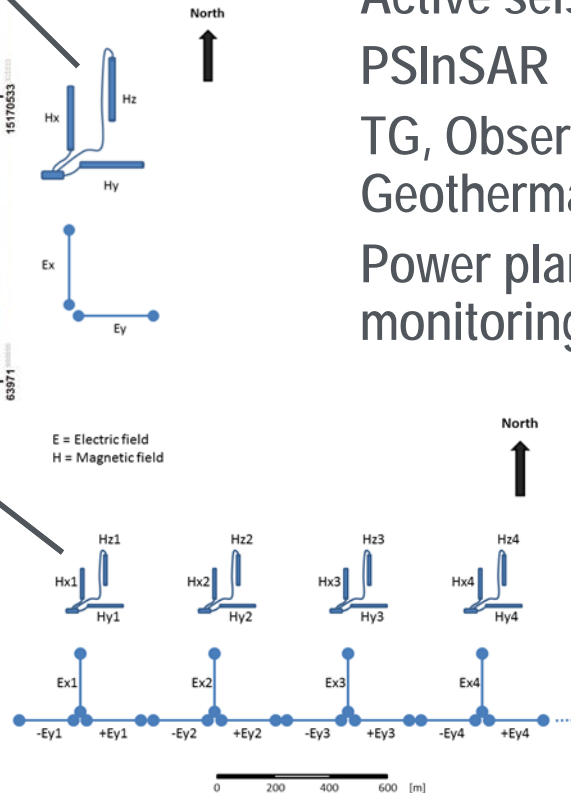
- Project AOI
- - - historic long-offset 3-component seismic line
- MT station

- ◆ Active Producer
- ◆ Active Injector
- ◆ Idle well
- DOE Observation Well
- ▲ 2015-17 TG/Obs Well

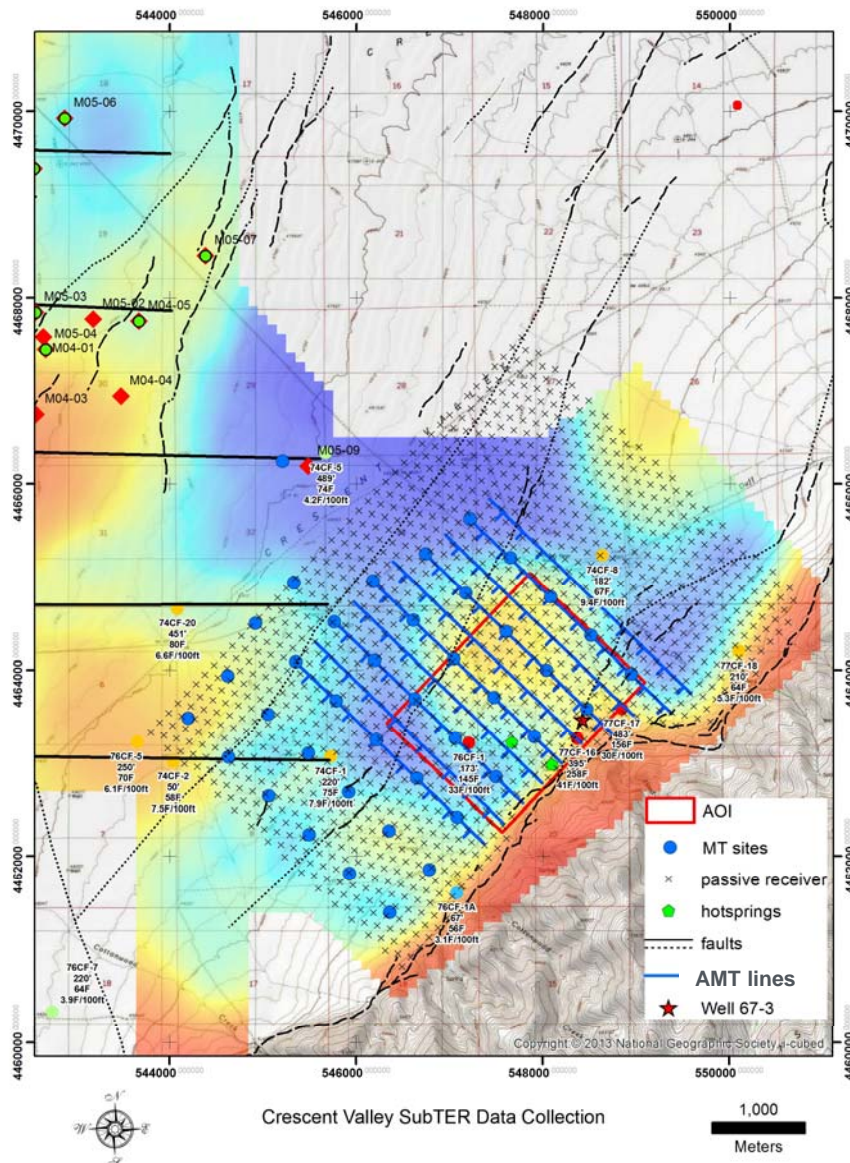


USG Data

- Gravity
- Magnetics
- Active seismic
- PSInSAR
- TG, Observation, and Geothermal drilling
- Power plant and wellfield monitoring

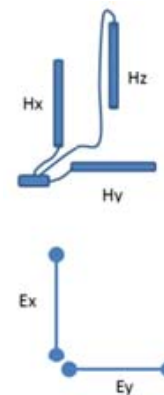


E = Electric field
H = Magnetic field



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

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

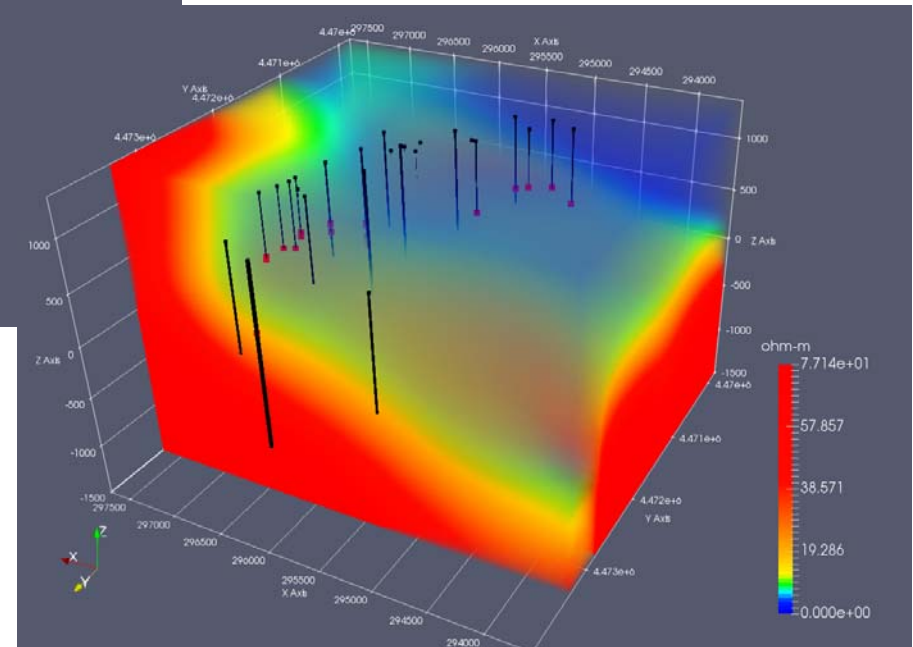
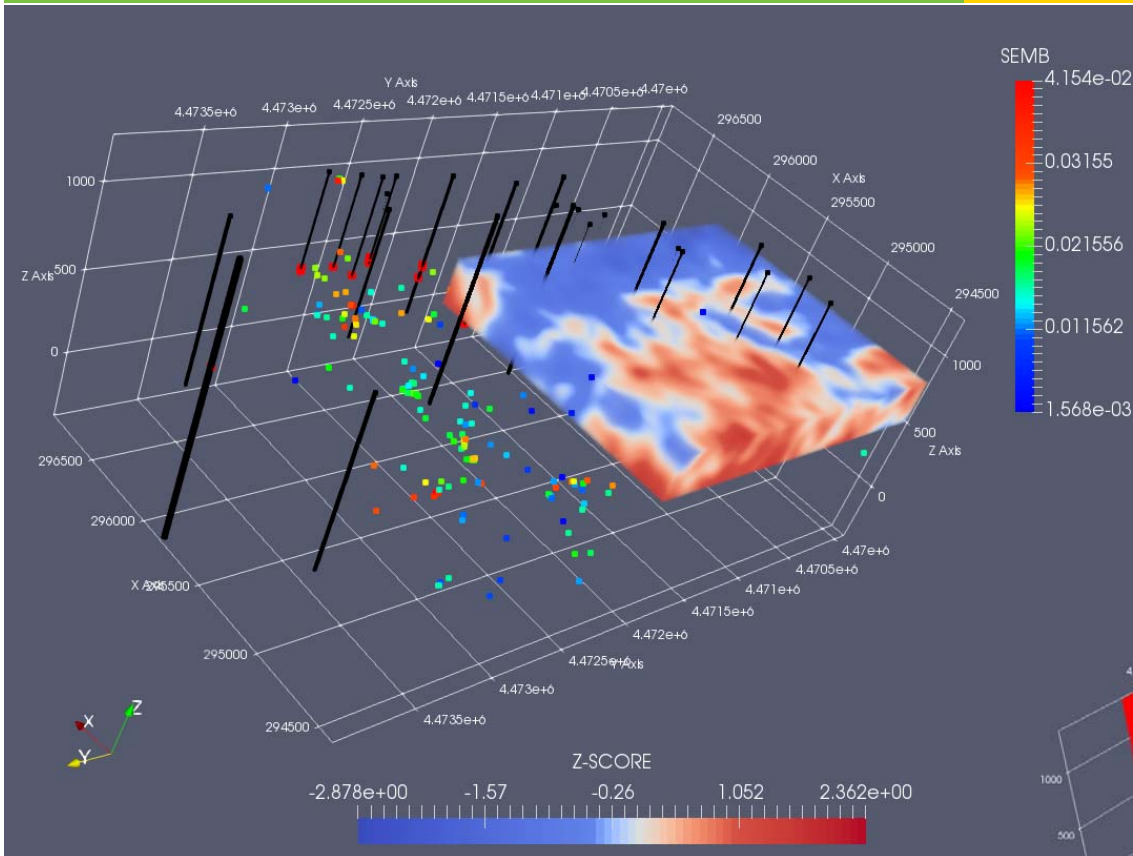
Technical Accomplishments and Progress continued

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Tentative new completion date
5. Processing, joint inversion, and analysis of newly acquired datasets	To begin 11/17 when EM processing complete	3/31/2018
6. Final velocity model completed		3/31/2018
7. Semblance volume completed with final velocity models		4/30/2018

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

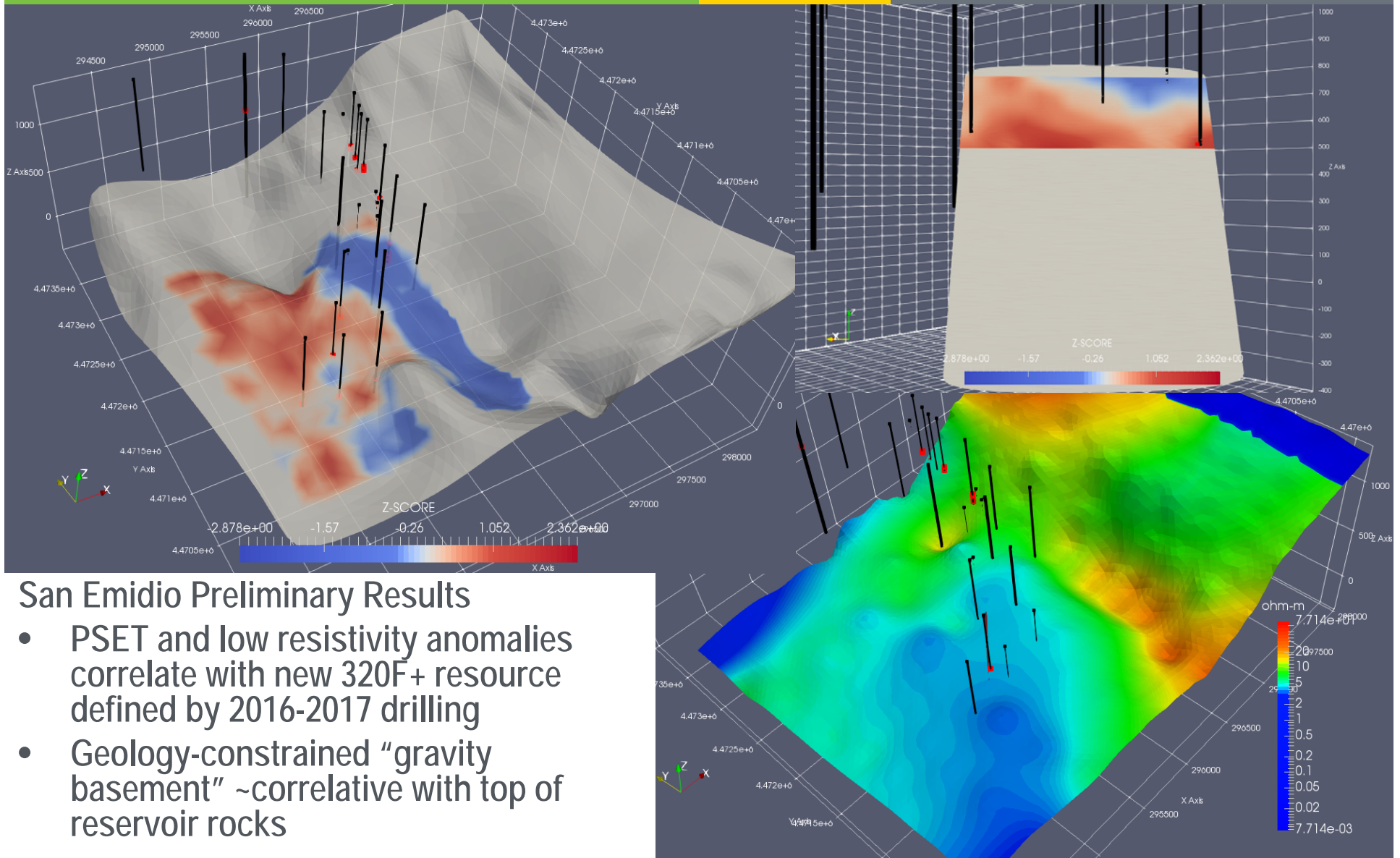
Technical Accomplishments and Progress continued



San Emidio

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

Technical Accomplishments and Progress continued



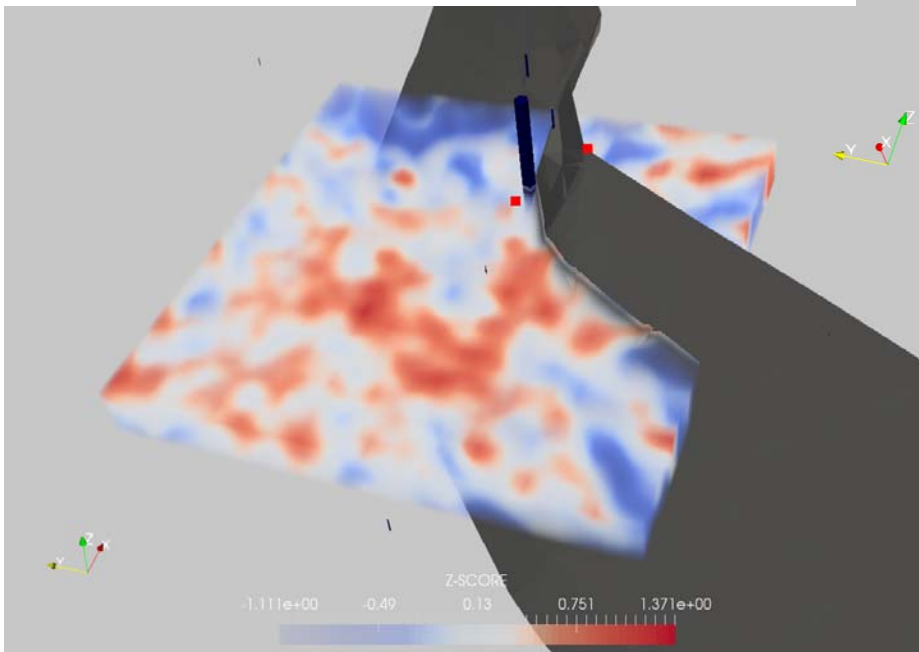
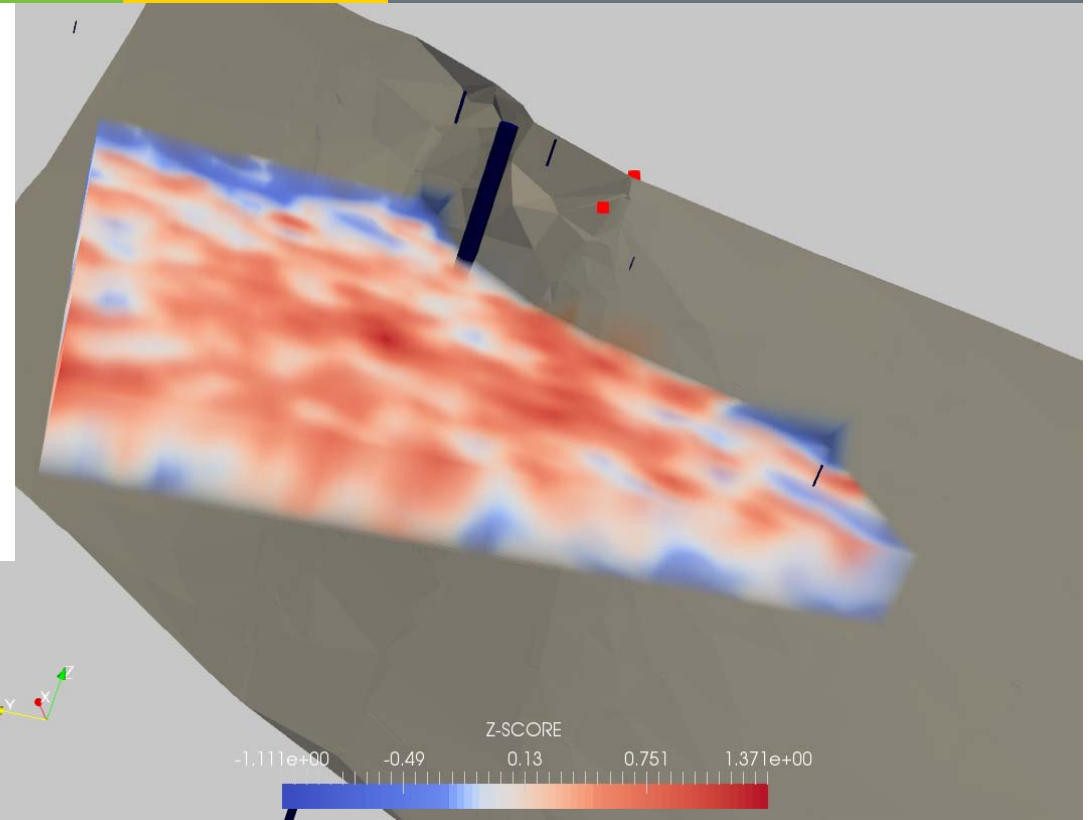
San Emidio Preliminary Results

- 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

Milestone or Go/No-Go	Status & Expected Completion Date
5. Processing, joint inversion, and analysis of newly acquired datasets	Beginning October 2017; 3/31/2018*
6. Final velocity model completed	3/31/2018
7. Semblance volume completed with final velocity models	Work ongoing with simple velmod PSET volume; 4/30/2018
8. Integration of new and historic datasets into complete 3D model	5/31/2018
8.2. Drill targeting	5/31/2018
8.3. Finalize drill targets GO/NO-GO	5/31/2018
9. Permit drilling locations	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
10. Drill and test wells	12/31/2018
11. Final report	1/31/2019

*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