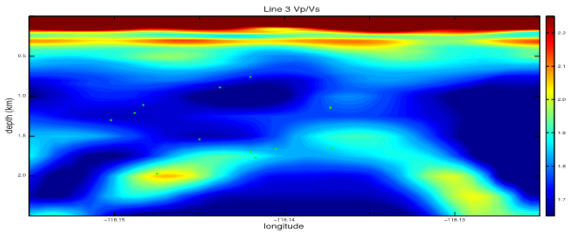
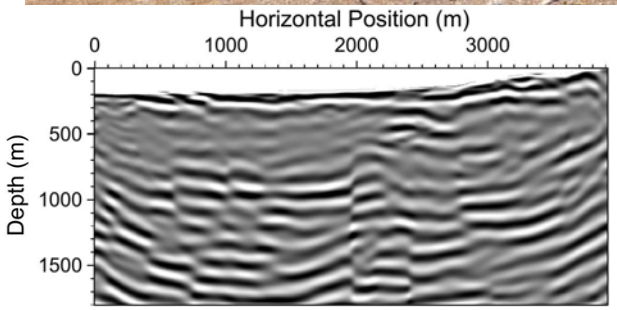
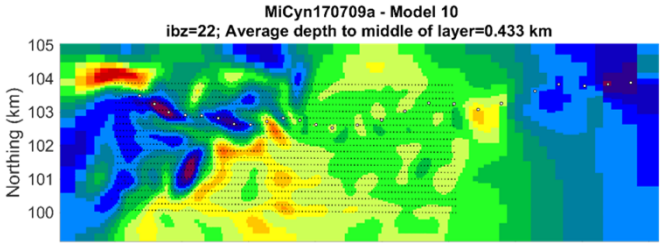
Eleven-Mile Canyon



Blue Mountain



Soda Lake



Fracture and Permeability Imaging Using Joint Inversion of Multi-type Geophysical Data

Project Officer: Eric Hass and Holly Thomas

Total Project Funding: $3M

November 14, 2017

Mandatory slide

Principal Investigator

Lianjie Huang

Los Alamos National Lab

Track 1: Hydrothermal Program General R&D

Relevance to Industry Needs and GTO Objectives

- Challenge: Reliable imaging of fractures and permeability is one of the biggest challenges in hydrothermal exploration and development.
- Impact: Successful fracture and permeability imaging will reduce the exploration risk, and lower overall costs for geothermal power projects.
- Innovative aspects:
  - Anisotropic full-waveform seismic inversion and imaging, rather than using isotropic techniques, to greatly improve reliability and resolution of fracture/fault imaging
  - “Virtual Seismometers” allow us to focus on the microseismically active zone to improve accuracy of microseismic imaging

Mandatory- may utilize multiple slides

Relevance to Industry Needs and GTO Objectives

- Innovative aspects:
  - Analysis of scattered seismic waves of microseismic data to improve fracture characterization
  - Joint ZTEM/MT and constrained MT to greatly improve resolution of resistivity
  - Joint inversion/cooperative interpretation of multi-type geophysical datasets to minimize the uncertainty of individual data analysis and optimize fracture and permeability imaging
- Impact on the following GTO's goals:
  - "Improving processes of identifying, accessing, and developing geothermal resources" and
  - "Overcoming technical obstacles and mitigating risk"

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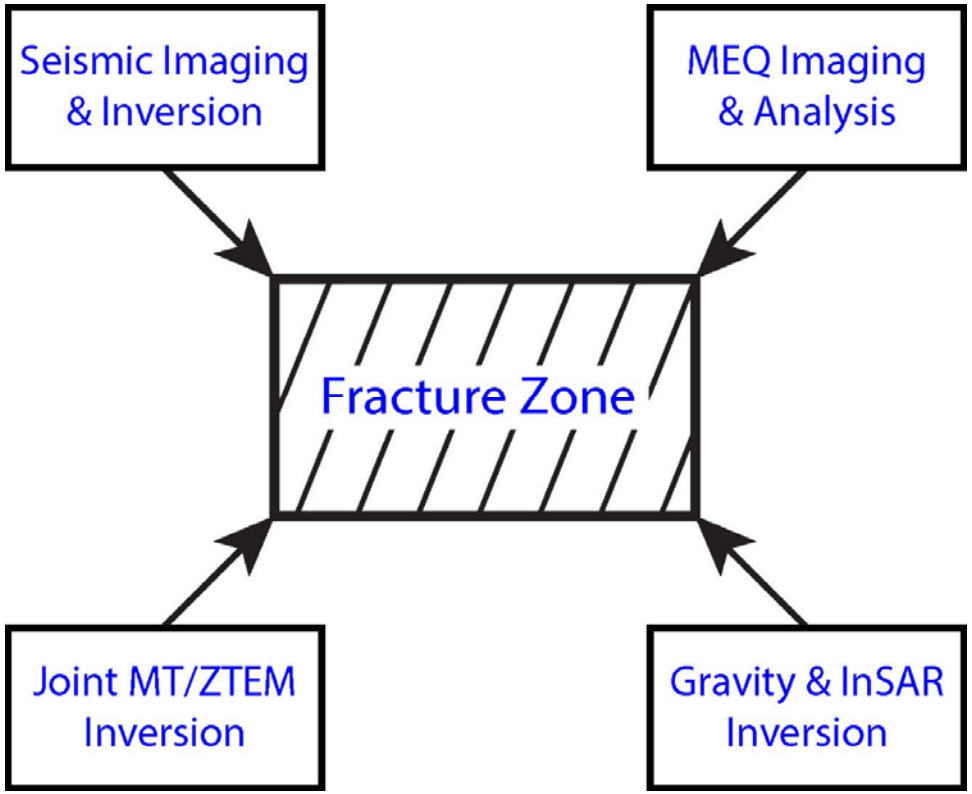
Methods/Approach

- To image and characterize fracture zones and map the spatial distribution of permeability using multi-type geophysical data



Geothermal Site	Data
Eleven-Mile Canyon (Navy GPO)	2D seismic, MT, ZTEM
Blue Mountain (AltaRock)	2D seismic, MEQ, MT
Soda Lake (Cyrq)	3D seismic, ambient noise, MT, gravity, InSAR

Mandatory- may utilize multiple slides

Methods/Approach

- LANL: Developed, implemented, and validated anisotropic full-waveform inversion and anisotropic reverse-time migration methods; verified the methods using seven 2D lines of seismic data from Blue Mountain, and five 2D lines of seismic data from Eleven-Mile Canyon.
- LLNL: Performed seismic interferometry of active and passive seismic data at Blue Mountain and Soda Lake; Located microseismic events at Blue Mountain; Performed "Virtual Seismometers" study to focus on the microseismically active zone.
- MIT: Located microearthquakes using a 3D model derived from anisotropic FWI inversion of seven 2D seismic lines from Blue Mountain
- University of Utah: Verified successful joint inversion of ZTEM/MT data from Eleven-Mile Canyon
- AltaRock Energy, Inc. and Navy Geothermal Program Office: Interpreted initial results of active seismic imaging, passive seismic imaging, and joint ZTEM/MT imaging.

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Technical Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Verify using 2D field data that LANL's new anisotropic seismic inversion can reduce 25% of data misfit	Verified using 2D field data from Blue Mountain and Eleven-Mile Canyon that LANL's new anisotropic seismic inversion can reduce more than 30% of data misfit	September, 2016
Verify using 2D field data that our new anisotropic reverse-time migration imaging can detect fracture zones	Verified using 2D field data from Blue Mountain and Eleven-Mile Canyon that our new anisotropic reverse-time migration imaging can detect fracture zones	September, 2017
Produce a 3D seismic model (Vp, Vs and Q) of the Blue Mountain and Soda Lake sites using active and passive seismic data.	Done using ambient noise correlation and active source interferometry combining historical seismic survey with current monitoring array data.	March, 2017

Mandatory- may utilize multiple slides

Technical Accomplishments and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Complete development of VSM moment tensor inversion algorithm	Done and tested on synthetic data.	August, 2017
Catalog, locate and estimate slip on Blue Mountain microseismicity	Done using matched field and VSM on data from AltaRock's current monitoring network. Continuing as new data arrive	September, 2017, and on-going
Develop 3D Joint MT/ZTEM Inversion	Developed 3D Joint MT/ZTEM Inversion	June, 2016
Locate microseismic events at Blue Mountain	Located microseismic events at Blue Mountain	September, 2017
3D Joint Inversion of 11 Mi Cyn Data	3D Joint Inversion of 11 Mi Cyn Data	June, 2017
3D MT Inversion of Soda Lake	3D MT Inversion of Soda Lake	June, 2016
3D MT Inversion of Blue Mountain	3D MT Inversion of Blue Mountain	June, 2017

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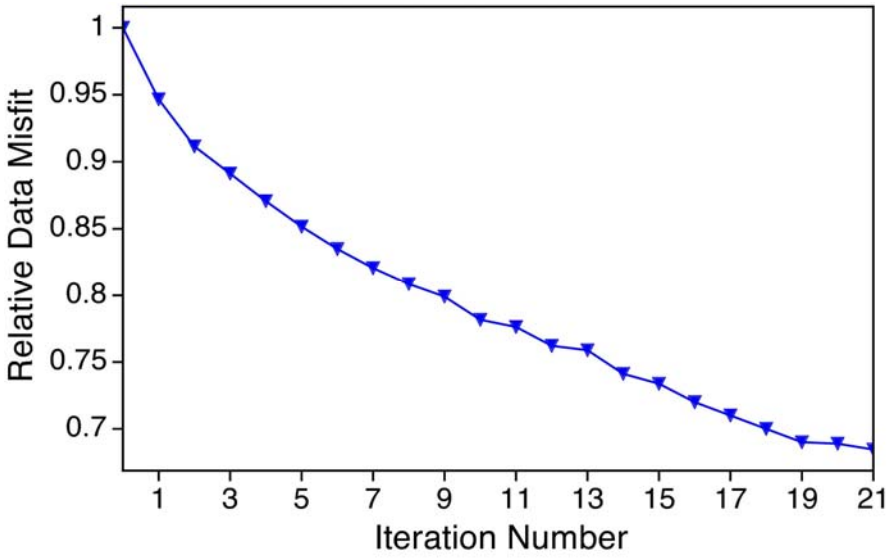
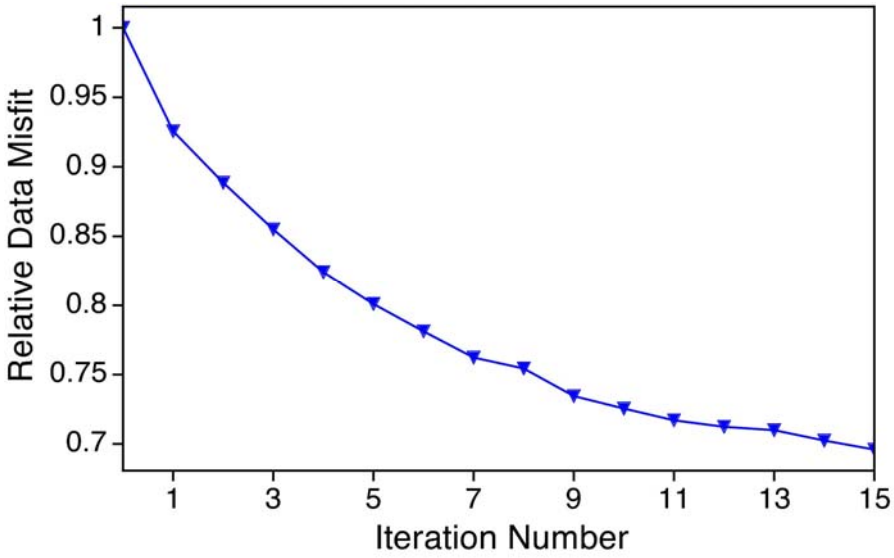
Build anisotropic models for anisotropic migration imaging



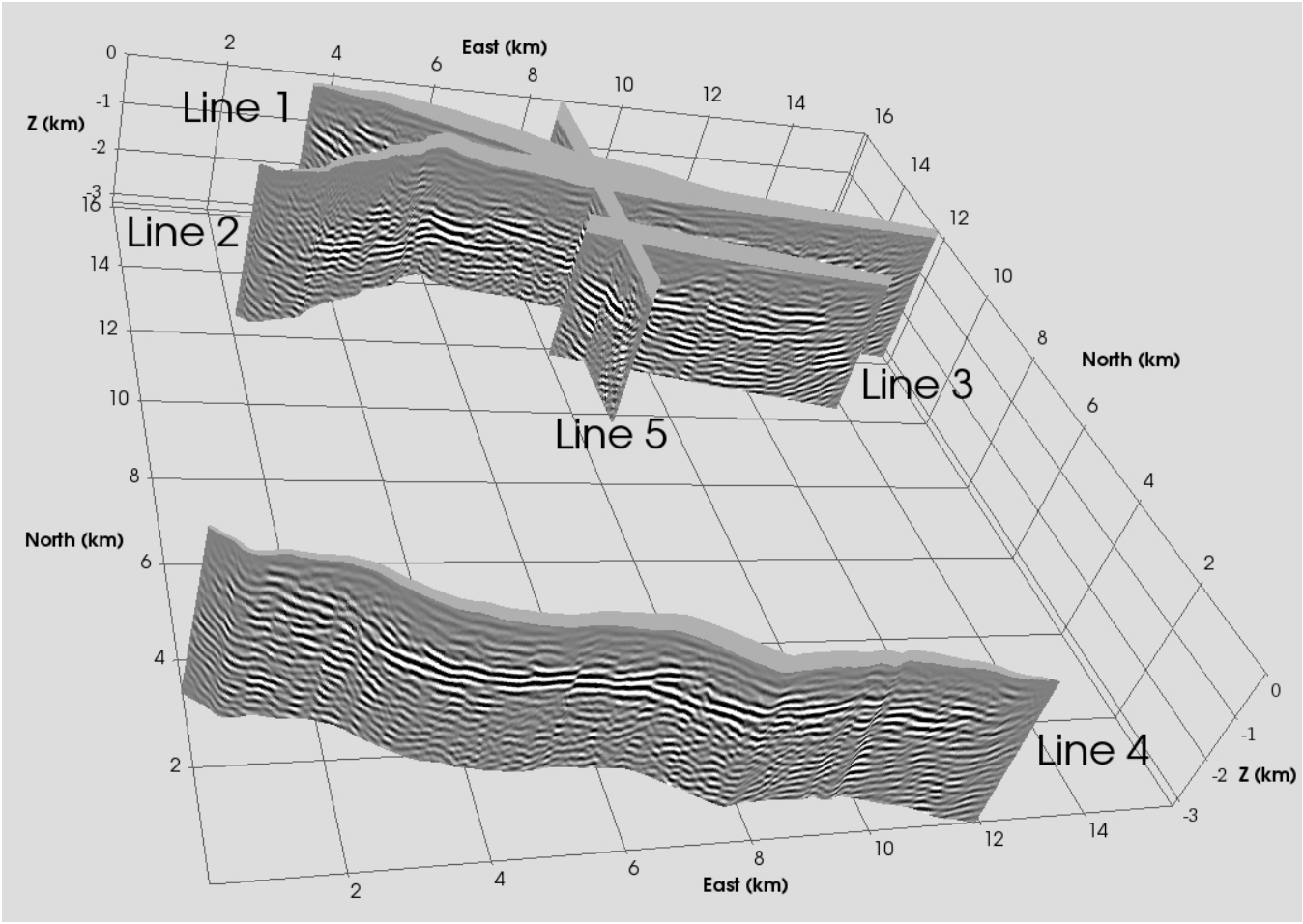
Anisotropic seismic inversion of 2D seismic data from Eleven-Mile Canyon. Data misfit reduction: **31.5%.**



Anisotropic seismic inversion of 2D seismic data from Blue Mountain. Data misfit reduction: **30.4%.**

Mandatory- may utilize multiple slides

Technical Accomplishments and Progress



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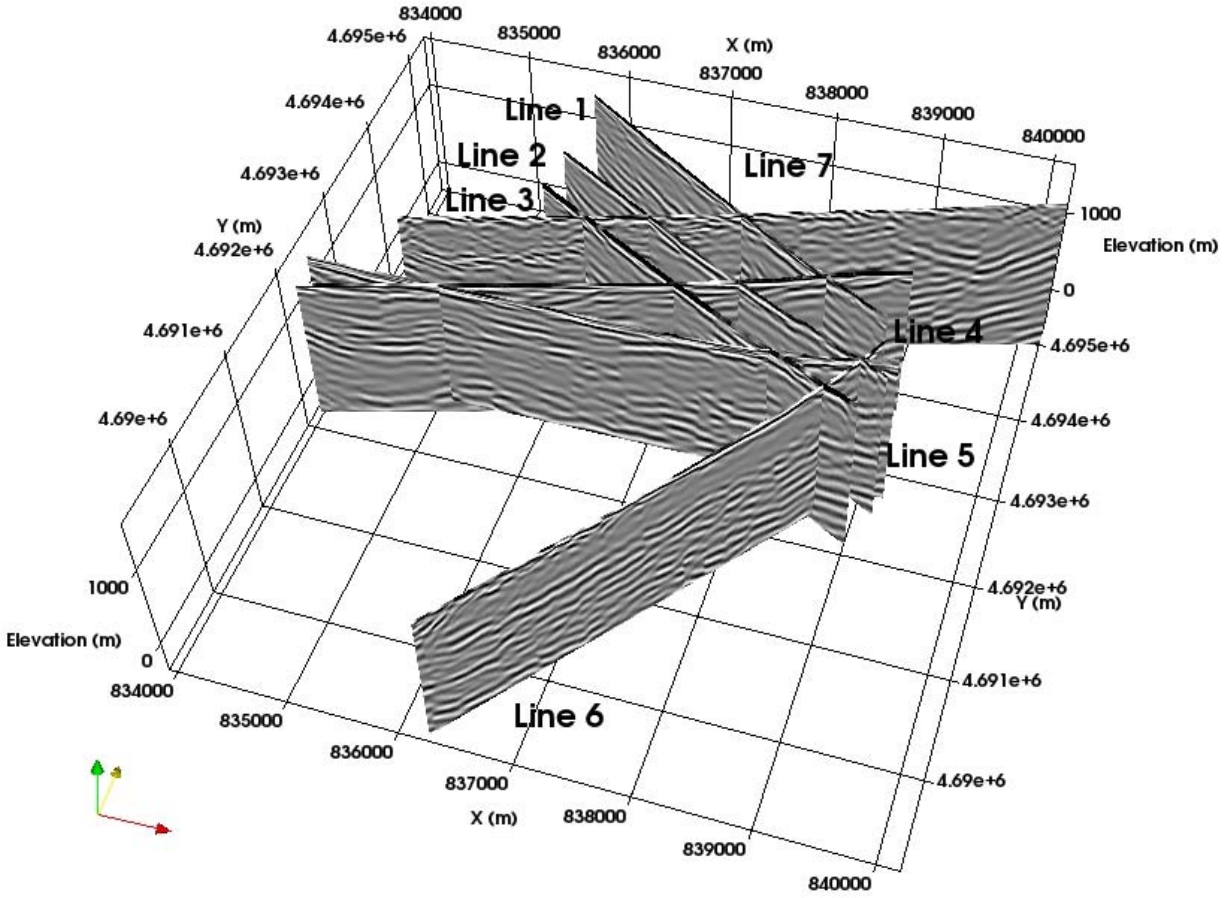
Technical Accomplishments and Progress



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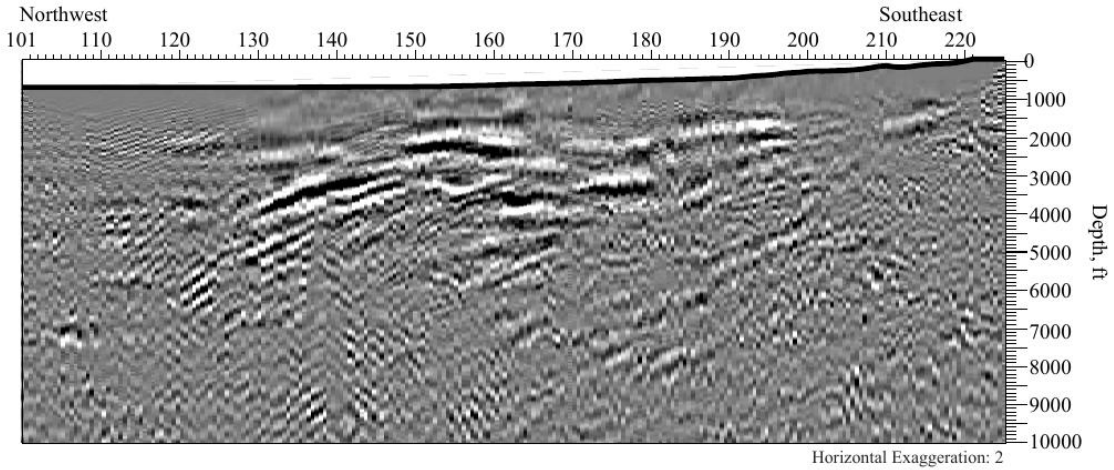
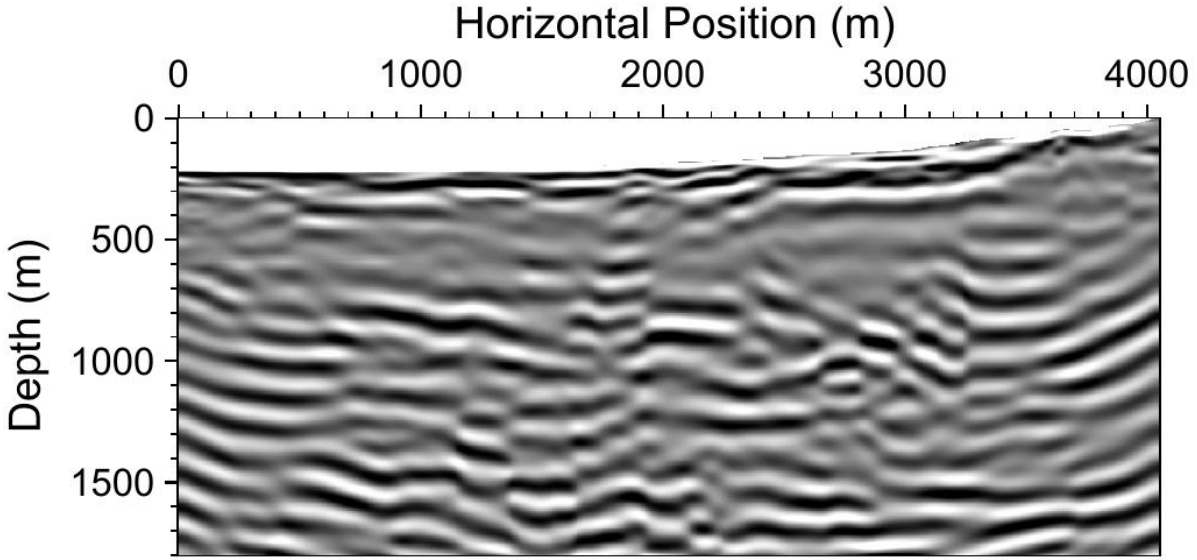
Optim's migration image



LANL's migration image



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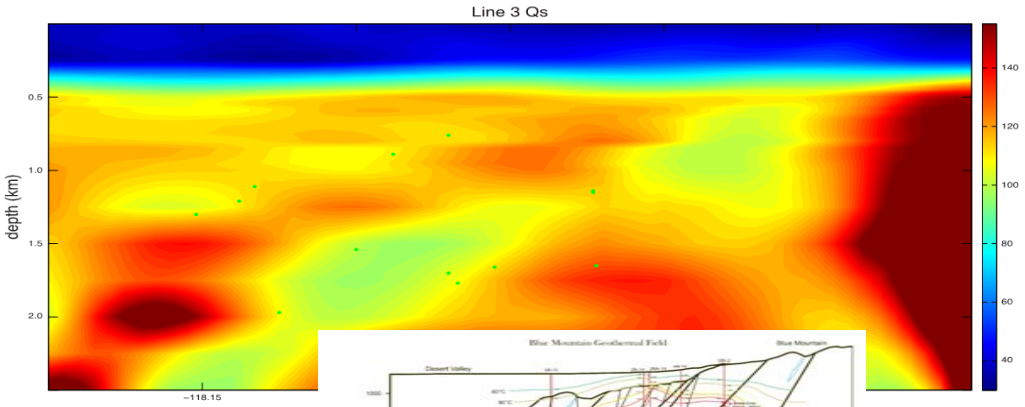
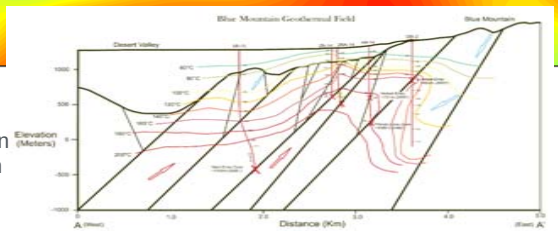
Technical Accomplishments and Progress

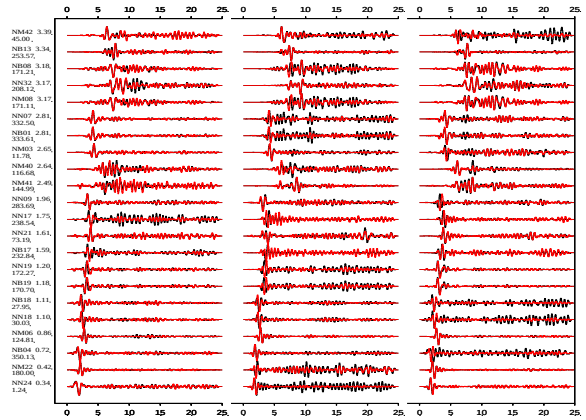
Seismic interferometry: sharp images of Vp, Vs and attenuation

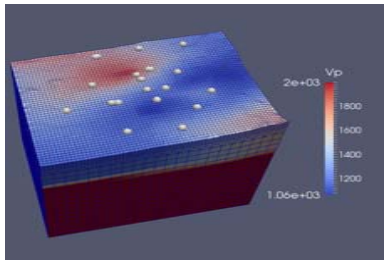




(Above) Attenuation tomography at Blue Mountain (Right) thermal cross-section from Melosh et al., 2008

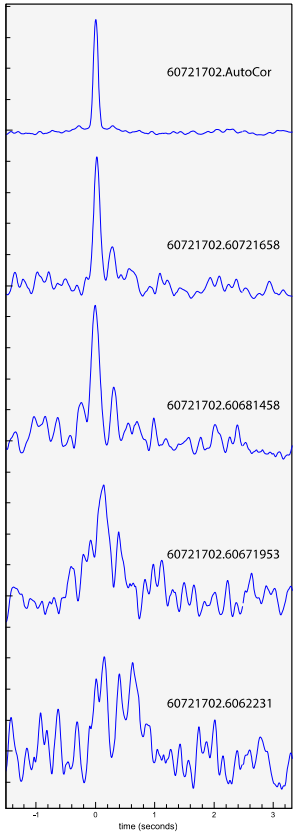
VSM fast, waveform inversion of direct inversion of microseismic Moment Tensors.





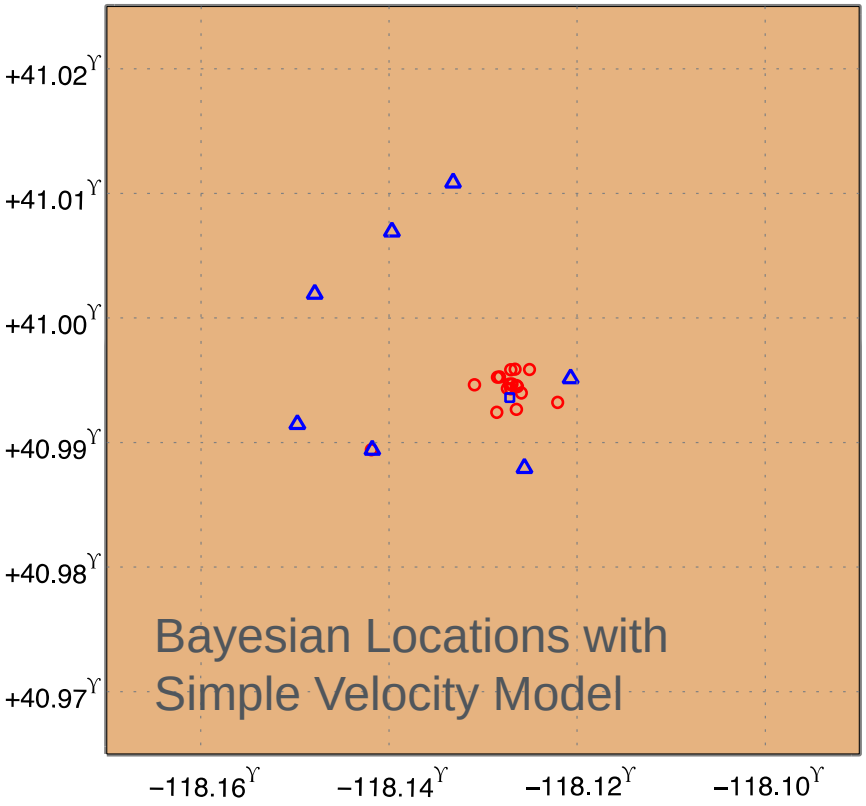
Synthetics calculated using the MT estimate (red) match the originally recorded waveforms (black).

Virtual Seismograms at Blue Mountain

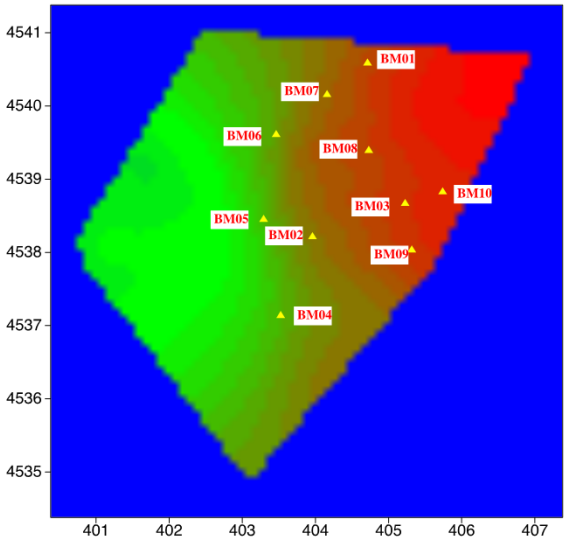


Above: the evolution of the VSM envelopes over time suggests an evolving pressure field.

Located microseismic events at Blue Mountain



Horizontal Slice Through 3D Velocity Model Derived for Blue Mountain Geothermal Site



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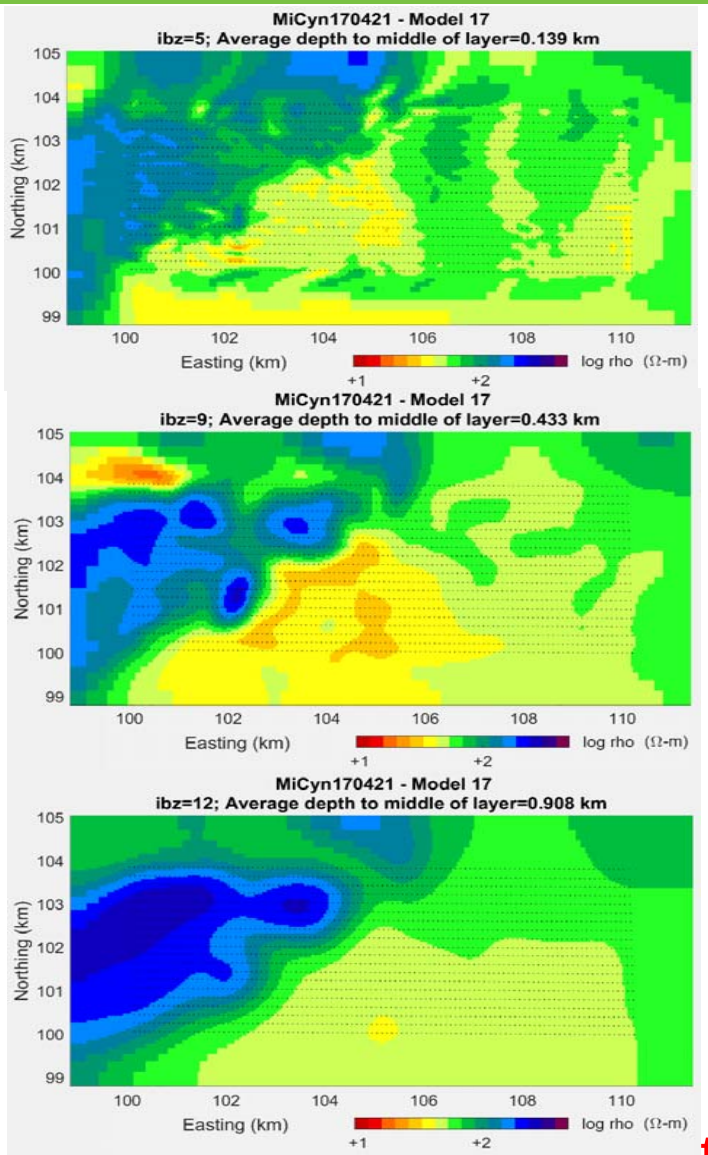
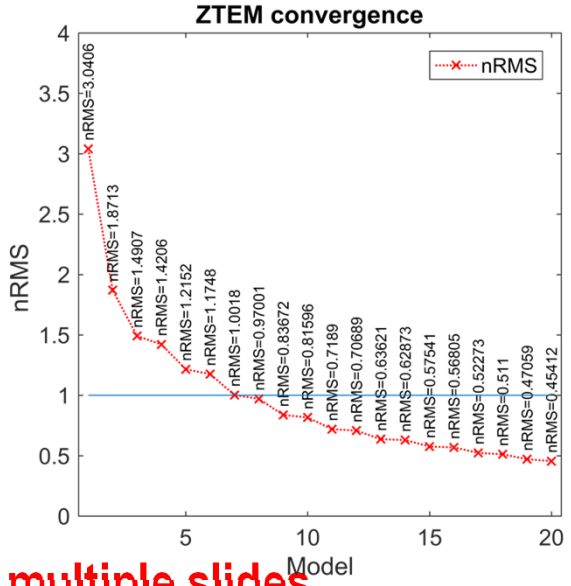
Technical Accomplishments and Progress



Eleven Mile Canyon 3D ZTEM (Only) Inversion

- 2040 ZTEM stations: 20 flight profiles, 200 m sep., 100 m data intervals 360 Hz – 30 Hz
- Mesh: 117 (x) x 261 (y) x 40 (z) nodes, 13 air layers; bird heights (62 – 179 m) included
- 100 ohm-m starting model, ZTEM data error floor of 0.01, ~5 hrs/iter. on 24 core w/s
- Good algorithm convergence to nRMS of ~0.5
- Possible hydrothermal clay cap in west-central portion of study area
- Transition from outcrop to valley alluvium from west to east



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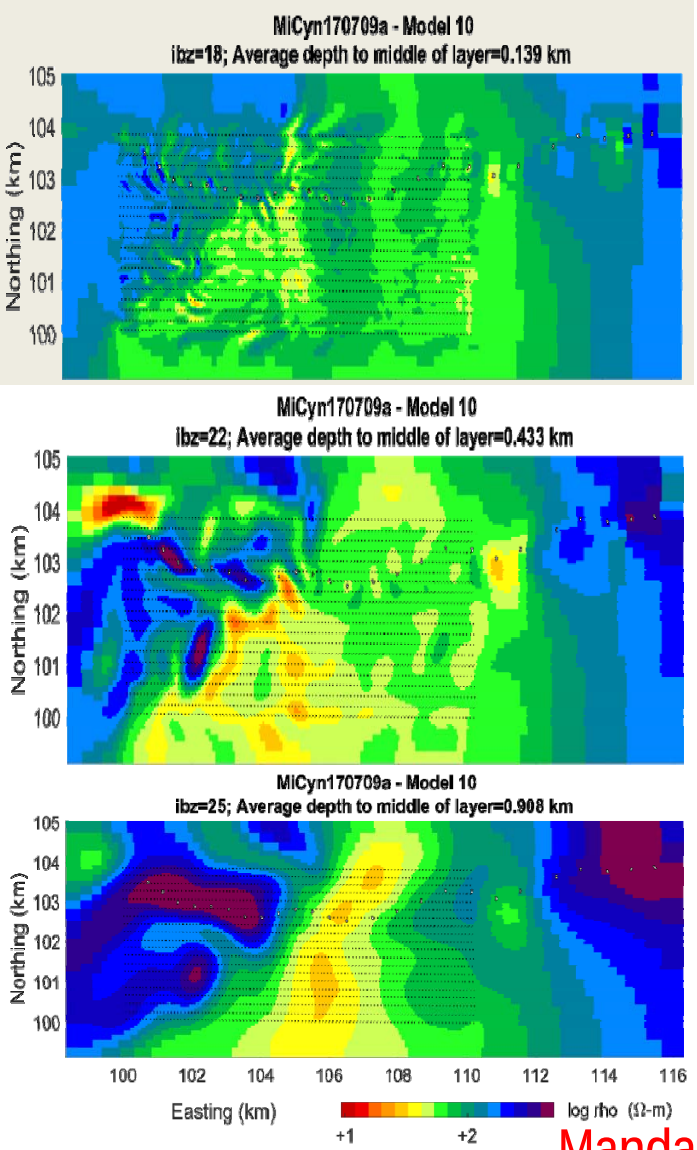
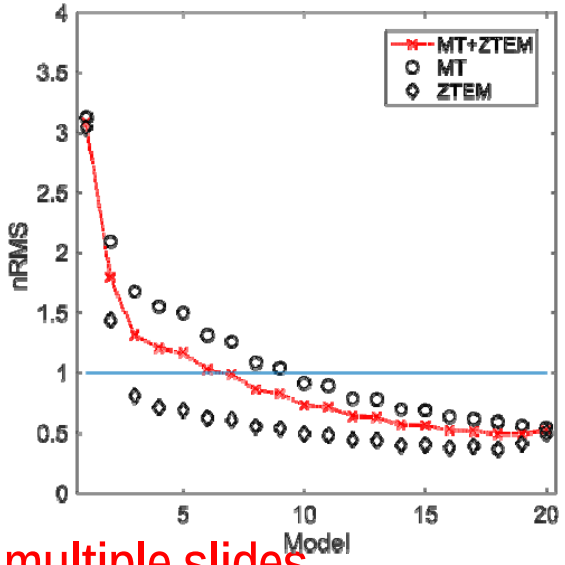


Eleven Mile Canyon 3D ZTEM/MT Joint Inversion

- 2040 ZTEM stations: 20 flight profiles, 200 m sep., 100 m data intervals 360 Hz – 30 Hz
- Mesh: 117 (x) x 261 (y) x 40 (z) nodes, 13 air layers; bird heights (62 – 179 m) included
- 100 ohm-m starting model, ZTEM data error floor of 0.01, ~5 hrs/iter. on 24 core w/s
- Good algorithm convergence to nRMS of ~0.5
- Possible hydrothermal clay cap in west-central portion of study area
- Transition from outcrop to valley alluvium from west to east



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Research Collaboration and Technology Transfer

- AltaRock, Cyrq, and Navy Geothermal Program Office provided multi-type geophysical data, and help interpretation of results.
- The research teams met/held telecons with industry and Navy Program Office collaborators, and presented results.
- Cooperative research activities between Utah and LANL for integrating new seismic and EM imaging technology.
- LANL shared full-waveform inversion results of velocity models with the teams for microseismic imaging.

Mandatory- may utilize multiple slides

Future Directions

FY18 will be focused on bringing together the different geophysical methods and multi-type geophysical data to jointly constrain the material model and image fracture properties.

- 3D anisotropic full-waveform inversion and reverse-time migration of 3D seismic data from Soda Lake.
- Use seismic imaging results to constrain MT inversion.
- Determine fracture characteristics using scattered microseismic waves
- Joint inversion/cooperative interpretation of multi-type geophysical datasets to characterize fracture zones.

Milestone or Go/No-Go	Status & Expected Completion Date
3D seismic inversion and imaging	On-going, to be complete by September, 2018
Joint seismic and MT inversion	On-going, to be complete by September, 2018
Scattered wave analysis	On-going, to be complete by September, 2018
Joint inversion/cooperative interpretation of multi-type geophysical data	On-going, to be complete by September, 2018

Mandatory Summary Slide

- Anisotropic seismic full-waveform inversion and anisotropic reverse-time migration produce clear subsurface images revealing fracture/fault zones that are invisible on industry state-of-the-art images.
- “Virtual Seismometers” allow us to focus on the microseismically active zone and improve accuracy and reliability of microseismic imaging.
- Unprecedented improvement is achieved by combining and inverting joint airborne (ZTEM) and ground (MT) EM data for resolving geothermal structures.

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