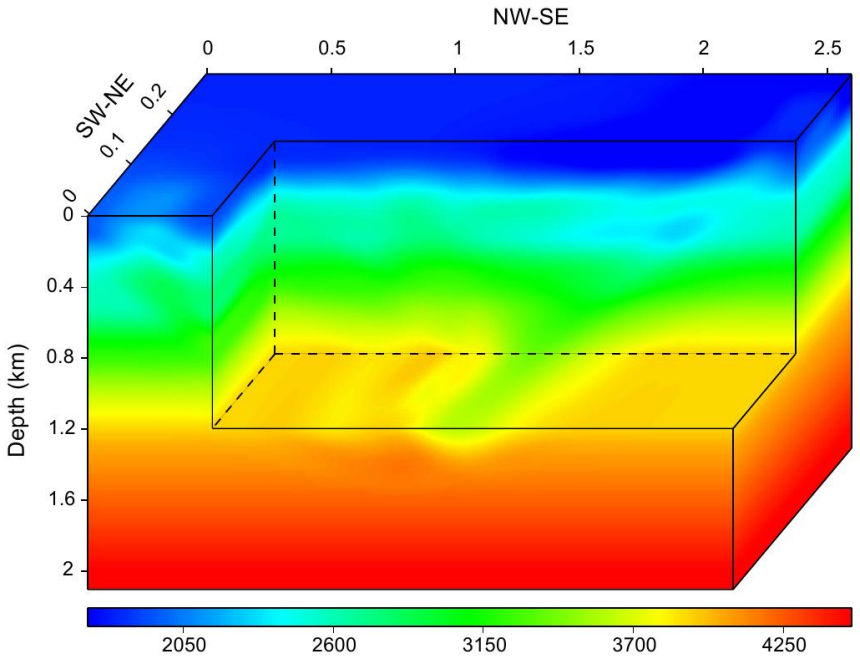


Joint Active and Passive Seismic Imaging of EGS Reservoirs

Project Officer: Sean Porse, Lauren Boyd

Total Project Funding: $3M

November 13, 2017

Mandatory slide

Principal Investigator

Lianjie Huang

Los Alamos National Lab

Track 3: EGS General R&D

Relevance to Industry Needs and GTO Objectives

- Challenge:
  - Commercial scale EGS development has not been realized despite more than 40 years of testing.
  - Estimates of thermal recoveries are low, despite extensive seismic volumes produced during stimulation.
  - Understanding the distribution of conductive fluid pathways is critical for targeting production and injection wells.
  - Obtaining improved 3D velocity models from sparse seismic data;
  - Obtaining accurate source mechanisms of MEQs using elastic-waveform inversion in the Fourier domain
  - Imaging fracture zones using sparse seismic data
- Impact: Success of the project will stimulate EGS development and reduce costs of conventional development by:
  - Improving capability to reveal MEQ source mechanisms and characterize fluid flow pathways
  - Providing improved targeting of high conductivity fractures
  - Reducing the risk of drilling dry wells

Relevance to Industry Needs and GTO Objectives

- Innovative aspects:
  - This project integrates ambient noise tomography of continuous recorded passive data, elastic-waveform inversion of VSP (or surface seismic) data, and moment tensor inversion of MEQs using full MEQ waveforms.
- Impact on the following GTO's goals:
  - "Improving processes of identifying, accessing, and developing geothermal resources" and
  - "Overcoming technical obstacles and mitigating risk"
  - Accelerating a commercial pathway to and securing the future of Enhanced Geothermal Systems (EGS)

Mandatory- may utilize multiple slides

Methods/Approach

- To improve subsurface velocity modeling building
  - develop an ambient noise tomography algorithm to obtain low-resolution velocity models.
  - develop and validate an elastic-waveform inversion algorithm in the time domain using the compressive sensing technique.
  - refine and validate a 3D elastic-waveform inversion algorithm in the Fourier domain.
  - use synthetic surface seismic and VSP data to validate the algorithms.

- To obtain accurate source mechanisms of MEQs
  - develop and validate a 3D elastic-waveform inversion algorithm in the Fourier domain for moment tensor inversion.

Mandatory- may utilize multiple slides

Methods/Approach

- To characterize fracture zones
  - develop and validate an anisotropic elastic-waveform inversion algorithm.

- The unique aspects of the approach include:
  - to develop elastic-waveform inversion algorithms in both the time domain and the Fourier domain to obtain a robust algorithm, and
  - to develop seismic-waveform inversion and imaging algorithms using a compressive sensing technique for sparsely acquired seismic data.
  - This approach will result in our ability to develop accurate velocity models using sparse seismic data that can be acquired at costs much lower than those required for full 3D surveys.

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
Develop and validate algorithms for velocity inversion	Developed and validated novel multi-scale full-waveform inversion algorithms	September, 2015
Develop and validate algorithms for inversion of source mechanisms and imaging of fracture zone	Developed and validated a new full-waveform inversion algorithm for inversion of focal mechanisms and imaging of fracture zone	December, 2016
Verify the capability of our joint active and passive imaging technique using field data from the Raft River EGS site	On-going	June, 2018

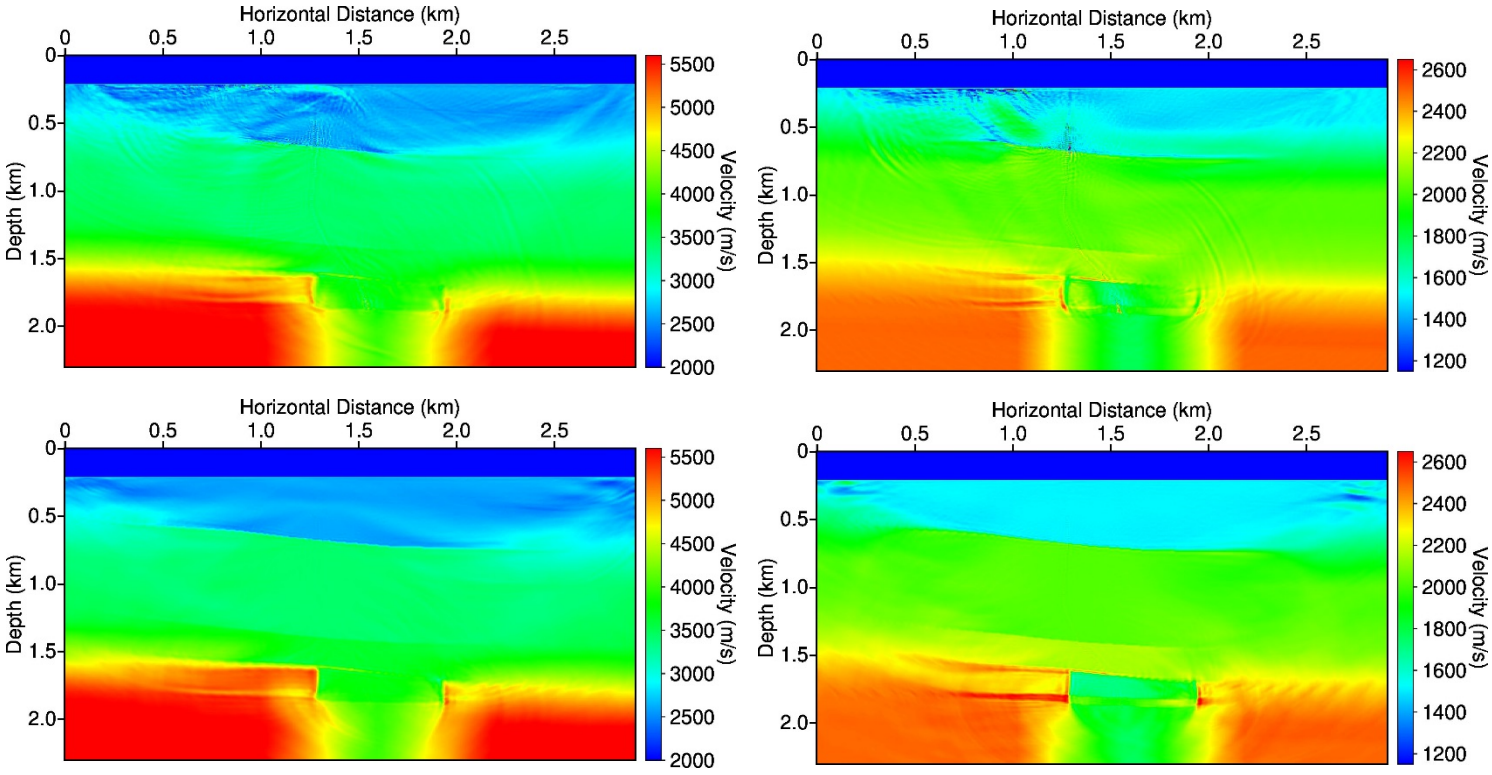
Mandatory- may utilize multiple slides

LANL: Multi-scale inversion: Implement and test multi-scale elastic-waveform inversion algorithm

- New multi-scale elastic-waveform inversion improves the inversion accuracy. Multi-scale in the temporal domain: envelope and multiple frequency bands; Multi-scale in the spatial domain: Wavelet transform. Validated using synthetic VSP data.

Top row: Single-scale inversion

Bottom row: Multi-scale inversion. Produces images with much fewer artifacts and higher quality

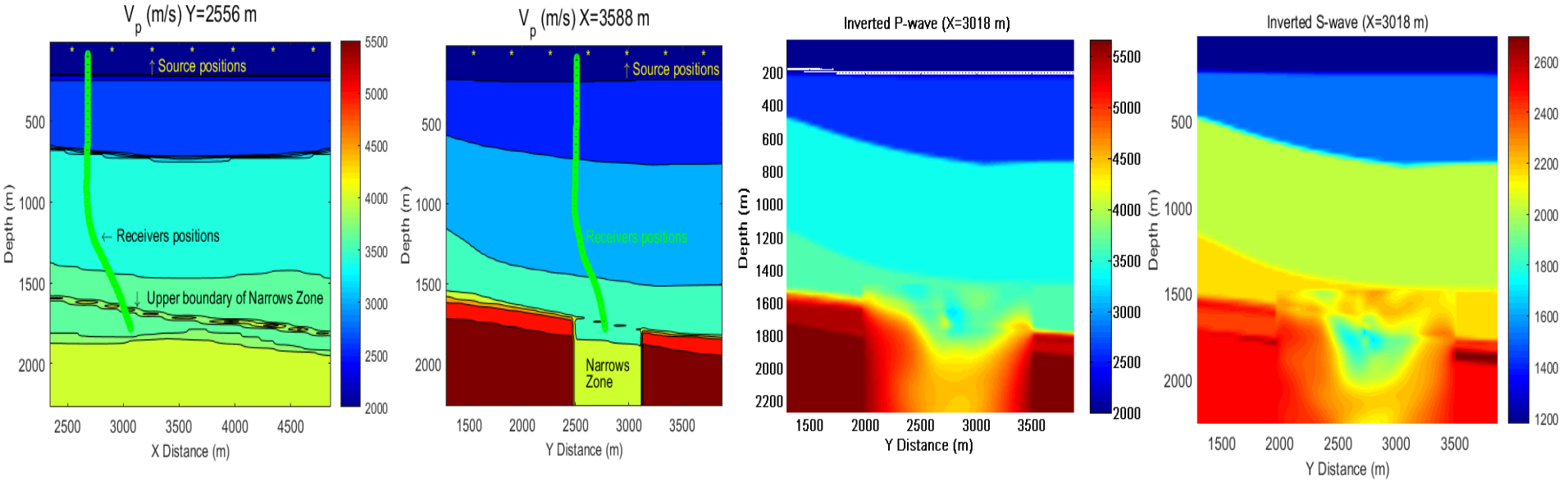


Compressional-wave velocity

Shear-wave velocity

LBNL: Improvements in subsurface velocity modeling building

- Waveform Inversion in the frequency domain
- refine and validate a 3D elastic-waveform inversion algorithm in the Fourier domain.
- use in experiment design study for VSP data acquisition at Raft River



- **To be applied to Raft River VSP field data**

LANL: Reverse-time migration: Develop and validate elastic reverse-time migration using compressive sensing

- New imaging can preserve the accuracy of least-squares reverse-time migration for sparse seismic data.

Velocity Model

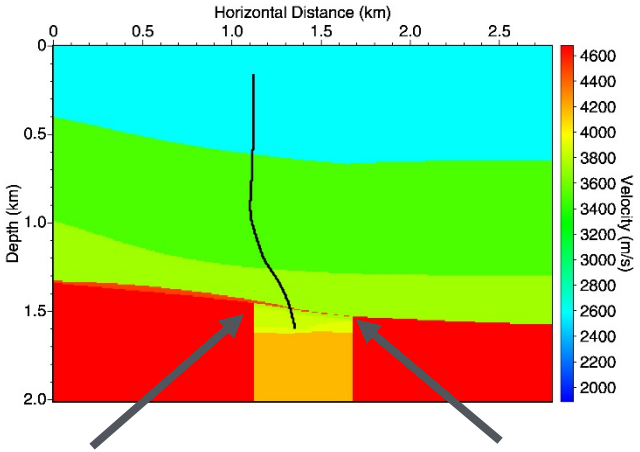


Image Using Full Dataset: 160 shots

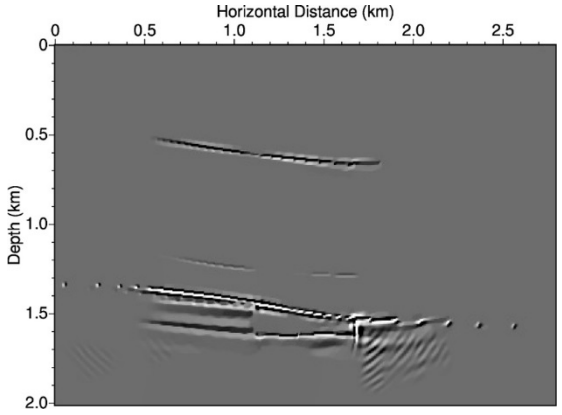
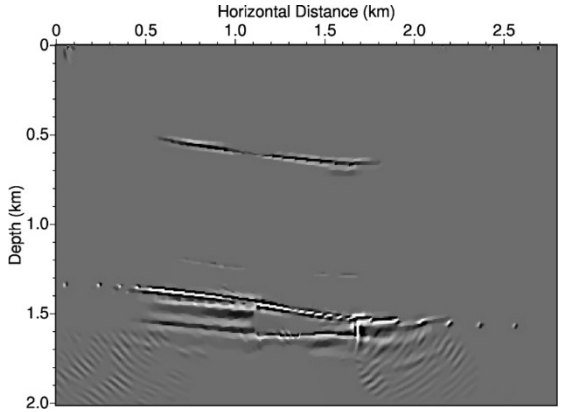


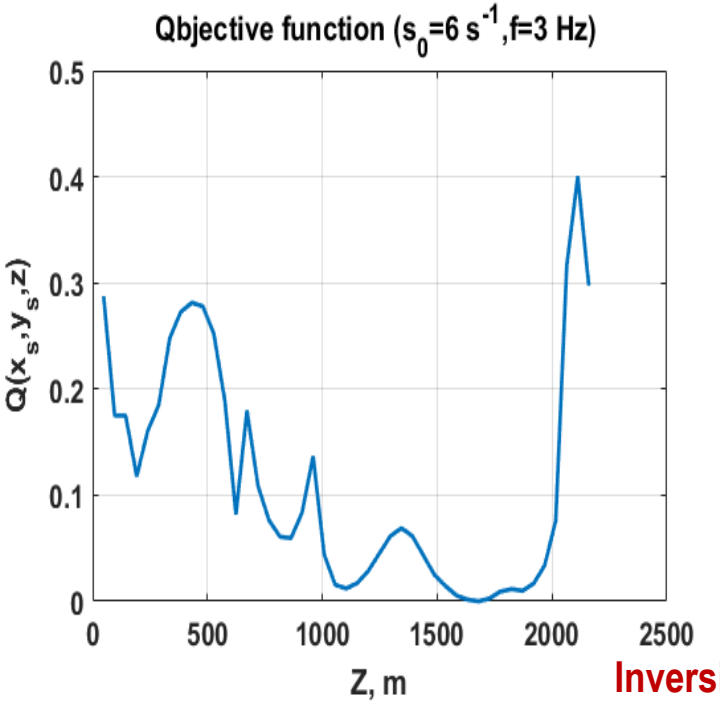
Image Using 10% of Data: 16 shots



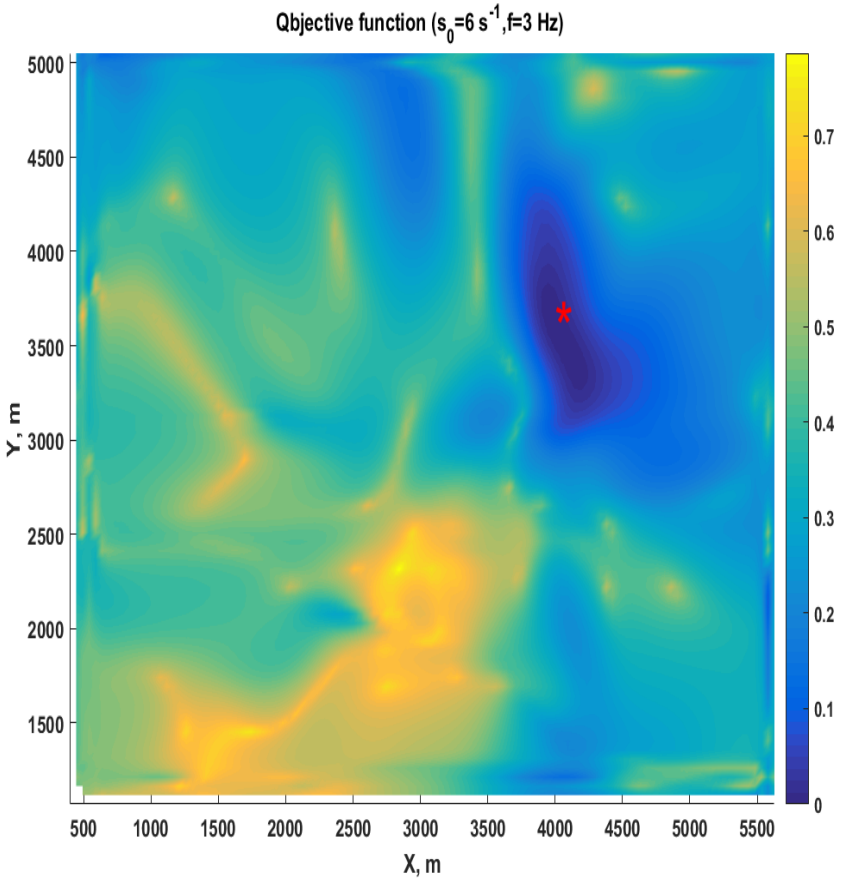
Note details associated with geothermal reservoir boundary (arrows) are readily visible in image formed using only a subset of the simulated seismic data, indicating that the new imaging method can produce quality images with sparse field dataset.

Moment Tensor Inversion Example Raft River

	Exact	Inverted
Mxx	0.500 + 0.0i	0.4997 - 0.0003i
Myy	0.200 + 0.0i	0.1999 - 0.0000i
Mxz	1 .000 + 0.0i	1.0002 - 0.0000i
Myy	0.500 + 0.0i	0.5002 + 0.0000i
Myz	0.100 + 0.0i	0.0999 - 0.0002i
Mzz	-1.000 + 0.0i	-1.0001 + 0.0004i



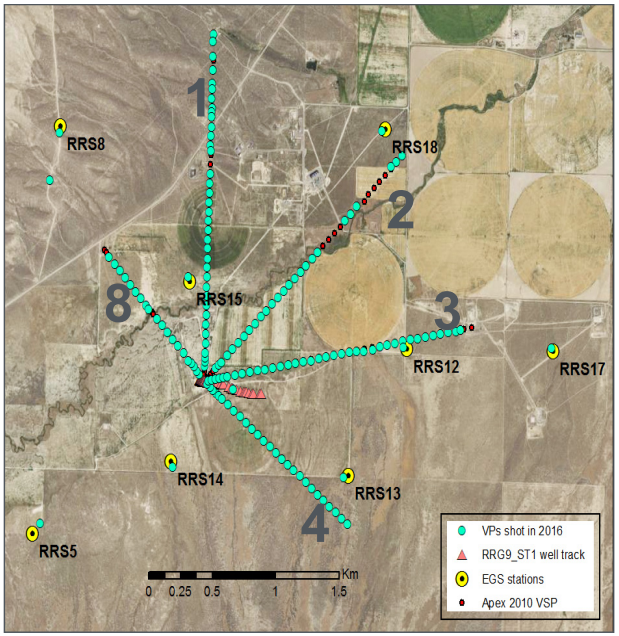
X_s=3996 m, Y_s=3612 m, Y_s=1680 m



Inversion results based on 3D elastic-model of Raft River EGS system

Raft River VSP Data Acquisition: May 2016, and Processing: March 2017

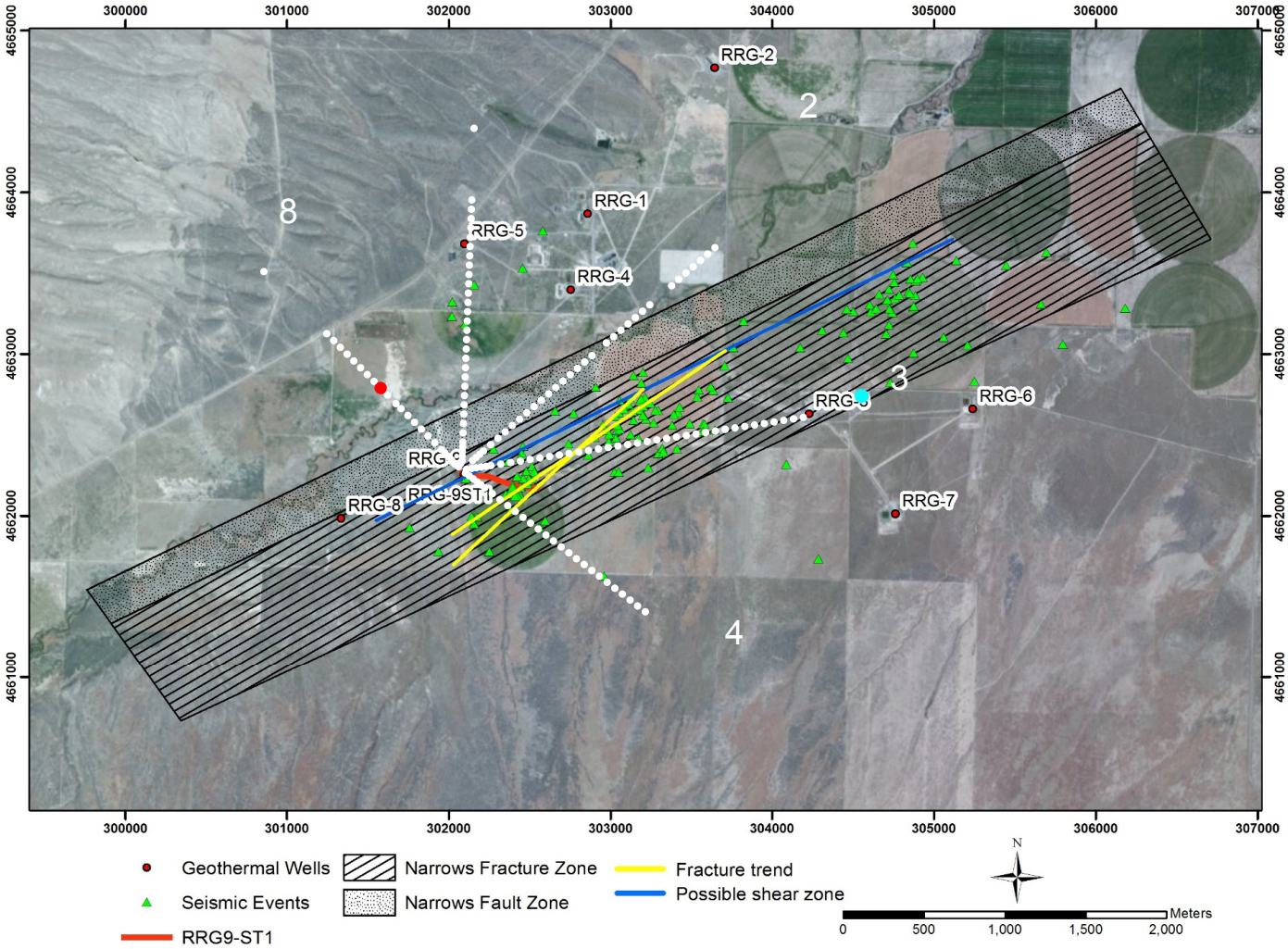
5 walkaway lines
3 VSP levels in well RRG-9 ST1

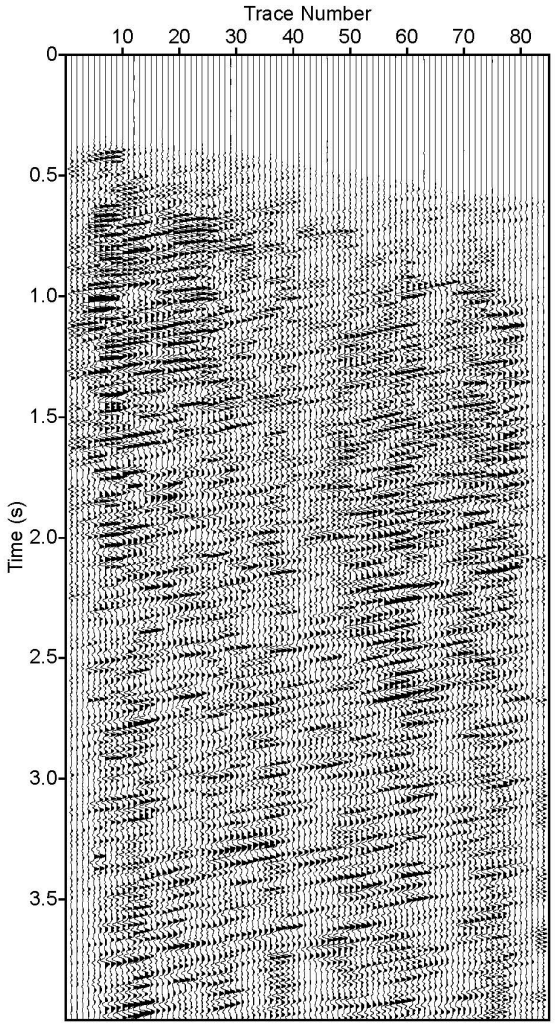


Contractor
Reservoir Imaging

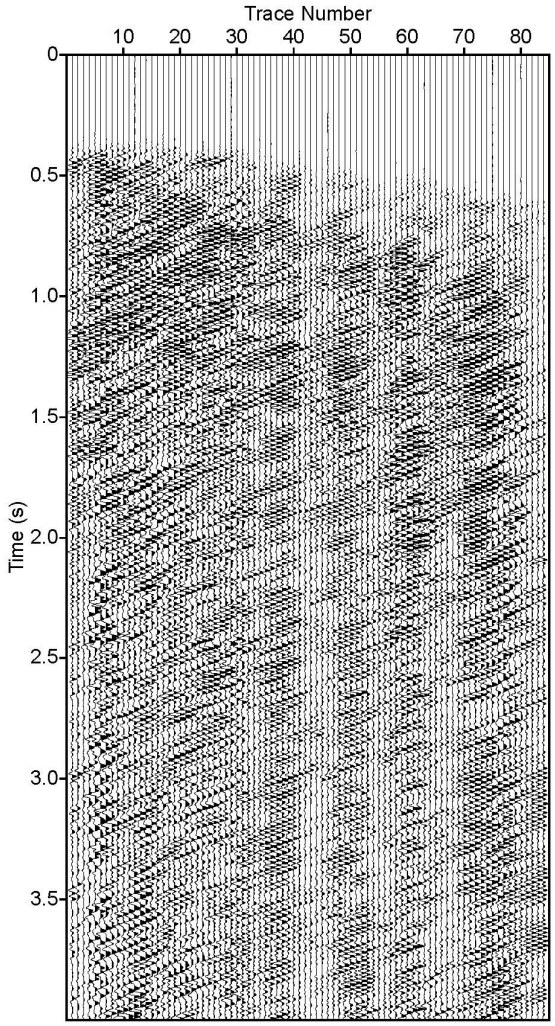
3-C geophone sondes, 15 Hz
30-level receiver array
Locking arm

Technical Accomplishments and Progress

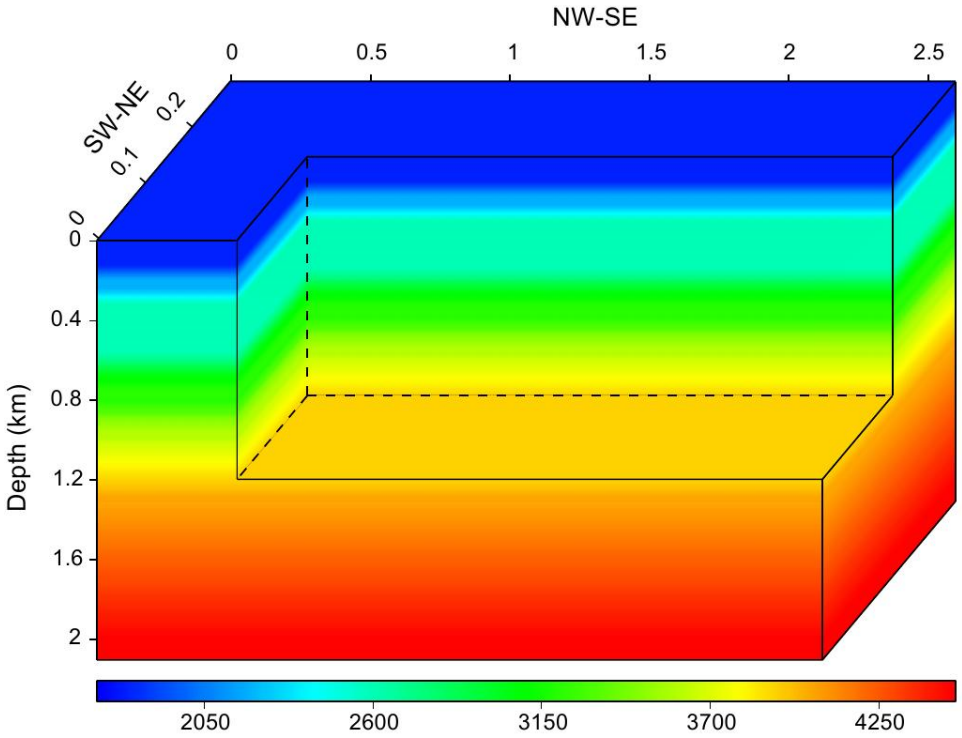




Processed VSP data



Initial Velocity Model



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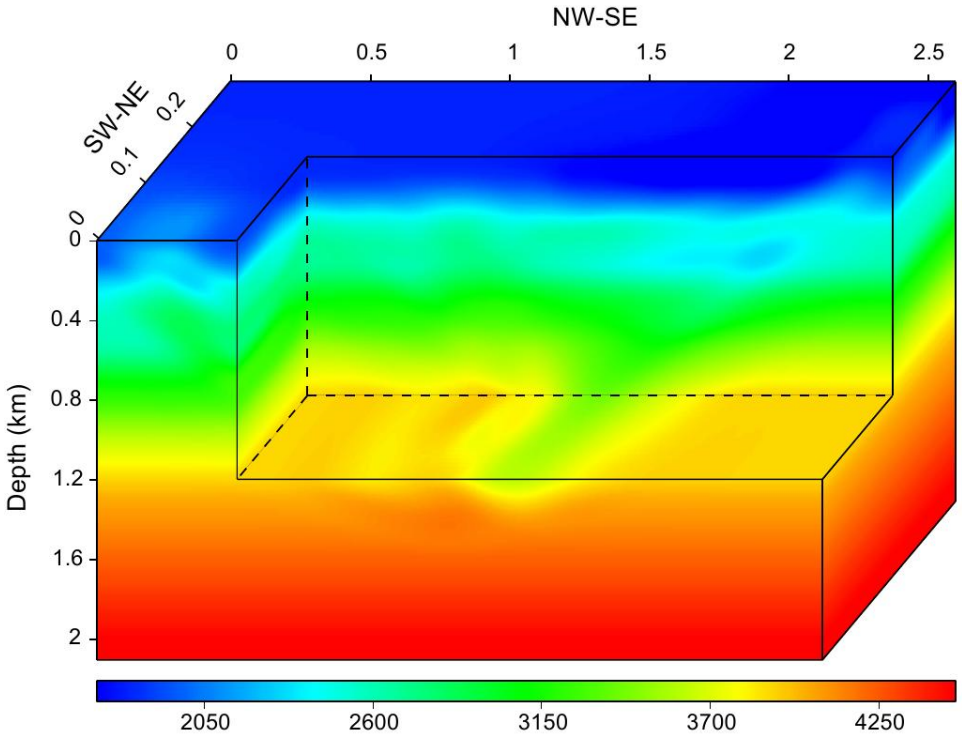
Full-Waveform Inversion



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Research Collaboration and Technology Transfer

- U.S. Geothermal Inc. provided well access for VSP data acquisition at the Raft River EGS site.
- The research teams met/held telecons and shared results.
- Patent Filed with United States Patent Office – Sept. 2017
  - Patent Pending: Moment Tensor Reconstruction based upon elastic-waveform inversion for earthquake source location and source mechanisms

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Future Directions

FY18 will be focused on field data applications.

- Apply newly developed inversion algorithm in the time domain to acquired VSP data.
- Apply newly developed imaging algorithm to acquired VSP data.
- Apply the inversion algorithm in the Fourier domain to acquired VSP data.
- Apply newly developed moment-tensor inversion algorithm to micro-earthquake data.
- Interpret imaging and inversion results of VSP and micro-earthquake data to infer fluid-flow pathways.

Milestone or Go/No-Go	Status & Expected Completion Date
Building velocity model	June 2018
Moment tensor inversion	June 2018
Interpretation of results	June 2018

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Mandatory Summary Slide

- LANL's new migration imaging algorithm can properly handle sparse seismic data.
- LANL's new multi-scale inversion algorithm can improve the velocity inversion accuracy.
- LBNL's full-waveform inversion algorithm can recover all moment-tensor components (focal mechanism) of micro-earthquake data.
- We have successfully acquired and processed VSP data from the Raft River EGS site.
- Our preliminary full-waveform inversion of the VSP data shows promising.

Mandatory- keep to one slide