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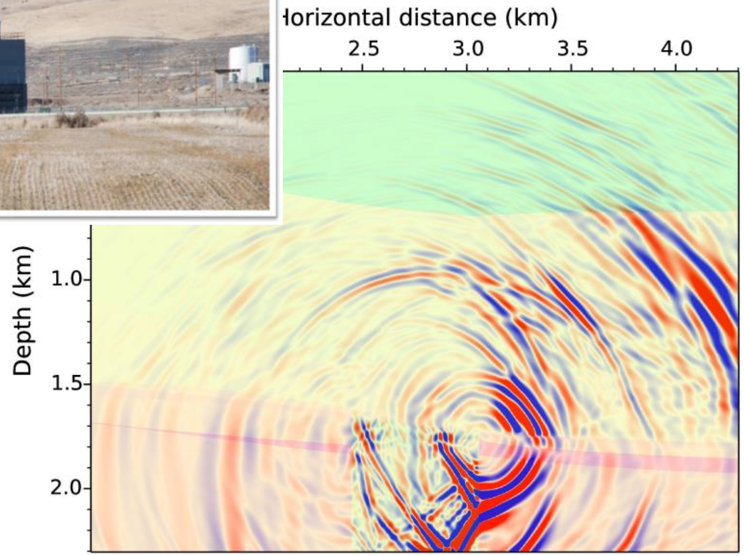

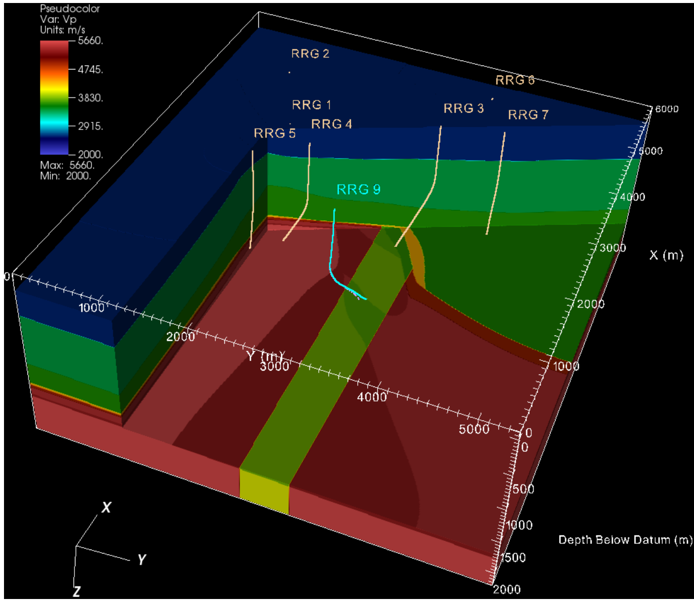

Joint Active and Passive Seismic Imaging of EGS Reservoirs

Project Officers: Sean Porse, Lauren Boyd

Total Project Funding: $3M

May 11, 2015

Lianjie Huang

Los Alamos National Laboratory

Track 4: EGS2

Relevance/Impact of Research

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- One of the major challenges to EGS development is the ability to map and characterize fluid pathways.
- Knowledge gaps: Recent investigations have shown that these pathways frequently do not show a clear relationship to microseismic activity. Information on the distribution and characteristics of the fluid pathways is required to optimize the targeting of production and injection wells and develop large-scale EGS reservoirs.
- The primary goal of this project is to develop new techniques using active seismic (VSP and/or surface seismic) and passive seismic data for high-precision mapping of fluid pathways.

Relevance/Impact of Research

- The technical challenges addressed include:
  - Obtaining improved 3D velocity models from sparse seismic data;
  - Obtaining accurate source mechanisms of MEQs using elastic-waveform inversion in the Fourier domain; and
  - Imaging fracture zones using sparse seismic data.
- 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: The successful completion of this research will improve our capability to reveal MEQ source mechanisms and characterize fluid-flow pathways in EGS reservoirs.

Scientific/Technical Approach

- To improve subsurface velocity modeling building, we will
  - develop an ambient noise tomography algorithm to obtain low-resolution velocity models. (on-going)
  - develop and validate an elastic-waveform inversion algorithm in the time domain using the compressive sensing technique. (on-going)
  - refine and validate a 3D elastic-waveform inversion algorithm in the Fourier domain. (on-going)
  - use synthetic surface seismic and VSP data to validate the algorithms. (on-going)
- To obtain accurate source mechanisms of MEQs, we will
  - develop and validate a 3D elastic-waveform inversion algorithm in the Fourier domain for moment tensor inversion.

Scientific/Technical Approach

- To characterize fracture zones, we will
  - develop and validate an anisotropic elastic-waveform inversion algorithm. (on-going)
- 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.

Year 1 work is to develop and validate algorithms for velocity inversion.

- We have obtained several months of continuously recorded seismic data from the Raft River EGS demonstration site, and initiated cross-correlation of ambient noise data recorded at different geophone stations. We will use these data for ambient noise tomography to obtain a low-resolution velocity model at the field.
- We have developed an elastic-waveform inversion algorithm using a compressive sensing technique for improving velocity inversion using sparse seismic data, and implemented and tested the algorithm for the 2D case.
- We have developed an optimized staggered-grid finite-difference modeling algorithm on rotated coordinates for simulating elastic-wave propagation in 2D anisotropic media. This provides an essential tool for seismic inversion and imaging in fractured media.

Year 1 work is to develop and validate algorithms for velocity inversion.

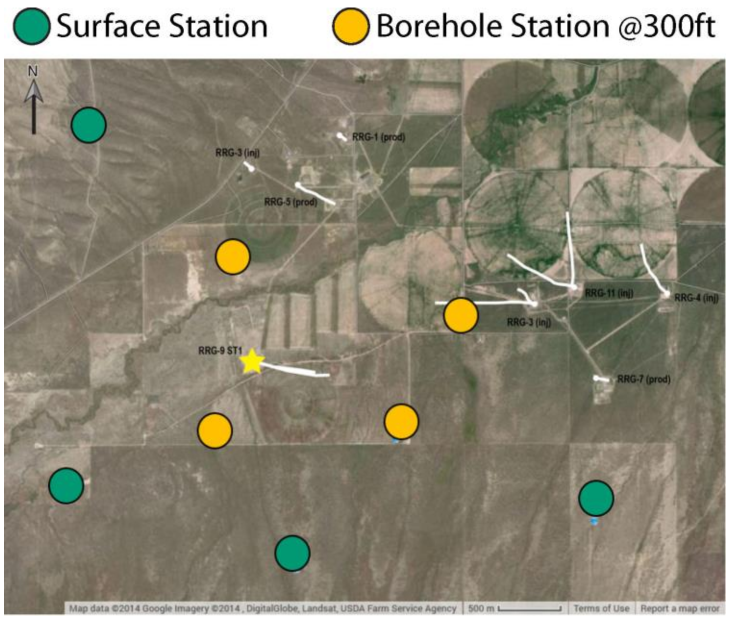
- We have developed an anisotropic elastic-waveform inversion algorithm for seismic inversion in fracture zones, and implemented the algorithm for the 2D case.
- We have implemented an elastic-waveform inversion algorithm in the Fourier domain for the 3D case, and tested the algorithm using synthetic seismic data.
- We have built a 3D isotropic geophysical model of Raft River EGS site using a geological model developed from well log interpretation. This model includes a fracture zone characterized by low isotropic seismic velocities. This model will be used to validate the velocity inversion.
- We presented two papers at 2015 Stanford Geothermal Workshop and submitted one paper to 2015 SEG Annual Meeting.

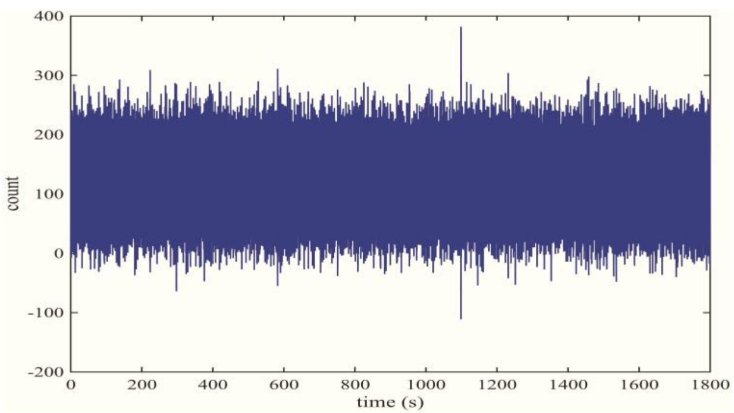
- **Challenges to Date:** The main challenges for our study of Raft River are the low noise levels in the ambient noise data, limited number of surface and borehole geophones (4 each), and the lack of information on the orientations of the borehole geophones. We are analyzing the ambient noise data in different frequency bands, double-checking the timing of the data, and rotating the noise data using some MEQ data as references.

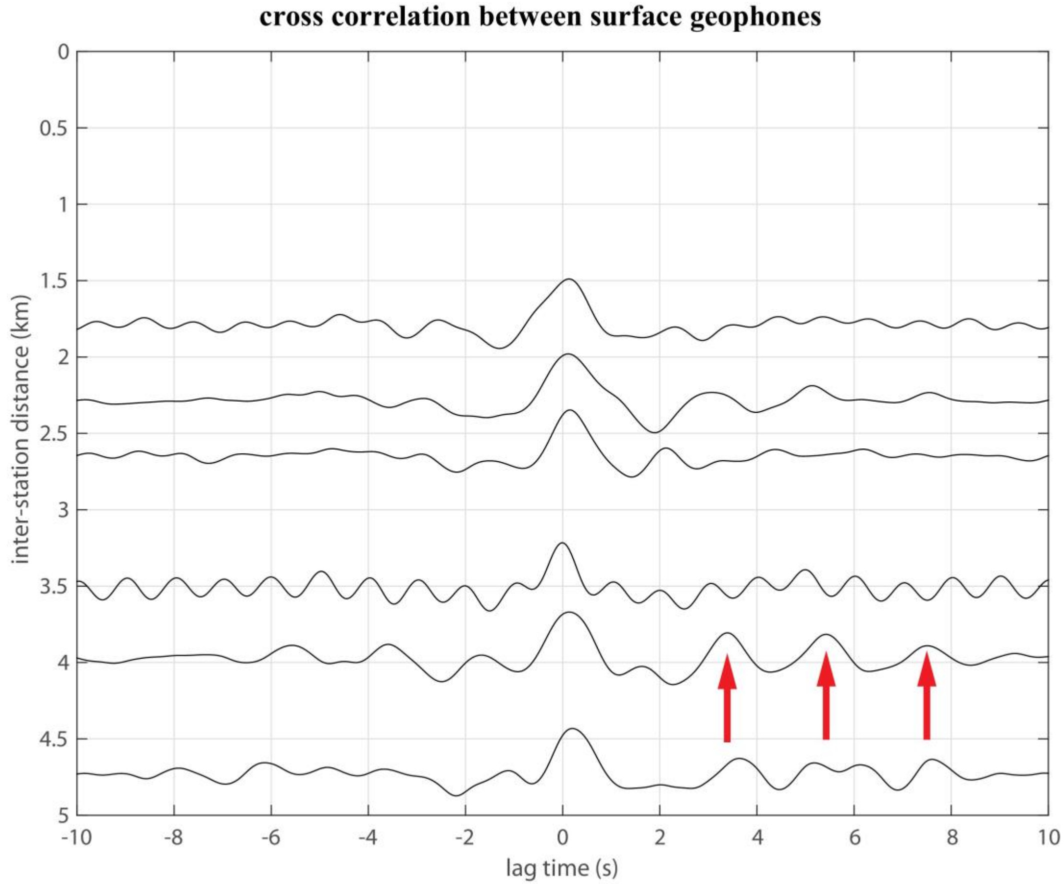
For Year 1:

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date to be Completed
Develop and validate ambient noise tomography method for velocity inversion	Same milestone/on-going	09/30/2015
Develop and validate elastic-waveform inversion in the time domain using a compressive sensing technique	Same milestone/on-going	09/30/2015
Refine and validate elastic-waveform inversion in the Fourier domain for 3D VSP inversion	Same milestone/on-going	09/30/2015
Build 3D geophysical models for the Raft River EGS site for validating velocity inversion	Same milestone/on-going	09/30/2015

Ambient noise data analysis

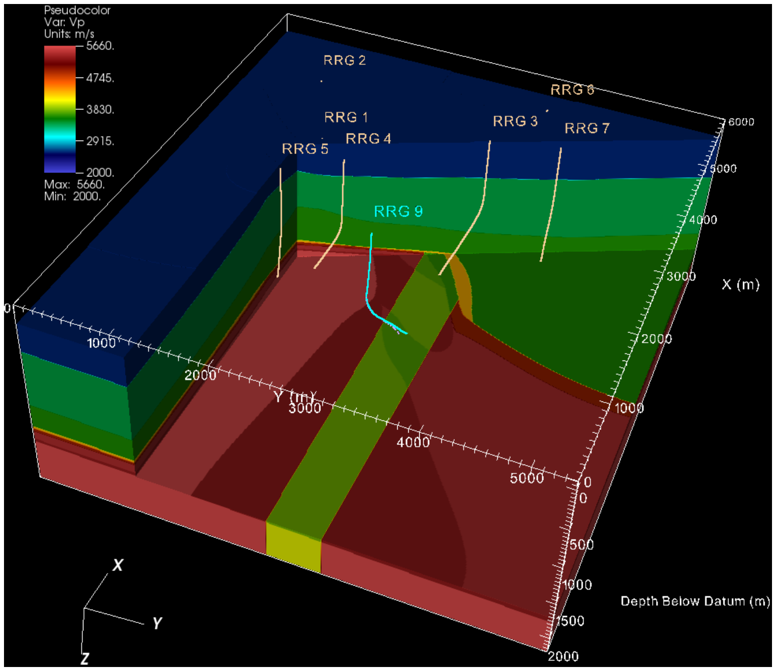


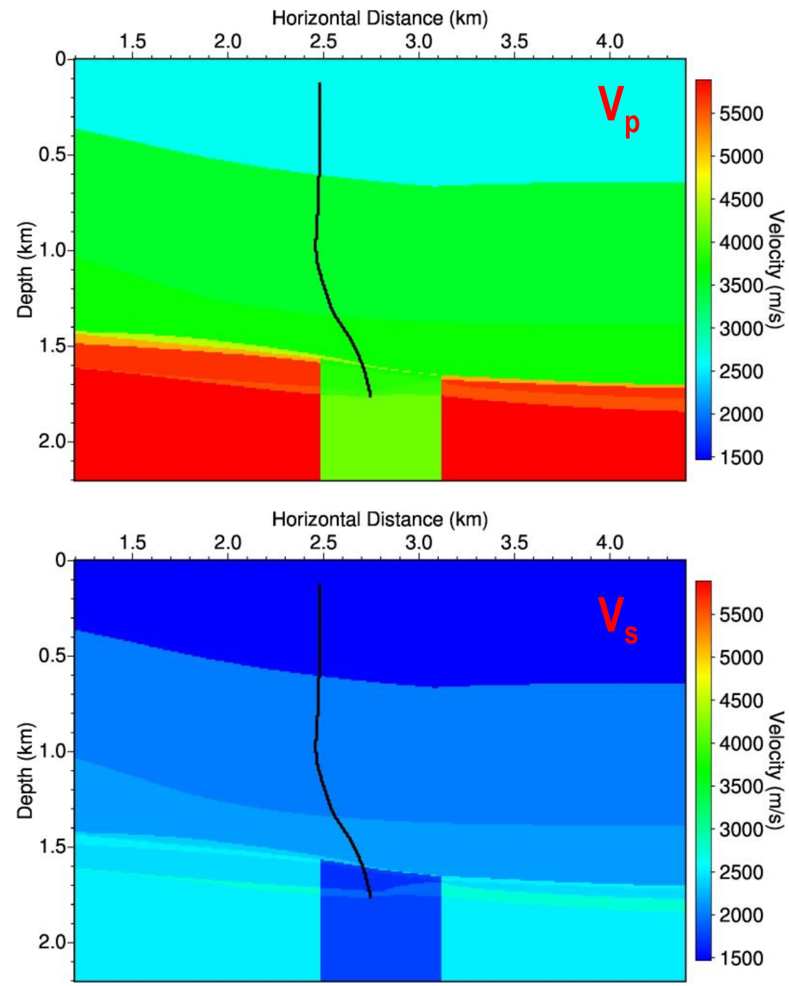




Frequency band: 0-1 Hz

Build 3D geophysical model of Raft River EGS site

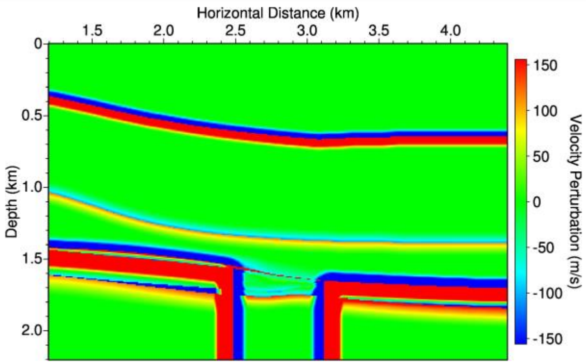




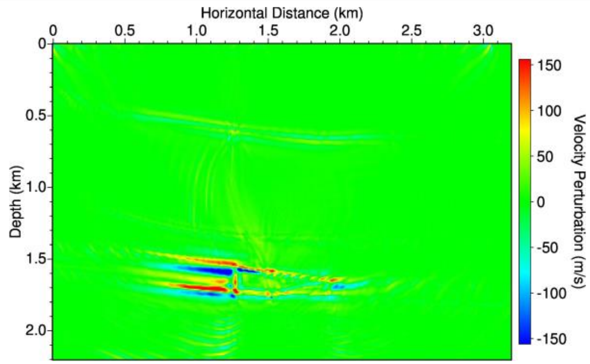
- Built a 3D isotropic geophysical model using a geological model developed from well log interpretation.
- The model contains a fracture zone characterized by low isotropic seismic velocities.

Develop elastic-waveform inversion method with compressive sensing

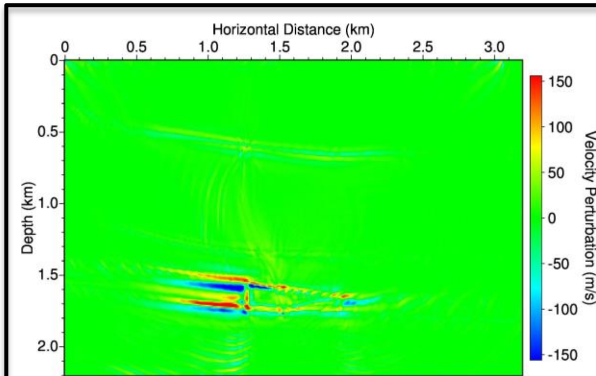
Inversion of synthetic VSP data for 200 shots and 207 receivers



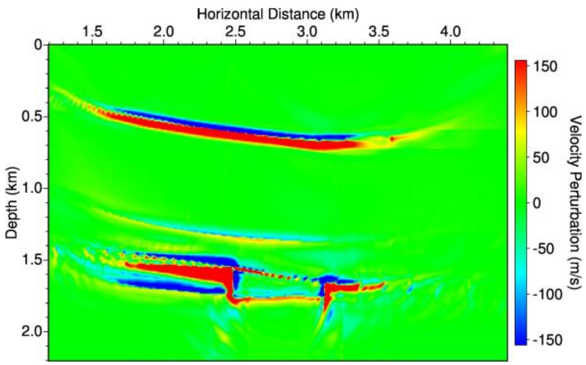
V_p^0-V_p



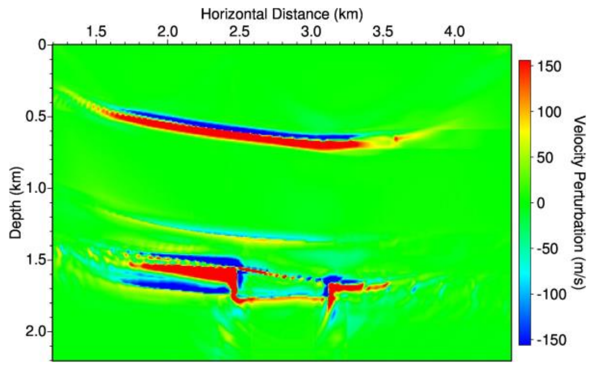
V_p^{EWI}-V_p with 20 shots



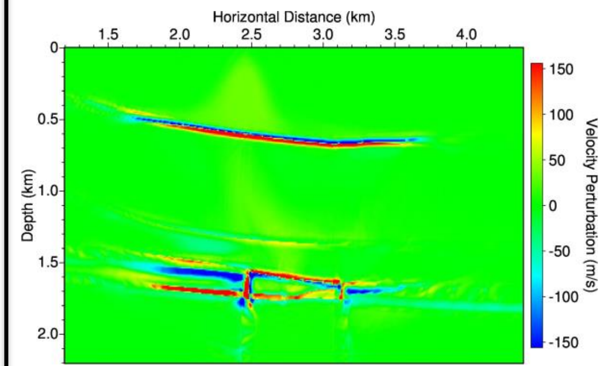
V_s^{EWI}-V_s with 20 shots



V_p^{EWI}-V_p with 200 shots



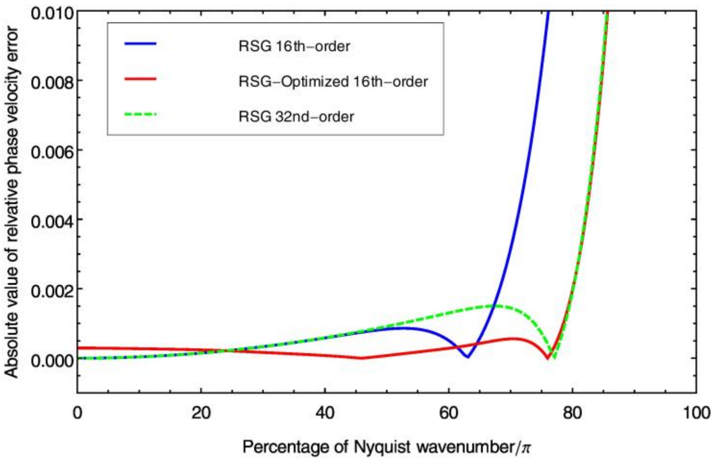
$V_p^{EWI\text{-}CS}$-V_p with 20 shots

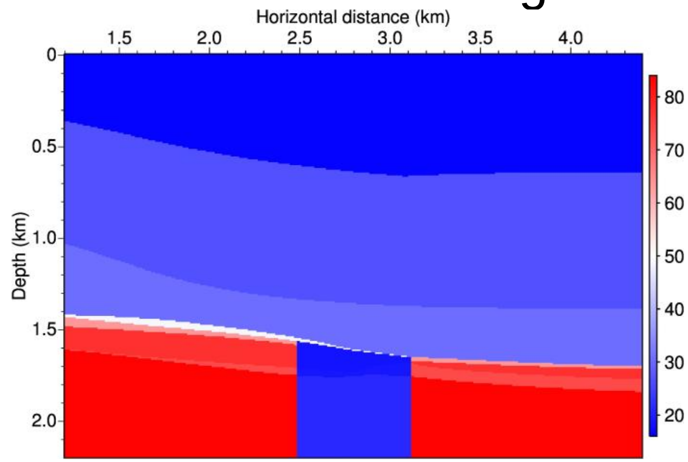


$V_s^{EWI\text{-}CS}$-V_s with 20 shots

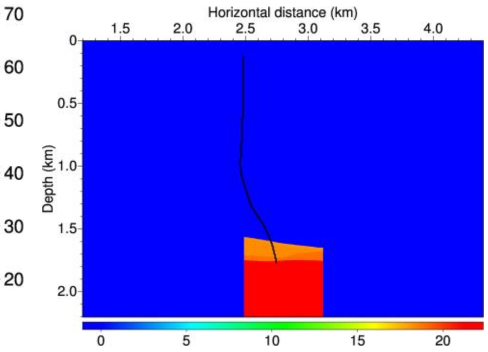
Develop an anisotropic elastic-wave modeling method

- Optimized staggered-grid finite-difference modeling in rotated coordinates

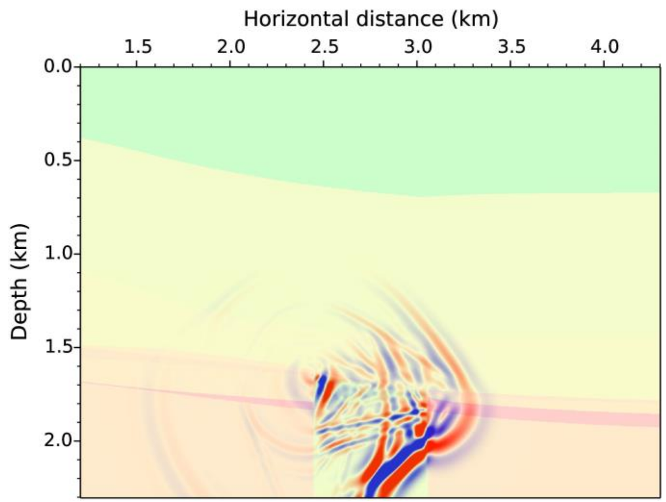


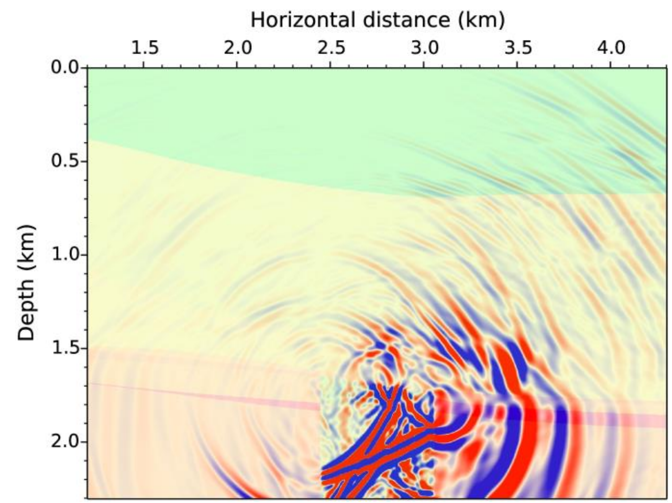


Vertical narrow zone contains vertical fractures.



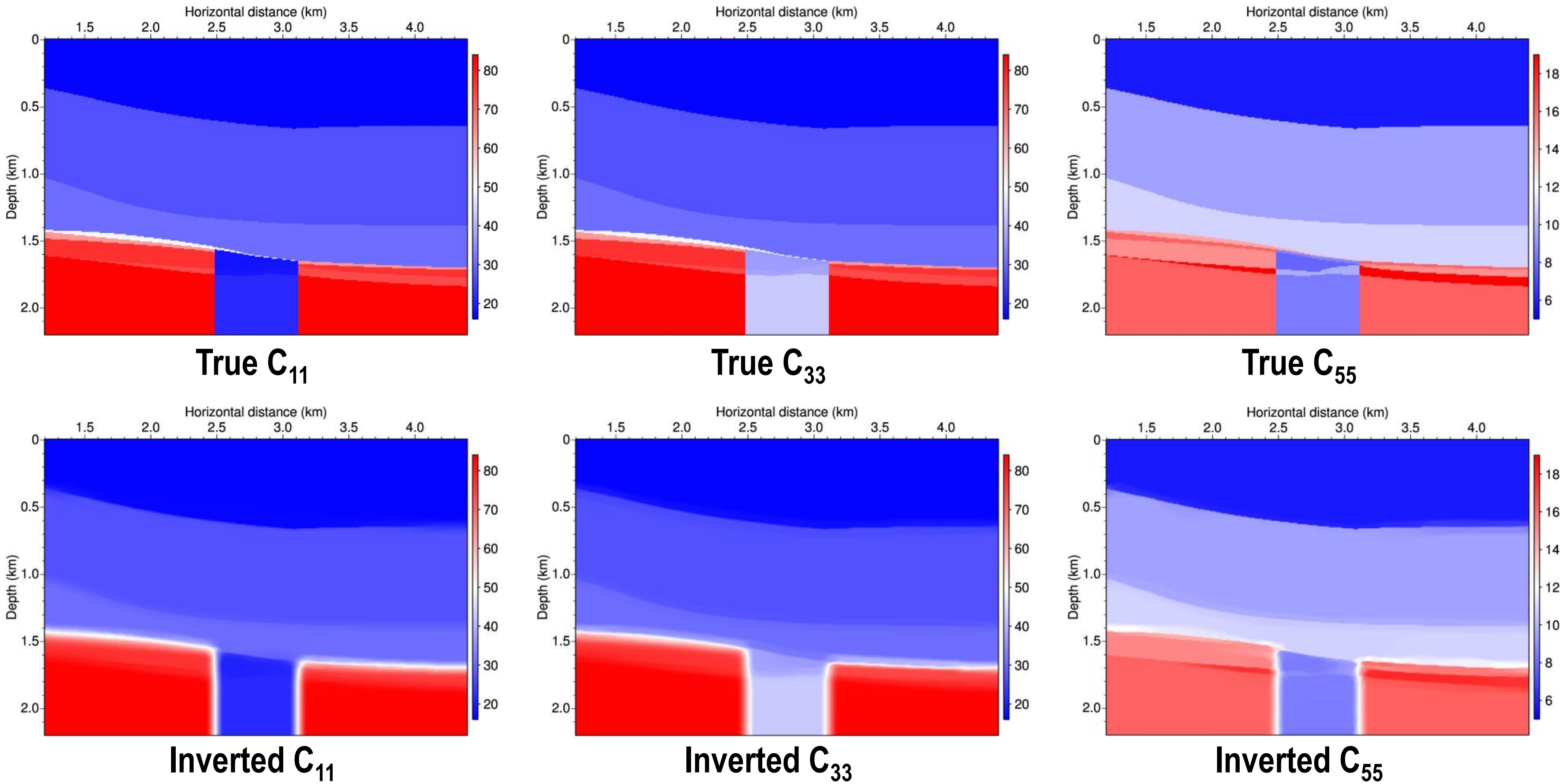
Snapshots of wavefield differences resulting from isotropic and anisotropic vertical narrow zones.





Develop a new anisotropic elastic-waveform inversion method

Inversion of synthetic surface seismic data for 192 shots and 192 receivers

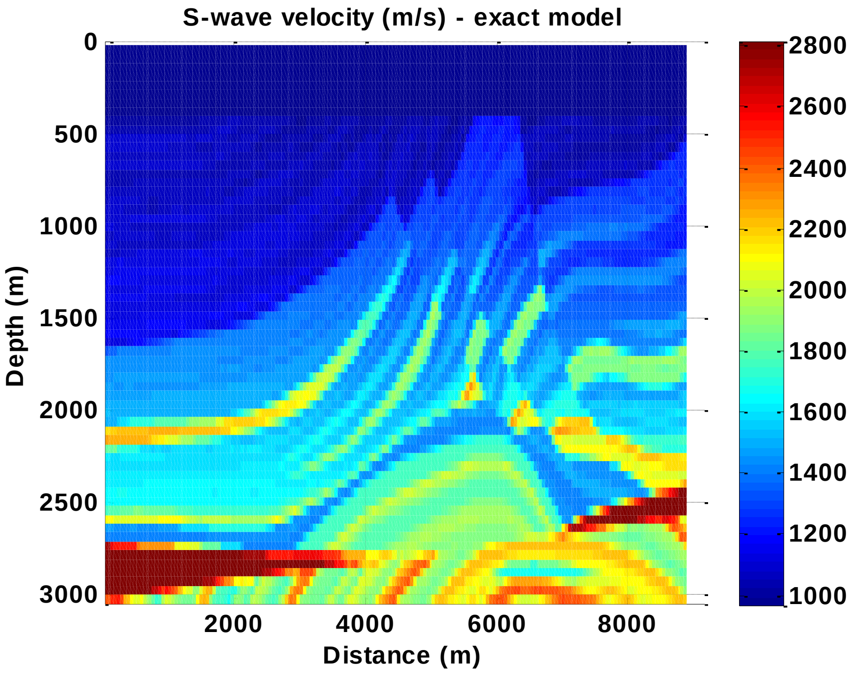


True C_{11} True C_{33} True C_{55}

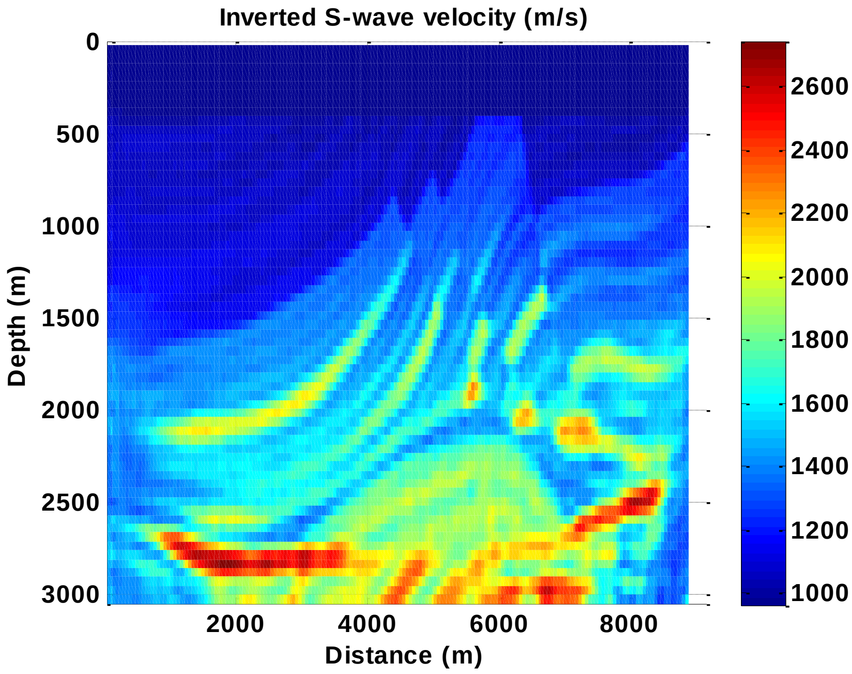
Inverted C_{11} Inverted C_{33} Inverted C_{55}

Develop 3D elastic-waveform inversion method in the Laplace-Fourier domain

- Develop a new inversion algorithm/work flow for inverting full-waveform seismic data.
- Is testing the algorithm using synthetic data from 3D geophysical model of Raft River EGS site.



Marmousi Model



Inversion Result

Future Directions

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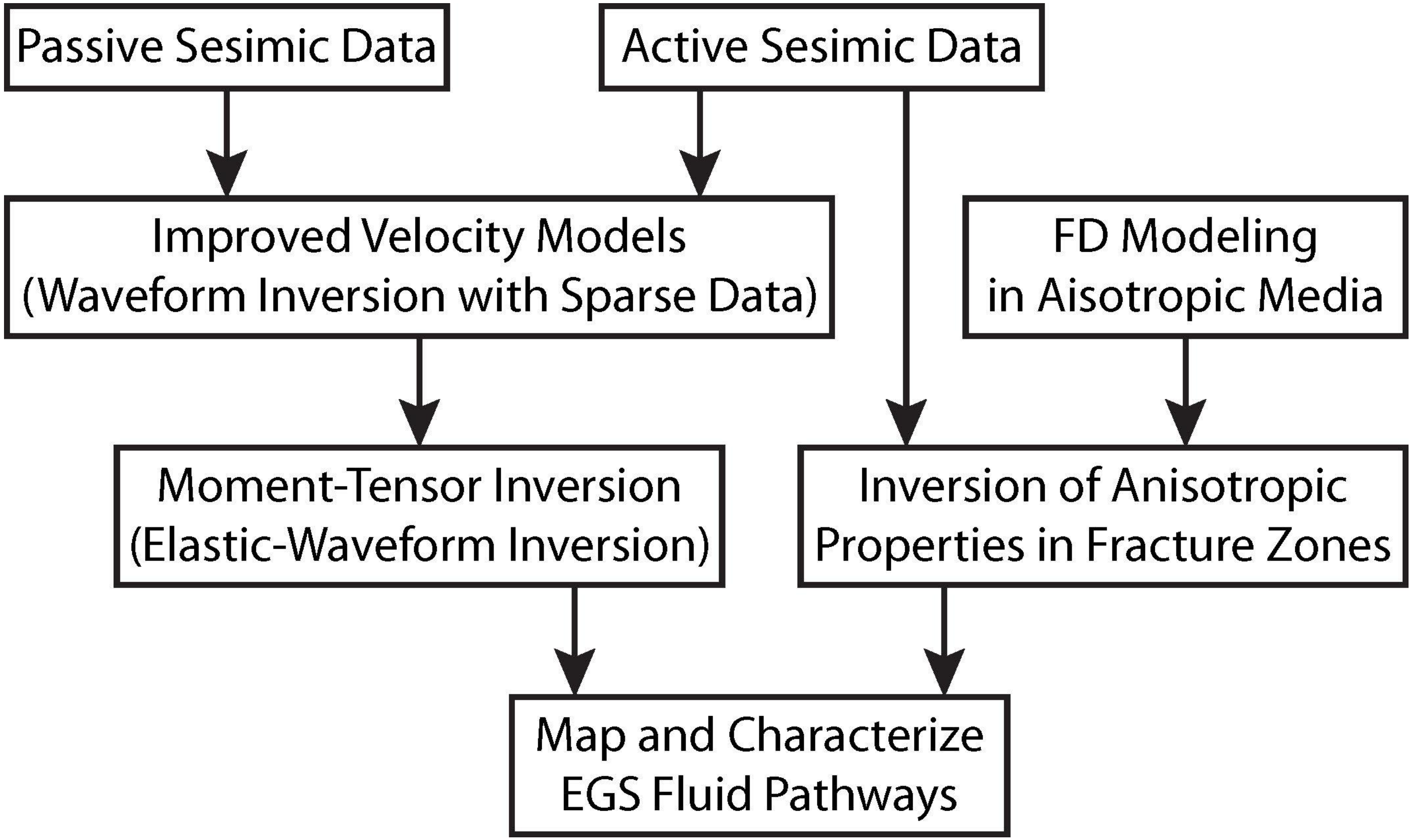
- Future plans for Year 1: Improve subsurface velocity model building
  - Continue analysis of the ambient noise data.
  - Extend the 2D isotropic and anisotropic elastic-waveform inversion algorithms in the time domain to the 3D case, and validate the algorithms using synthetic data.
  - Continue validating the 3D elastic-waveform inversion algorithm in the Laplace-Fourier domain using the 3D geophysical model of the Raft River EGS demonstration site.
  - Extend the 3D geophysical model of the Raft River EGS site by including anisotropic seismic velocity parameters to characterize oriented fractures in the fractured zone.
- Future plan for Year 2: Obtain accurate source mechanisms of MEQs and acquire 3D VSP data.
- Future plan for Year 3: Field data applications

Milestone or Go/No-Go	Status & Expected Completion Date
Develop and validate new elastic-waveform inversion algorithms	Expect to meet milestones by 09/30/2015 (Go/No-Go decision point)
Develop and validate elastic moment-tensor inversion algorithm; Acquire 3D VSP data.	Expect to meet milestones by 09/30/2016 (Go/No-Go decision point)
Verify field data applicability	Expect to meet milestones by 09/30/2017

Mandatory Summary Slide

- The ambient noise data from the Raft River EGS site shows that the field is fairly quiet and the noise is weak.
- Our 2D elastic-waveform inversion algorithm in the time domain with a compressive sensing technique can produce accurate velocity models using sparse seismic data.
- Our optimized, time-domain staggered-grid finite-difference algorithm on rotated coordinates in 2D provides an essential tool for seismic inversion and imaging in anisotropic, fractured EGS reservoirs.
- Our 2D anisotropic elastic-waveform inversion algorithm in the time domain provides a useful tool for characterizing fracture zones.
- Our 3D elastic-waveform inversion in the Fourier domain shows encouraging results for velocity images near a VSP well.
- We have built a 3D isotropic elastic model of Raft River EGS site using well logs and geologic information from the site.

Additional Information



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