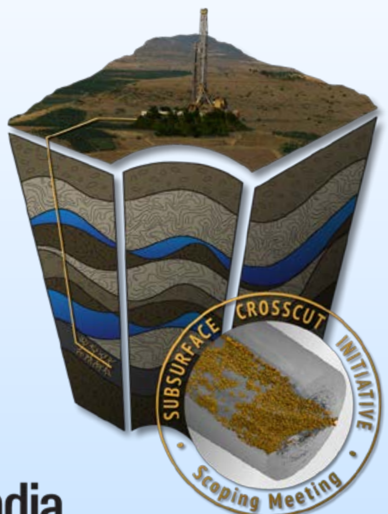
Imaging Fracture Networks Using Joint Seismic and Electrical Change Detection Techniques

Hunter A. Knox

Sandia National Laboratories



U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 16-18, 2016

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Subsurface Technology and Engineering Research (SubTER), Development and Demonstration

U.S. Department of Energy (DOE) SubTER

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- https://twitter.com/SubTERCrosscut
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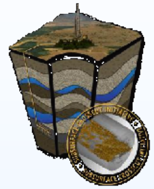

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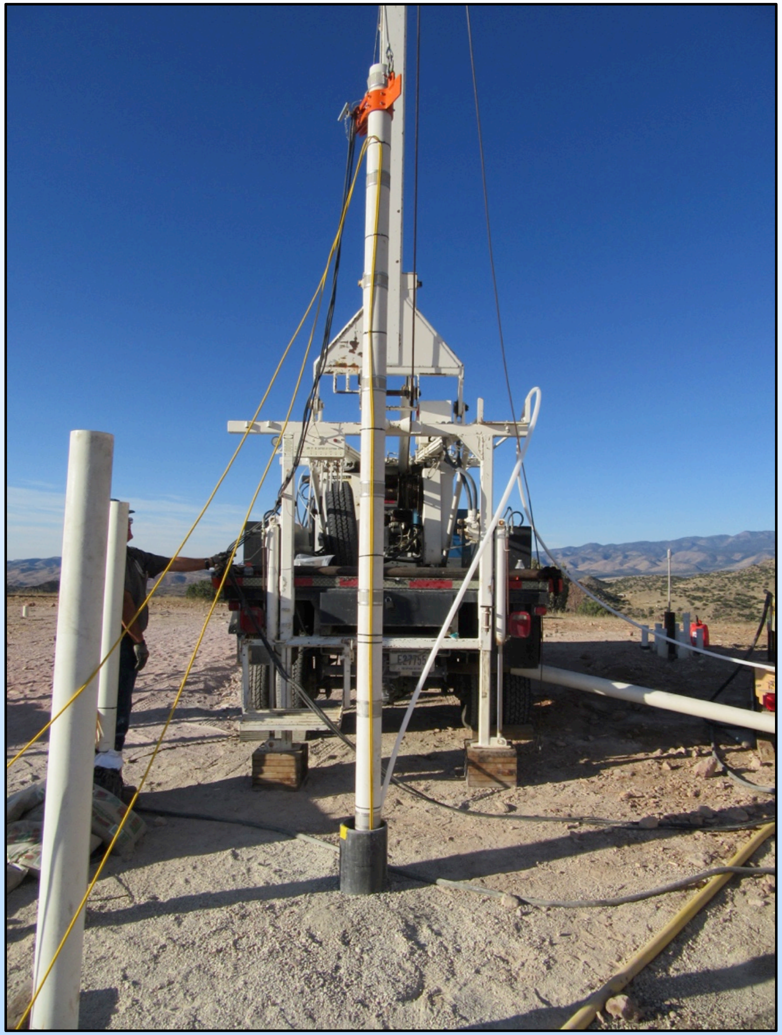
Presentation Outline

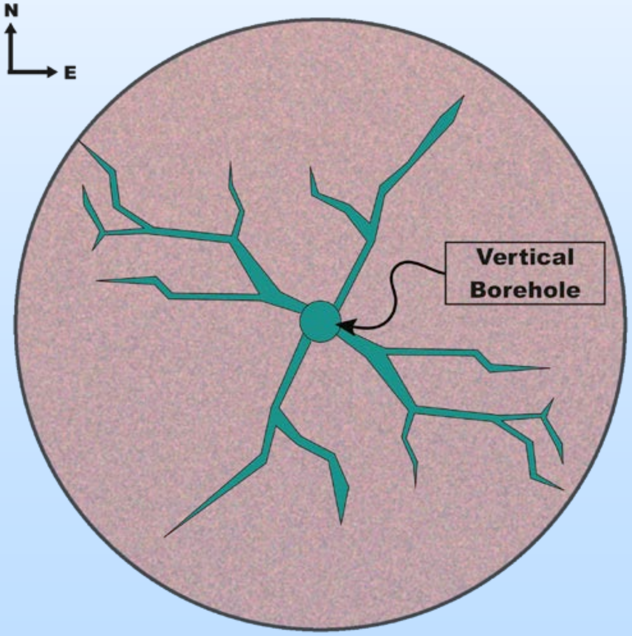
- Benefits to the Program & Project Overview
- Technical Status:
  - Field site
  - Installation
  - Test Plan
  - Video Data
  - Seismic Results
  - Distributed Acoustic Sensing (DAS) Results
  - Constant Pressure Test Results
  - Real-time Electrical Resistance Tomographic (ERT) Results
  - Joint Inversions
  - Inversion For Fracture Conductivity
  - Automatic Picking Results
- Accomplishments to Date
- Synergy Opportunities
- Concluding Remarks
- Questions
- Appendix



Benefit to the Program

Problem Statement:

Real time methods of characterizing fracture networks and monitoring fracture flow are required to provide actionable feedback during stimulation, injection, and extraction operations.



Current Limitations:

1. Data may be insensitive to small-scale fractures that are important to system function.
2. Data collection and processing times limit temporal and spatial imaging resolution.
3. Important fracture attributes (e.g. permeability) are not routinely estimated.

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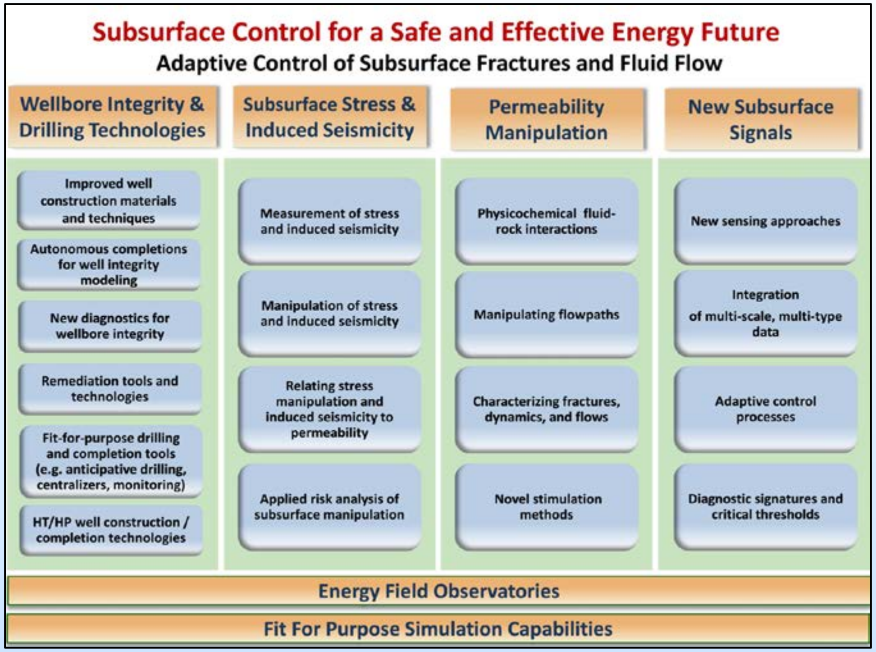
Project Overview:
Goals and Objectives

Demonstrate geophysical imaging technologies that will characterize:

1. 3D extent and distribution of fractures stimulated from two explosive sources
2. 3D fluid transport within the stimulated fracture network through use of a particulate tracer

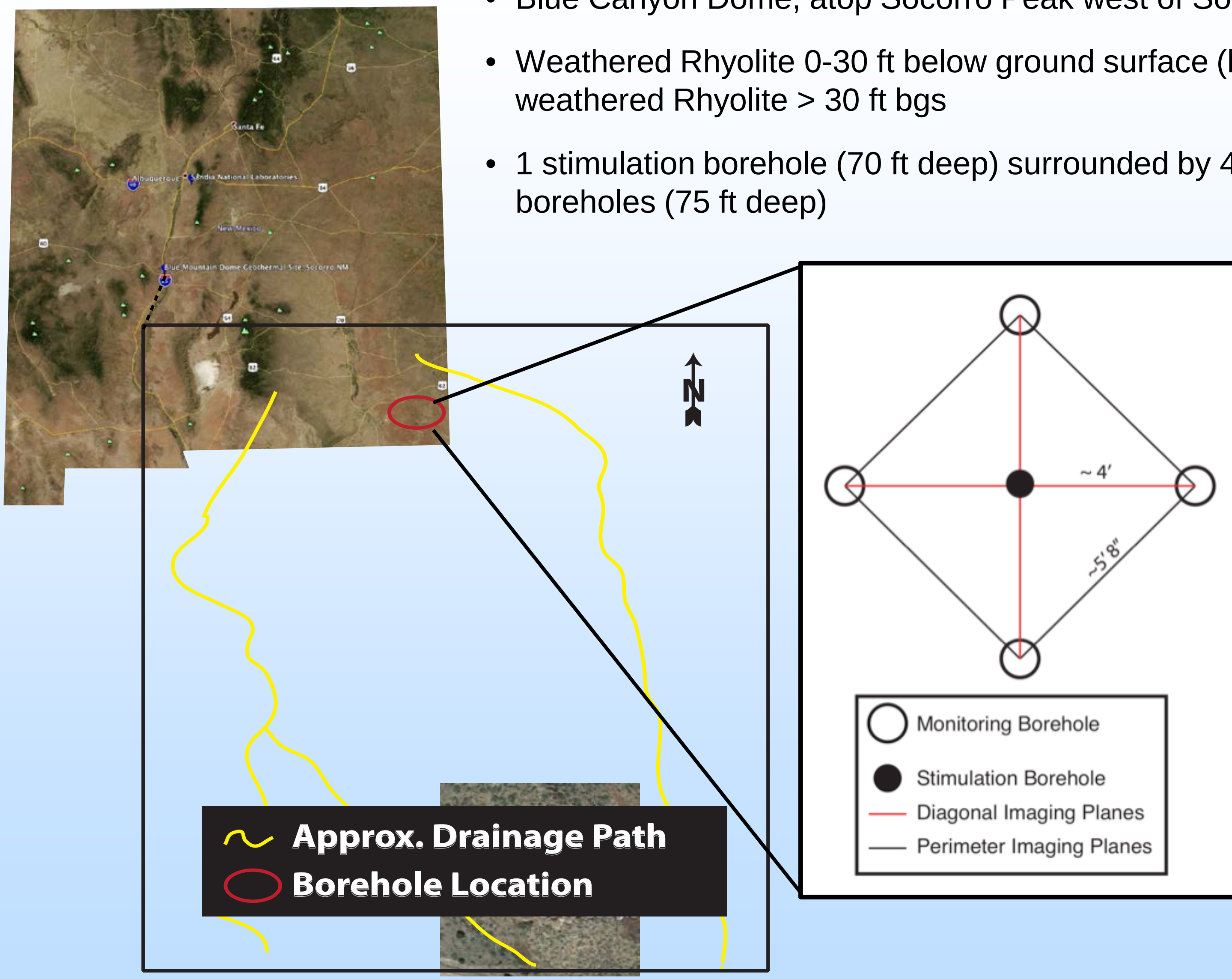


These data will also be used to:

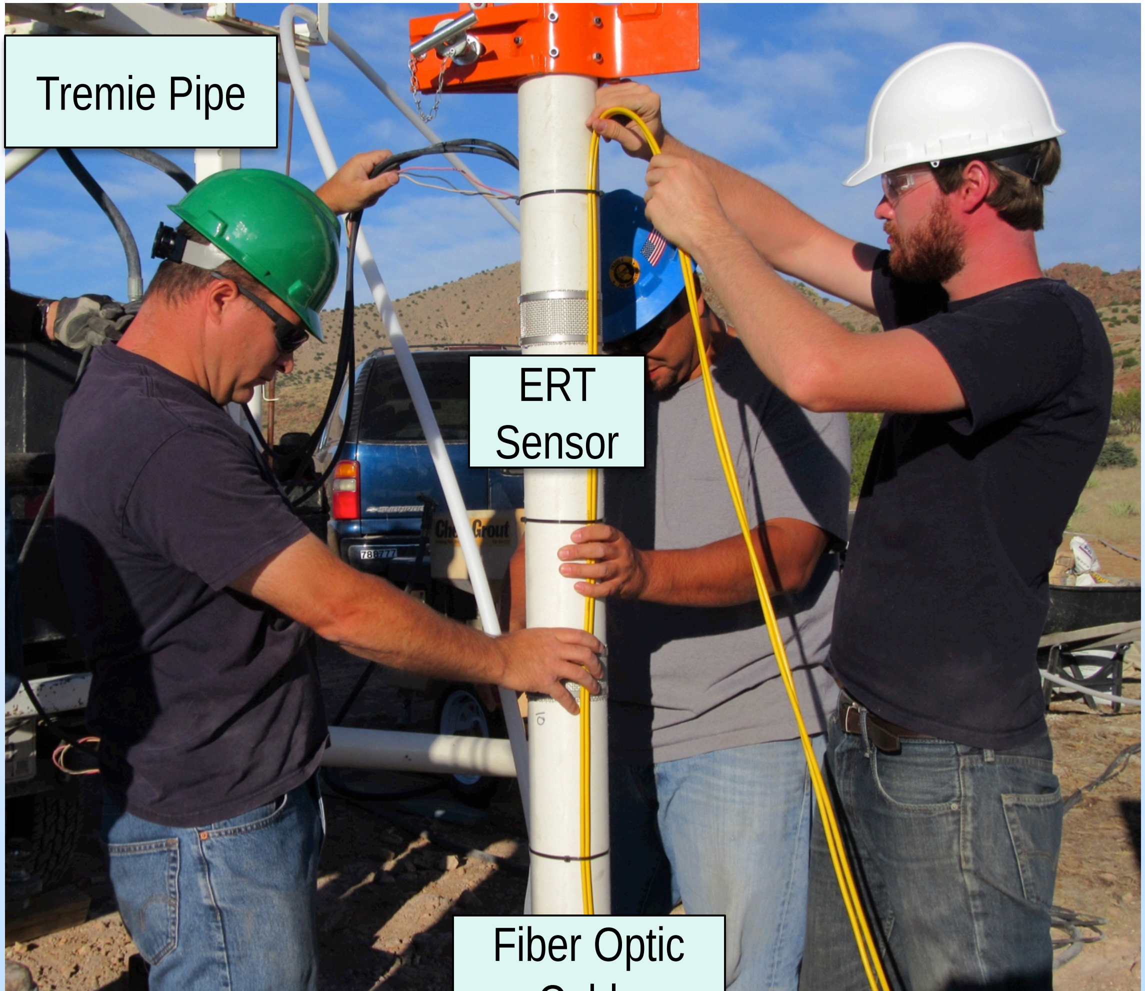
1. Develop methods of estimating fracture attributes from seismic data
2. Develop methods of assimilating disparate and transient data sets to improve fracture network imaging resolution
3. Advance capabilities for near real-time inversion of cross-hole tomographic data

Field Site:

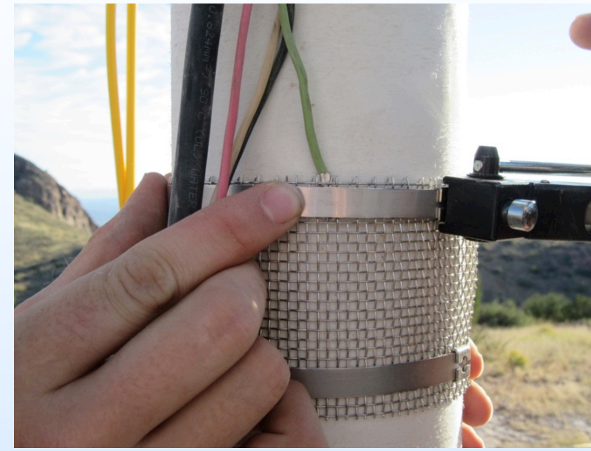
- Blue Canyon Dome, atop Socorro Peak west of Socorro, NM
- Weathered Rhyolite 0-30 ft below ground surface (bgs); Un-weathered Rhyolite > 30 ft bgs
- 1 stimulation borehole (70 ft deep) surrounded by 4 monitoring boreholes (75 ft deep)



Installation - Fall 2015



ERT Installation



Fiber Loop & Deepest ERT Sensor

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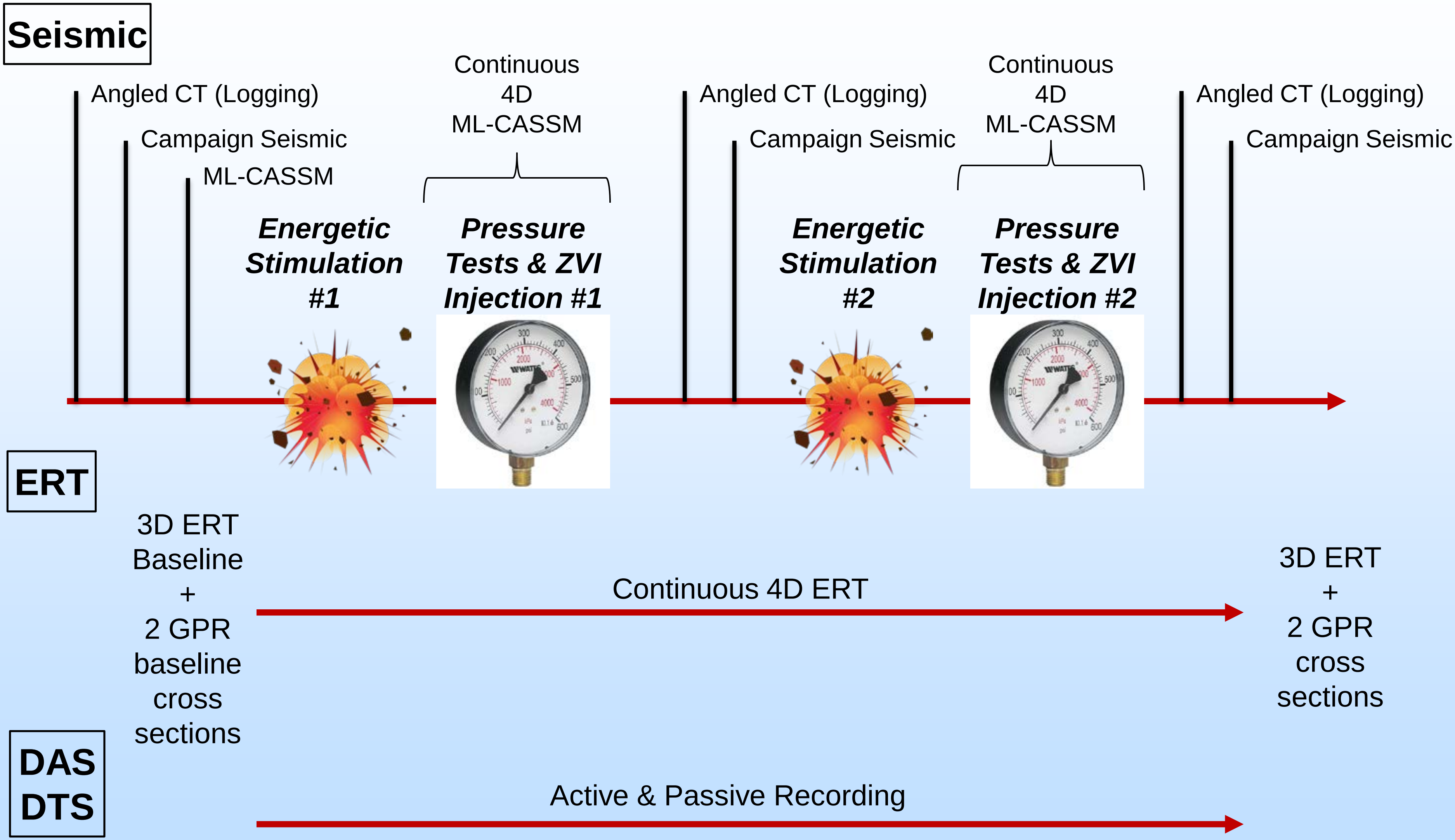
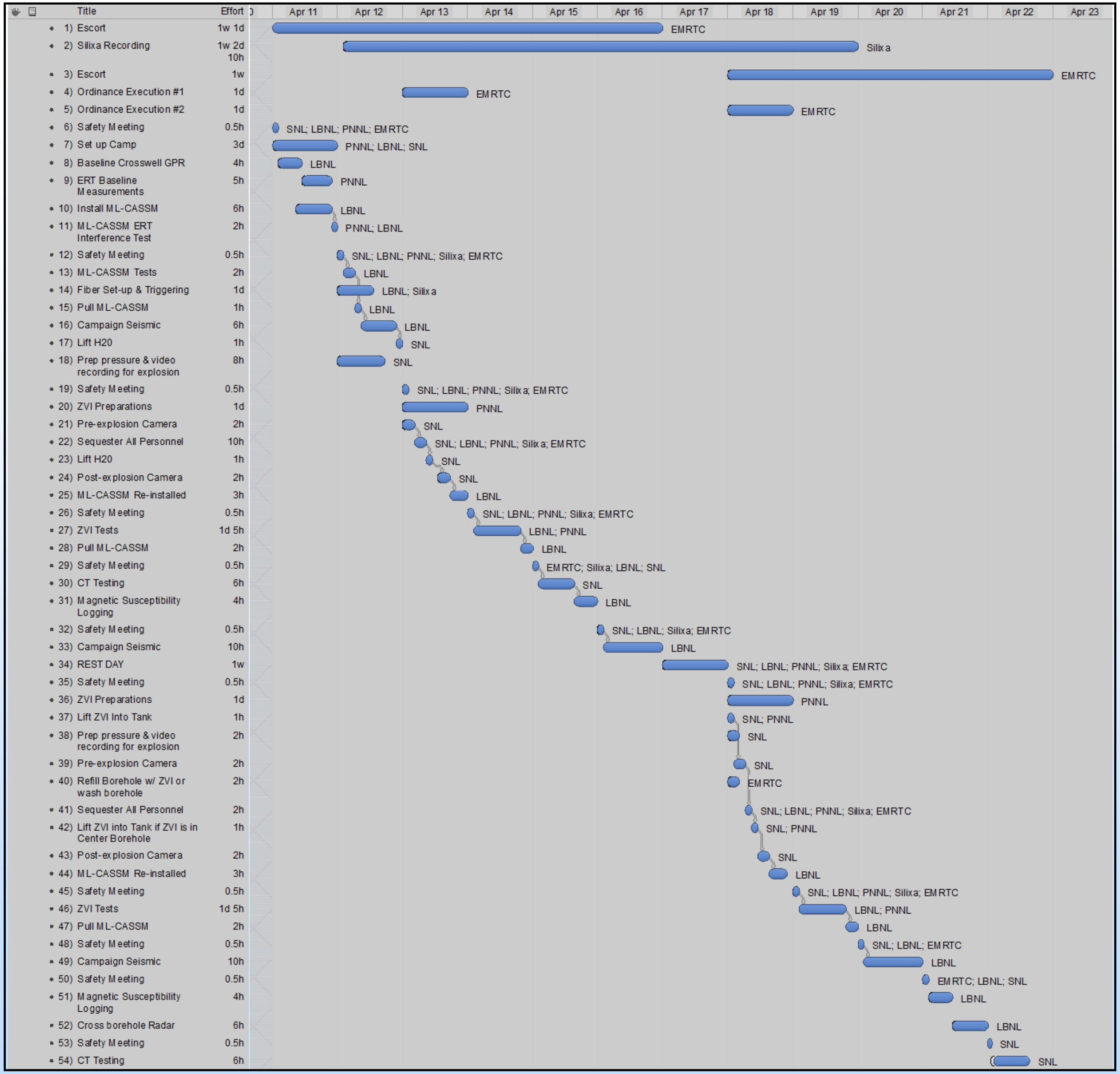
Field Campaign – April 2016



Field Campaign April 2016 Gantt Chart



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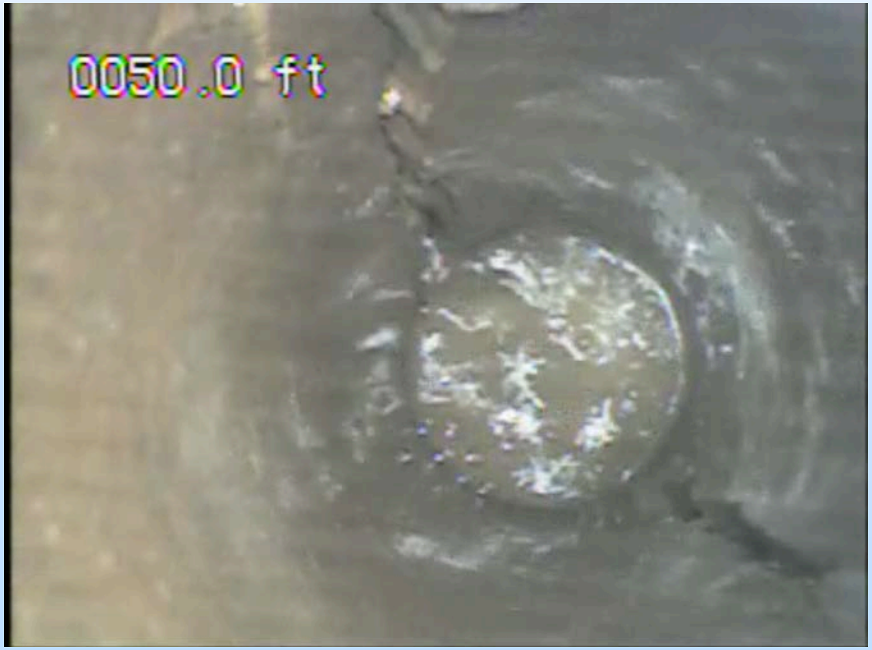
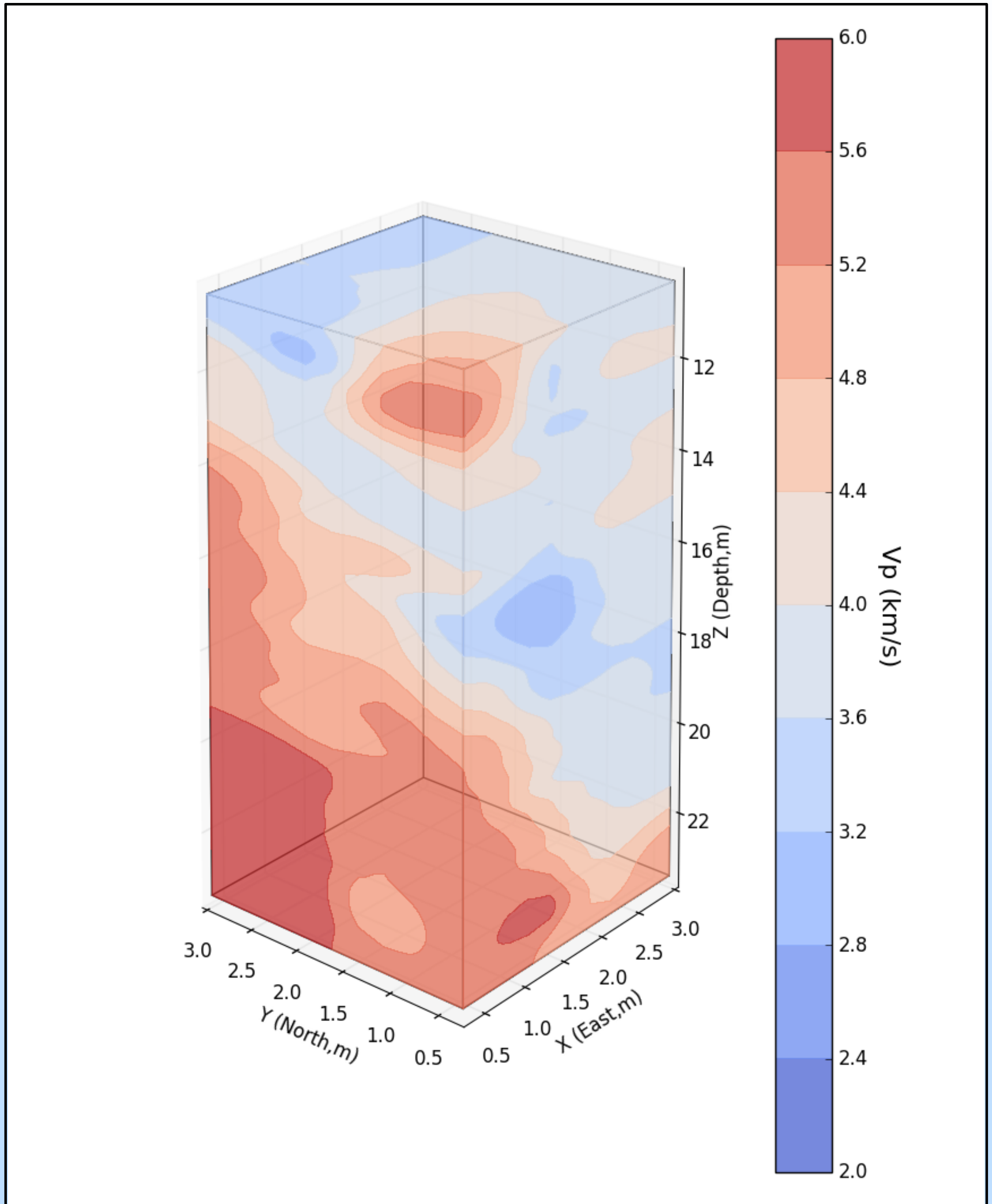
Energetic Stimulation #2



Downhole Camera Footage

- Camera data is from post energetic stimulation #2
- Camera is located 50.0 ft below ground surface (bgs)
- Shot depths in both cases were 58-65 ft bgs
- Two near vertical fractures are visible
- Close examination appears to show that the fractures are self propped
- Along other sections of the borehole, more than 2 fractures were visible

Seismic Tomography



Acquisition

- 9 different vertical source-receiver offsets for each tube pair (0º, 15º, -15º, 30º, -30º, 45º, -45º, 60º, and -60º)
- Acquisition time for each one of these tests is only about 6.5 hours
- 1 week to pick the data and 2 days to perform the inversion.
- Each tomogram is constructed using approximately 25,000 picks over the 8x8x35 foot (2.44x2.44x10.7 m) volume.

Observations

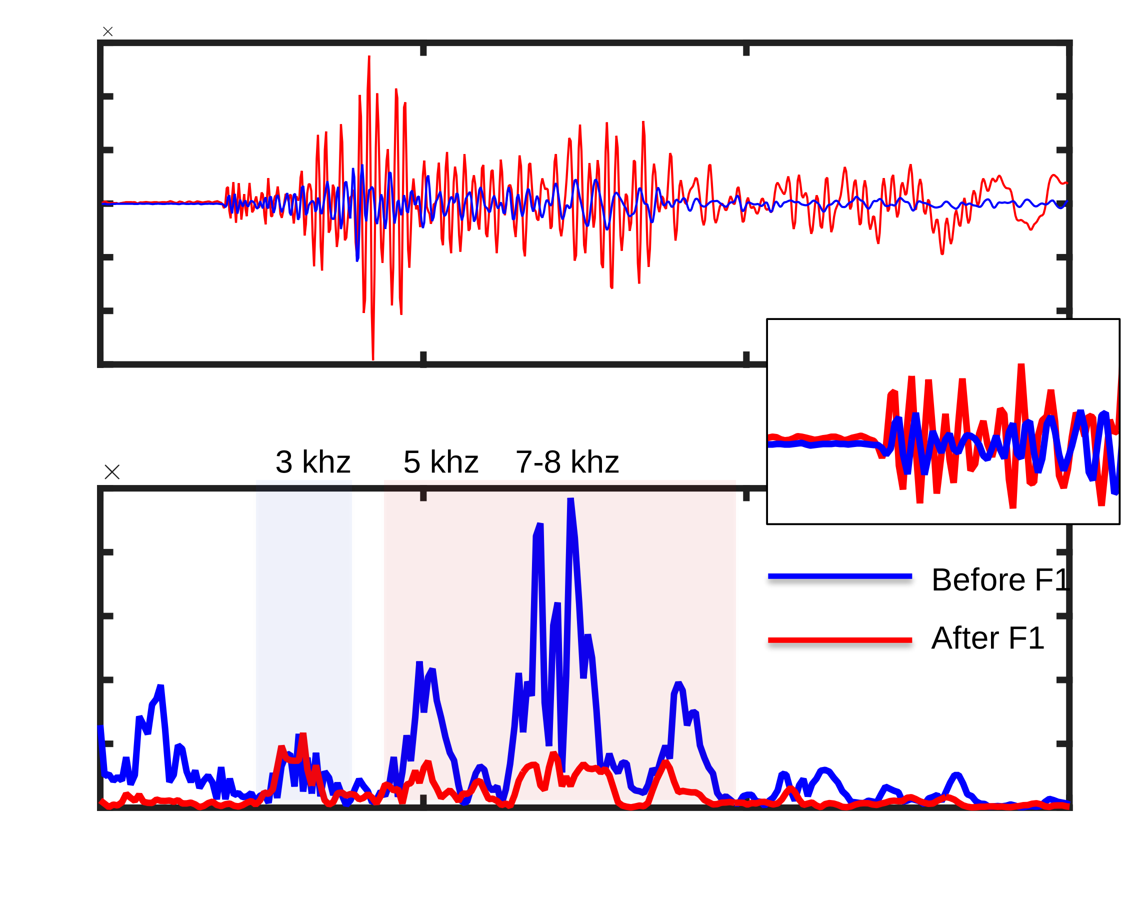
- Big changes in coda
- Coherent (in depth) changes in arrival time
- Initial tomogram (pre-shot) shows similar structure to ERT

ML-CASSM

- ***Goal***: map fracture time evolution & effects of fluid pressure
- Largest ML-CASSM system deployment to date (22 S x 72 R)
- Data recorded before/after fractures + continuously during pump tests & zvi injection
- System active for 1.5 weeks, recorded 55,000 gathers ~ 2000 tomographic datasets
- Challenges included : high wind noise levels, power instability, cable issues

ML-CASSM Data : Fracture Impact

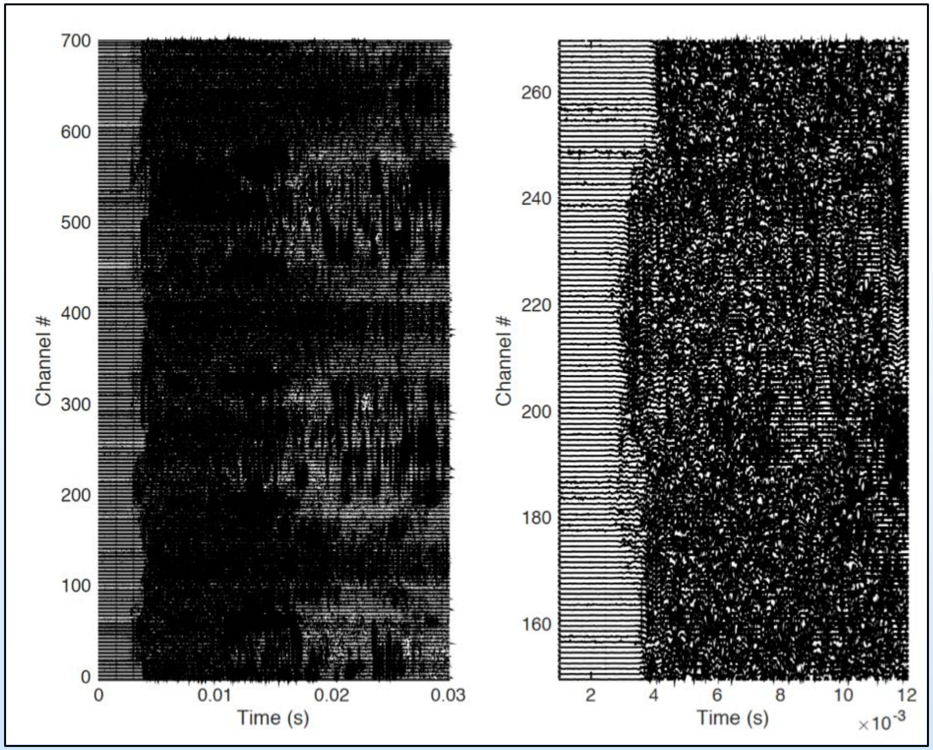
West to North, source at ~21 m

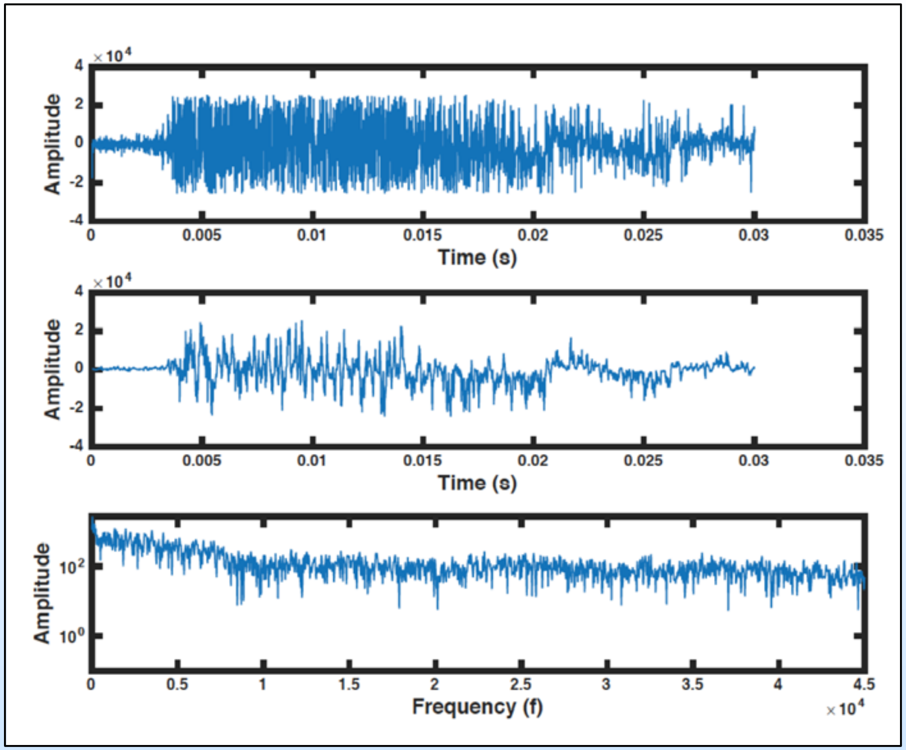


Observations

- Baseline, excellent bandwidth (signal to 10 khz and beyond)
- Fracturing induced significant attenuation change (visible in A & f)
- Higher order resonances of source particularly attenuated.
- Only small change in P-phase (velocity reduction)
- Big changes in coda

Distributed Acoustic Sensing (DAS) – Shot #1 Data Example





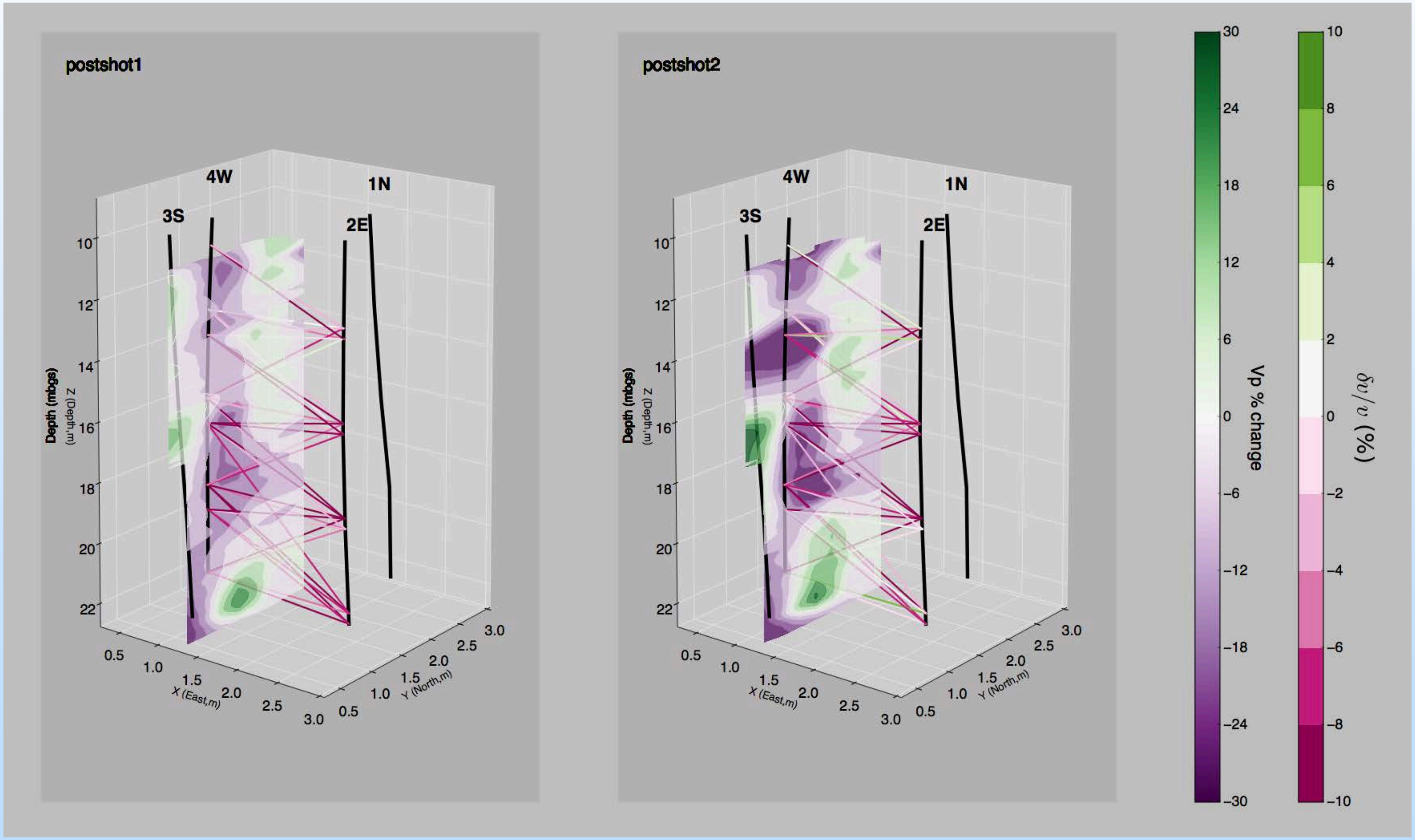
(**Left**) Gather after despiking, bandpass (top end at 50 khz), and trace balancing. Left is a large subset (700 traces) right is a zoom around first break in one of the wells. Data is temporally aliased.

(**Right**) Top: raw trace; Middle: after despiking and filtering; Bottom: amplitude spectrum

DAS - Seismic Interferometry

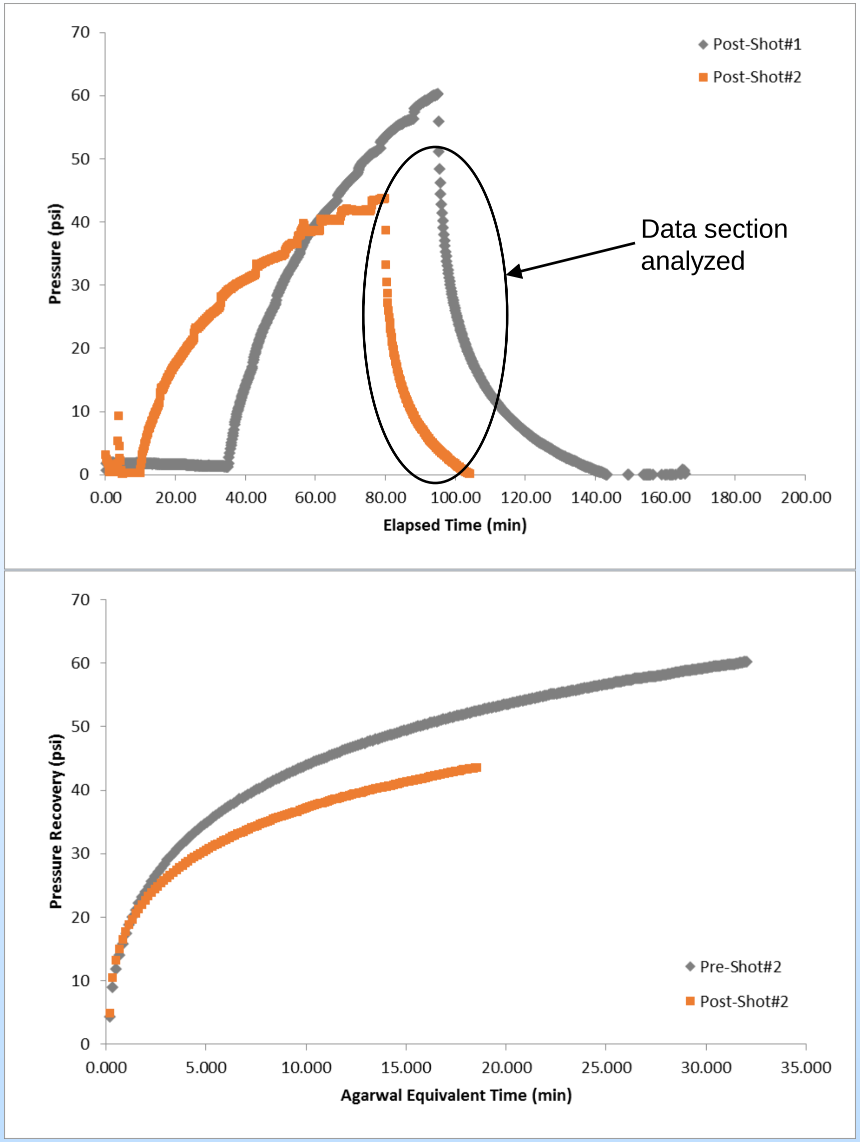
1. Cross-correlate ambient noise recordings between channels
2. Stack to increase signal-to-noise ratio
3. Measure relative velocity variations (dv/v) based on delay in phase arrivals

END GOAL = Detect temporal and spatial changes in seismic velocity



Constant-Rate Injection Testing

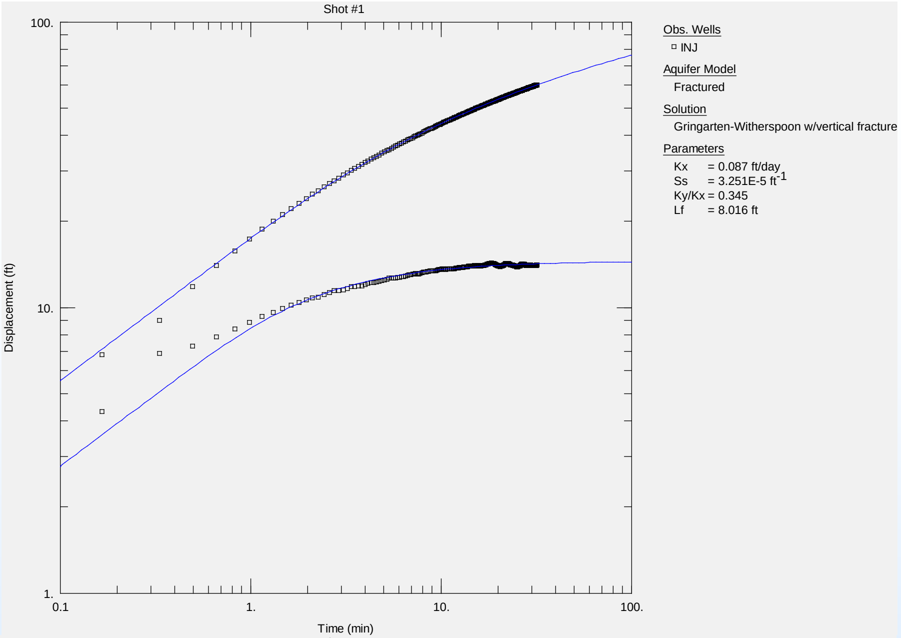
- Analysis of pressure falloff data section for quantitative estimates of hydraulic conductivity (K)
- Comparison of successive tests provides a measure of change in K associated with stimulations
- Agarwal (1980) time transformation applied to allow analysis of pressure falloff response using standard analytical well-function models
- Pressure falloff data fit to a vertical fracture model (Gringarten and Witherspoon, 1972)
- Difference in hydraulic response for three borehole conditions tested was readily apparent

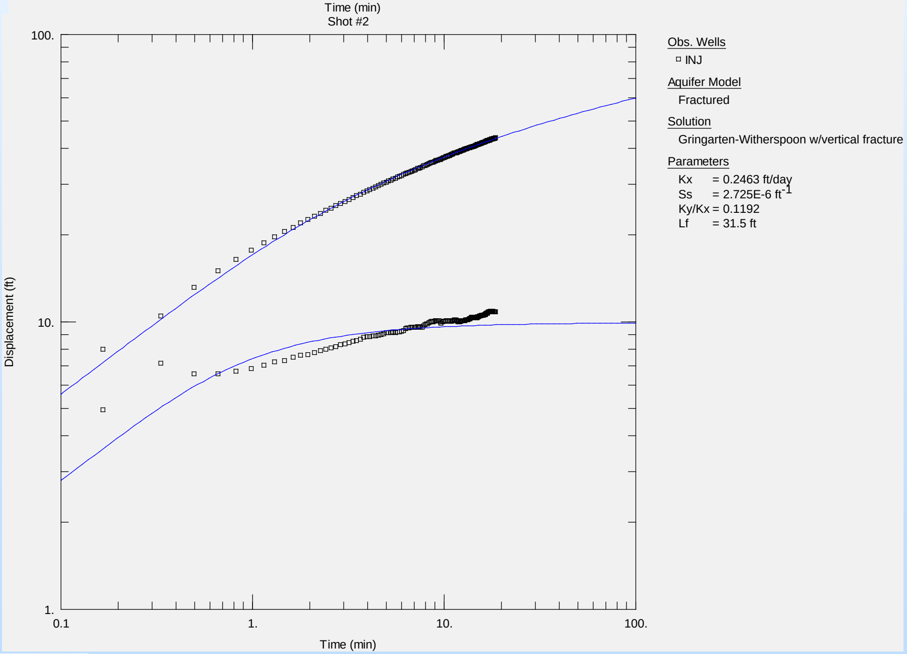


Constant–Rate Injection Test Analysis

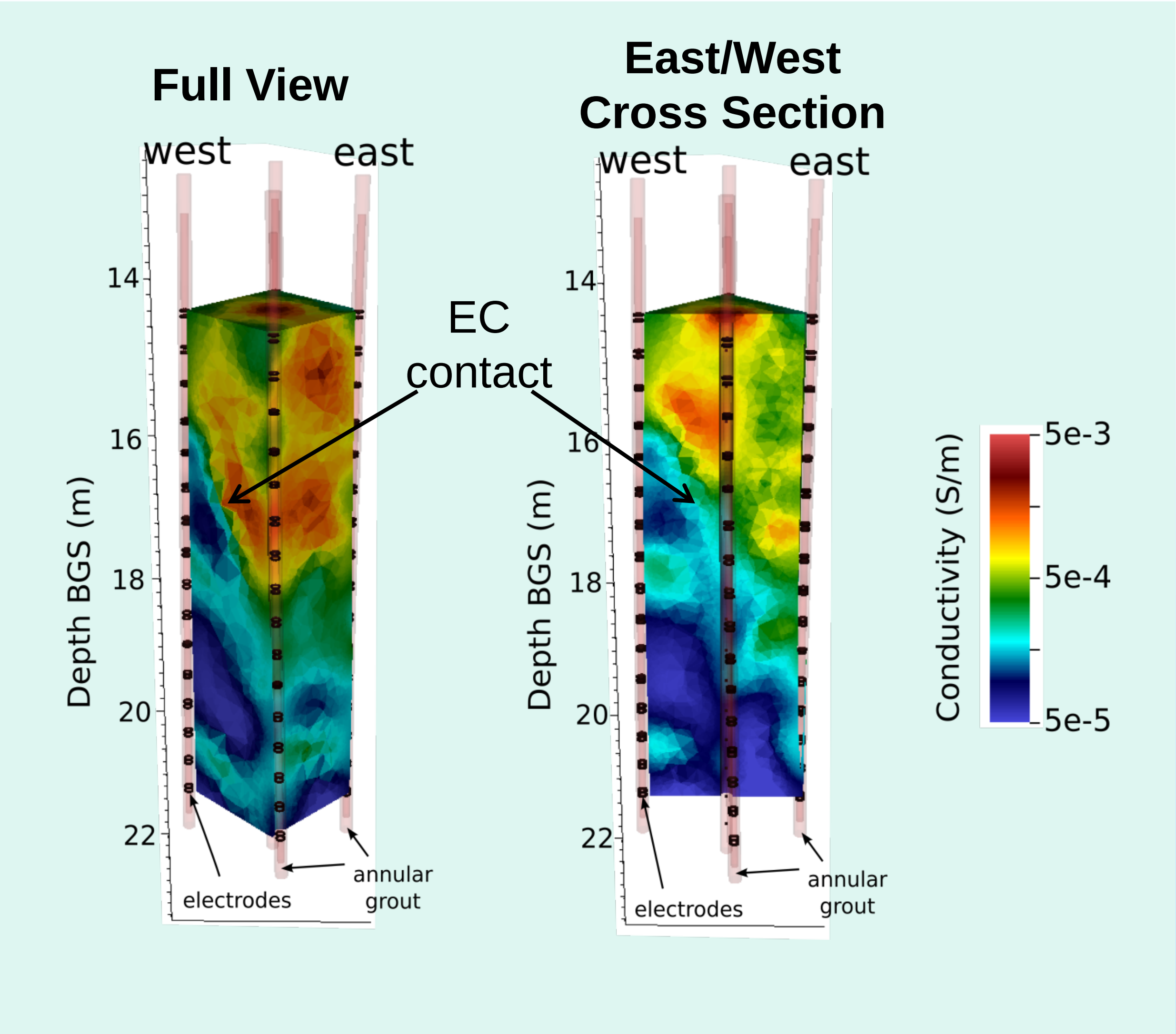
- Fit of pressure and pressure derivative (diagnostic) data to a vertical fracture model

	Hydraulic Conductivity (ft/d)	Permeability (md)
Baseline	7E-5 to 3E-9 (book value range)	2E-2 to 1E-6 (book value range)
Post-Shot #1	0.087	32
Post-Shot #2	0.25	92





Pre-fracture Baseline ERT Image



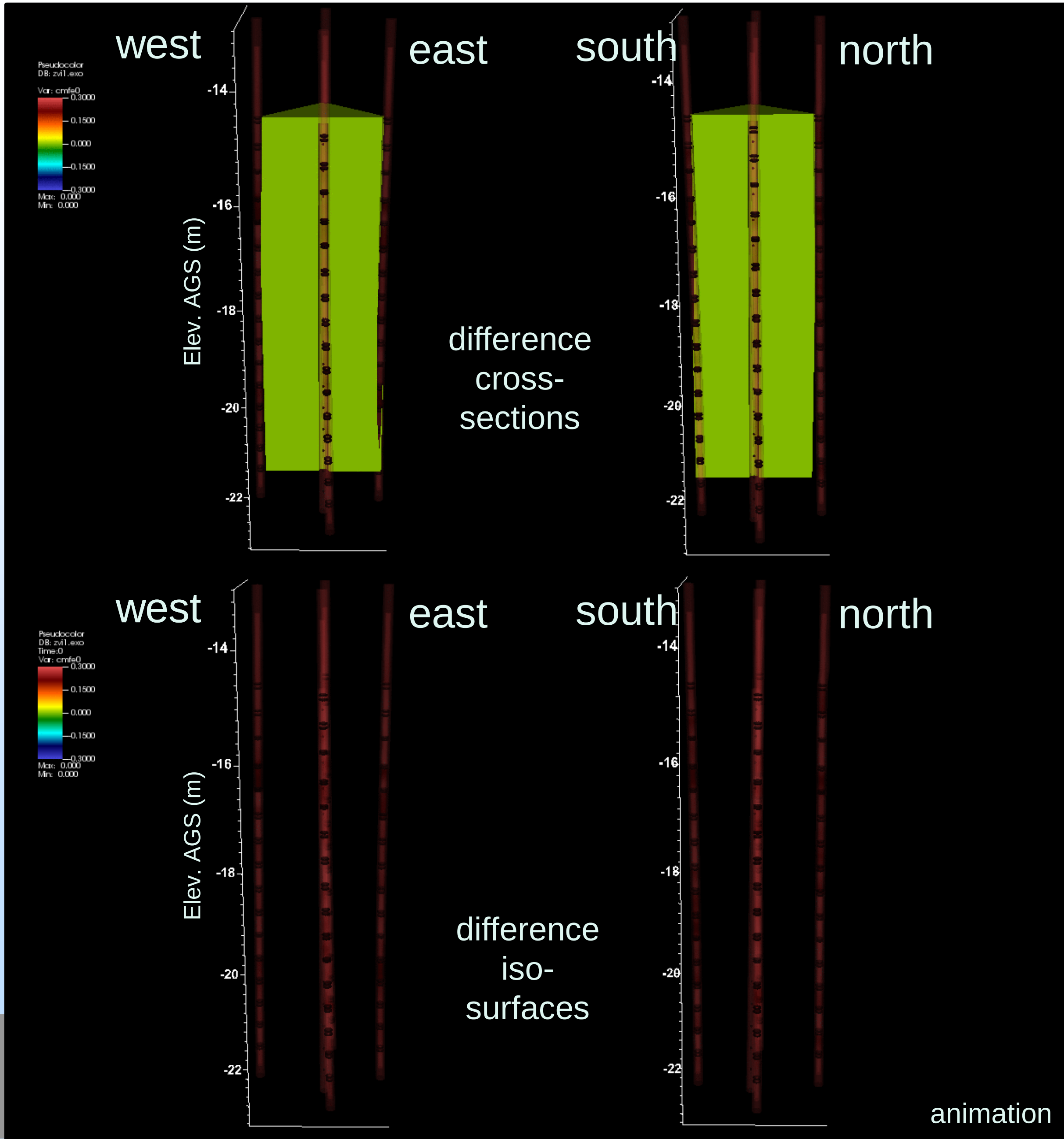
- Low electrical conductivity (EC) with high variability (2 orders of magnitude)
- Steeply dipping EC structure
- Highly resistive rock deep in the section (more competent?)

Real-time 4D imaging during ZVI injection

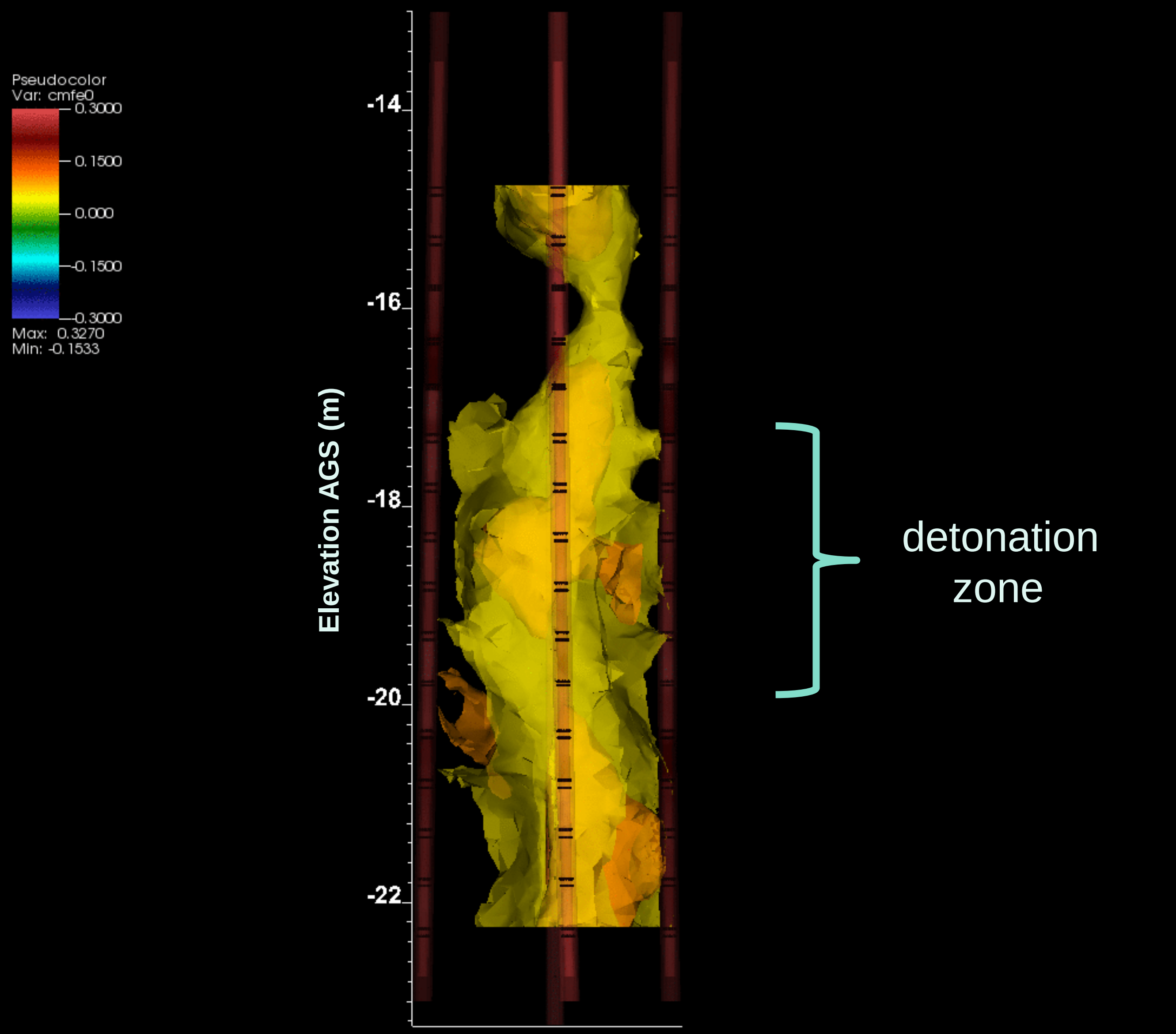
- Injection time: 3 hrs
- Injection vol: 110 gal
- Image frame rate: 15 min.

NOTES:

- Post detonation camera log shows multiple dominant vertical fractures.
- ZVI solution appears to migrate primarily into the east/west trending fracture.
- ZVI reaches outer boundaries of imaging zone, likely beyond



Fly-around view of ZVI-filled fracture zone



animation

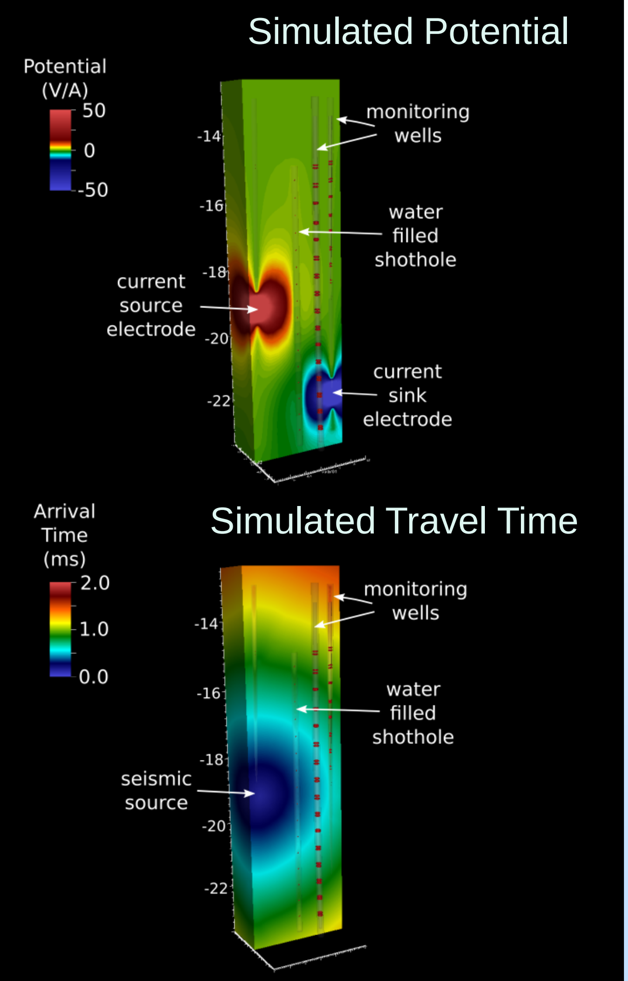
Joint Inversion Development

- Enables ERT and Seismic/Radar data to be jointly inverted
- Leverages assumption that fractures induced changes in geophysical properties are co-located.
- Joint constraints significantly improve resolution.
- **Goal:** ‘*Real-time’ joint inversion of large-N travel time and ERT data for fracture characterization and/or flow monitoring.*

<u>Algorithm Development</u>

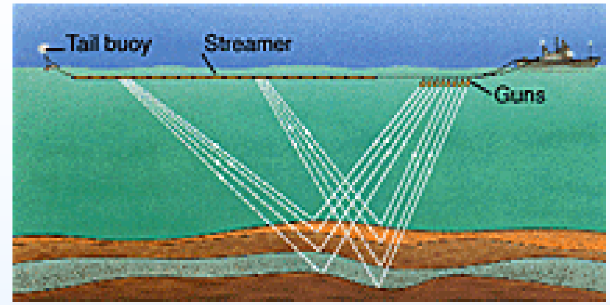
- Highly scalable parallel modeling/inversion
- Side by side forward simulations
- Unstructured tetrahedral mesh (finite element for ERT, fast marching method for travel time)
- Advanced a priori constraints
- Fresnel Volume Sensitivity
- Status: Complete (Simulated), Testing (Field)

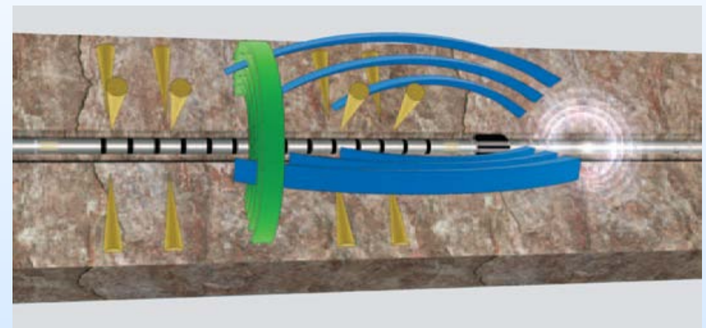
Joint ERT/Seismic Simulation

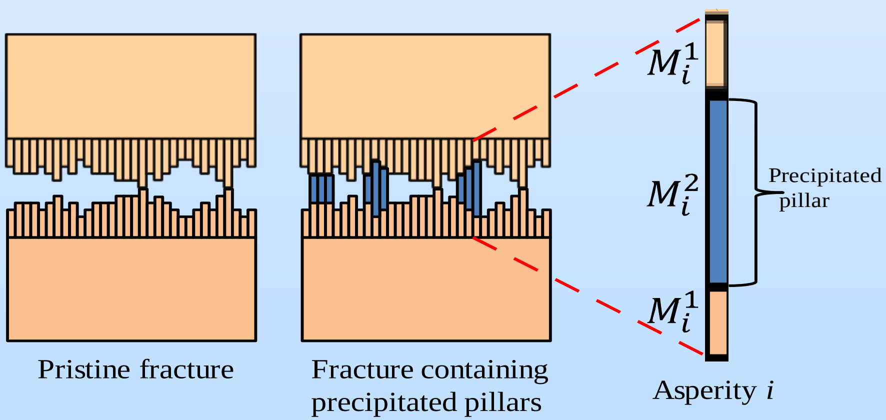


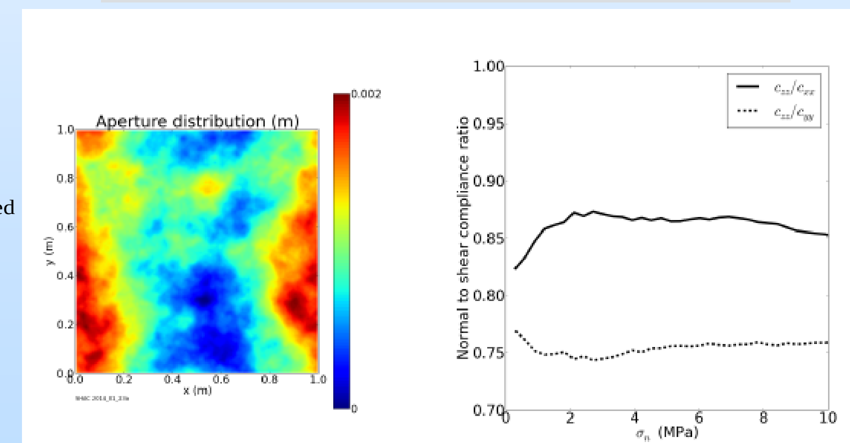
Inversion for fracture conductivity

- Remote sensing of fractures
- How can we extract the most information? Permeability?
- Move beyond empirical rules
    - Self-consistent
    - Predictive



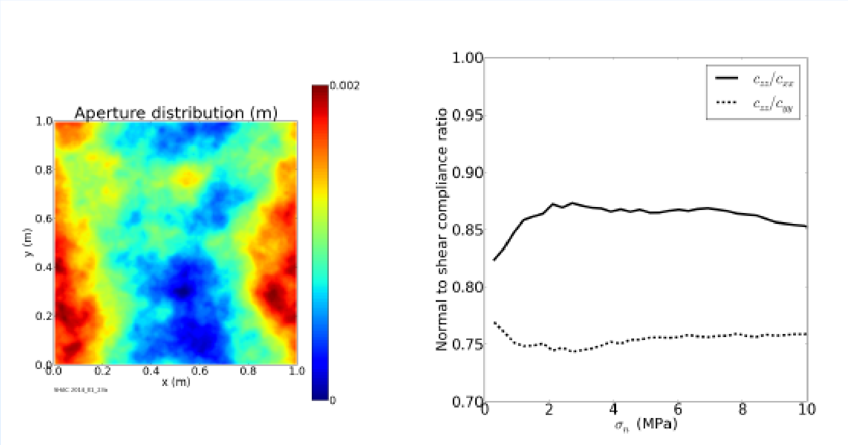






Our approach: Improvements that deliver results early and can be extended to a next-generation capability

- **Current effort:** Apply a modified version of Sayers and den Boer (2012) workflow
  - Utilize latest models coupling geophysics-mechanics and conductivity (Morris et al., 2016)



- **Future:** Introduce additional self-consistent fracture models to develop a next-generation workflow:
  - Predictive – Different geological settings
  - Extensible – Different geophysical attributes

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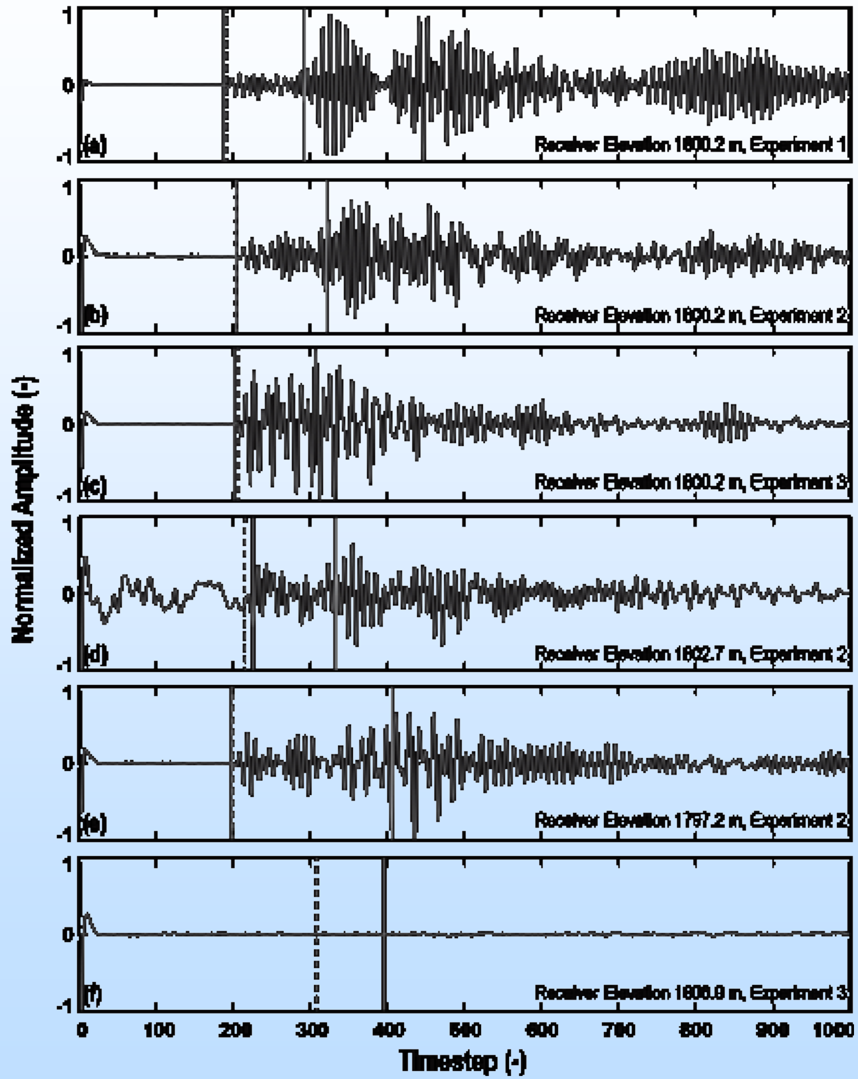
Automatic Picking Results

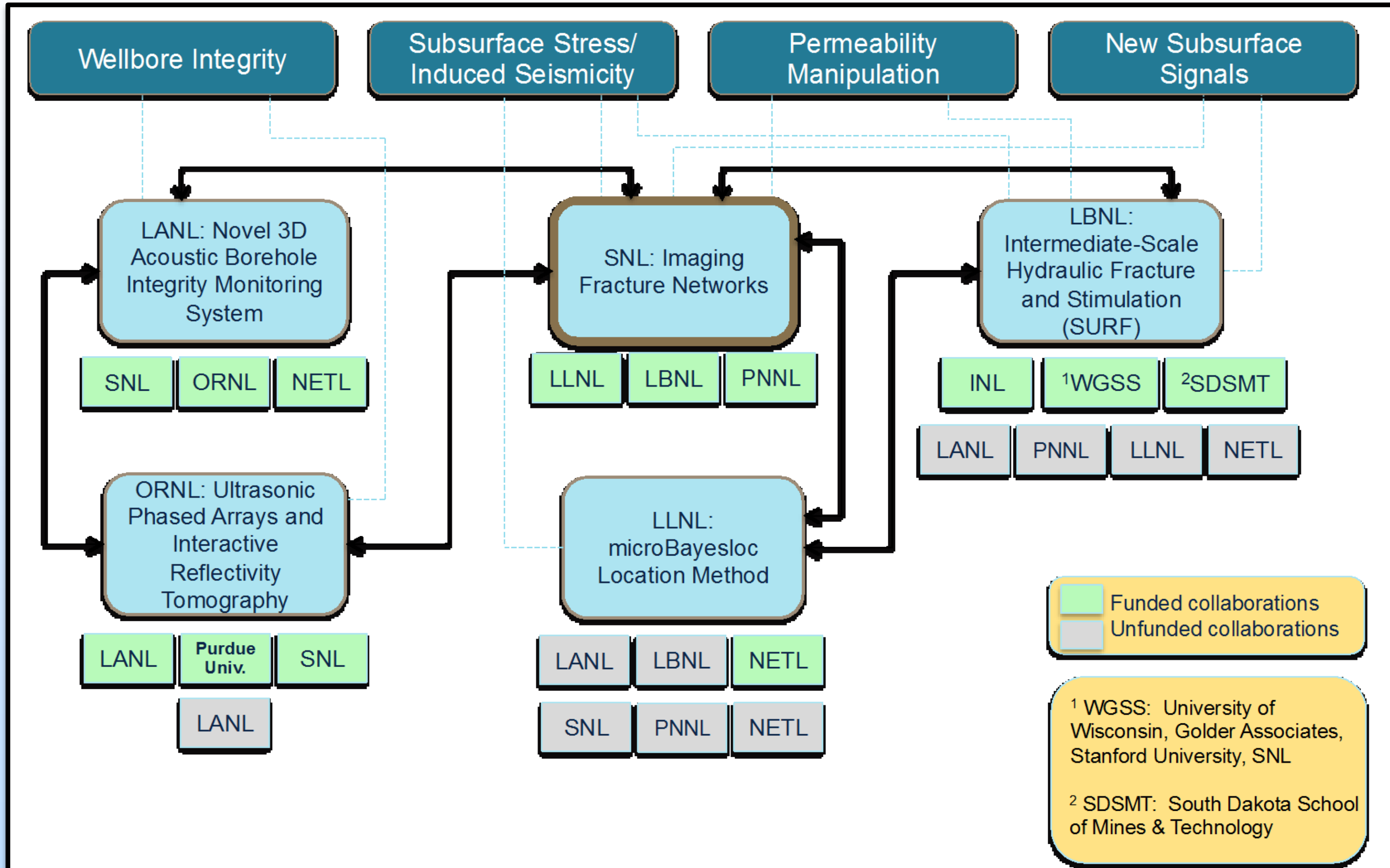
- The automatic first arrival time estimates are mostly reliable.
- Misestimated first arrival times are identifiable by their large changes in velocity from their neighbors.
- *S*-wave arrivals are more problematic, but, for low angle offsets and in undamaged rock, the estimates provide a meaningful constraint to the velocity structure of the rock
- The amount of time required to perform the analysis is short (less than 10 s for 120 traces)



Accomplishments to Date

- **Demonstrated:**
  - Successful multi-organizational (FFRDC, private industry, and academia) scientific collaboration and field execution
  - High resolution (spatial and temporal) geophysical imaging
  - Real-time imaging of fracture generation and tracer migration
  - Dense multi-disciplinary data acquisition
- **Developed and/or Improved:**
  - Joint inversion of geophysical data
  - Inversion for fracture conductivity
  - Automatic picking of high frequency seismic data
  - 3D change detection imaging using DAS technology

Synergy Opportunities



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Questions?

National Lab Team
April 2016 Fracture Test

Publications & Presentations

1. Knox et al. *Imaging Fracture Networks Using Joint Seismic and Electrical Change Detection Techniques*. DOE NETL Carbon Storage R&D Project Review Meeting, August 2015.
2. Knox et al. "Imaging Fracture Networks Using Angled Crosshole Seismic Logging and Change Detection Techniques." *2015 AGU Fall Meeting*. Agu, 2015.
3. Knox et al. *Imaging Fracture Networks Using Joint Seismic and Electrical Change Detection Techniques*. CODA Conference, March 2016 (Invited).
4. Knox et al. "Imaging Fracture Networks Using Joint Seismic and Electrical Change Detection Techniques." The 50th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association, 2016.
5. Knox et al. *High Energy Stimulations Imaged with Geophysical Change Detection Techniques.* Geothermal Resources Council Annual Meeting. September, 2016.
6. Knox et al. High Energy Stimulations Imaged with Geophysical Change Detection Techniques. GSA Pardee Symposium, "Mastery of the Subsurface The Challenge to Improve Subsurface Energy Systems". GSA Annual Meeting, Denver, CO. September, 2016.

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