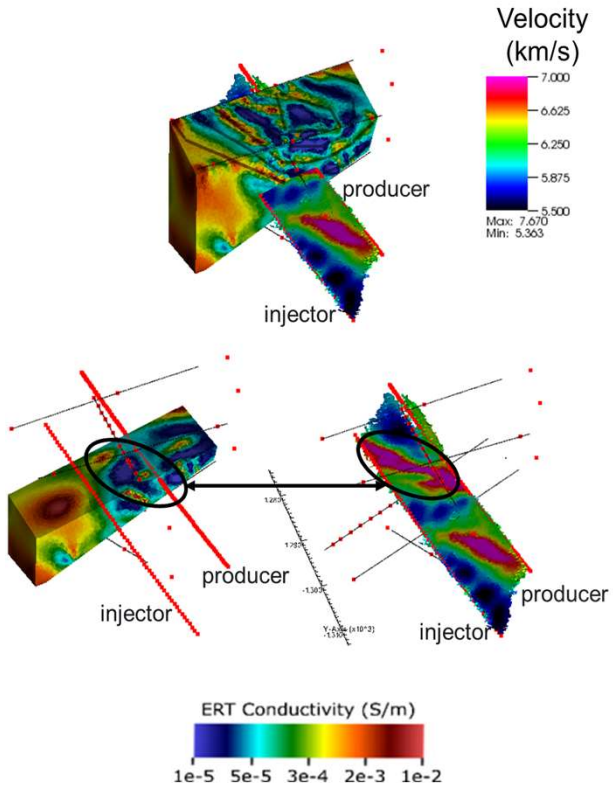
Demonstrating Near Real-Time Joint Inversion of ERT and Seismic Data

Presented by Piyoosh Jaysaval, Ph.D.

Participants:
Tim Johnson (PI), Todd Schaef (PM), Piyoosh Jaysaval, Yue Zhu, and Parker Sprinkle

Pacific Northwest National Laboratory



Overview and Impact

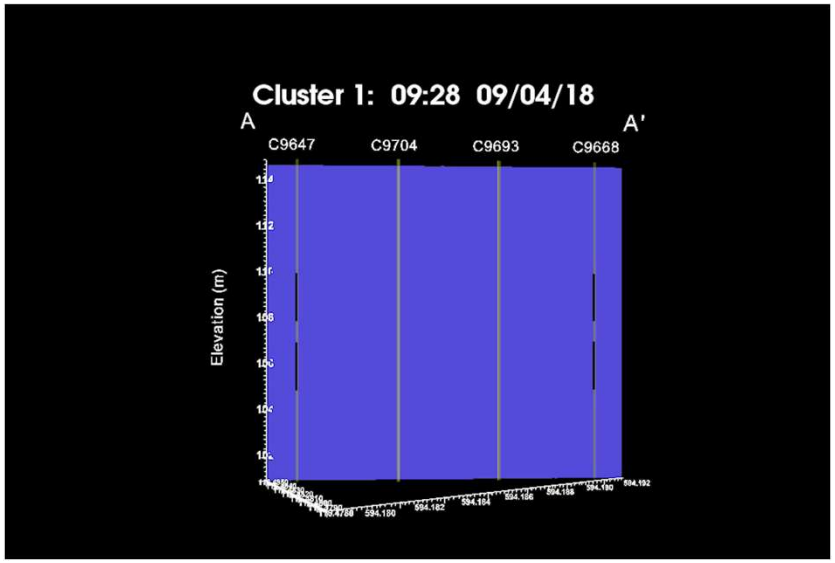
Overview:

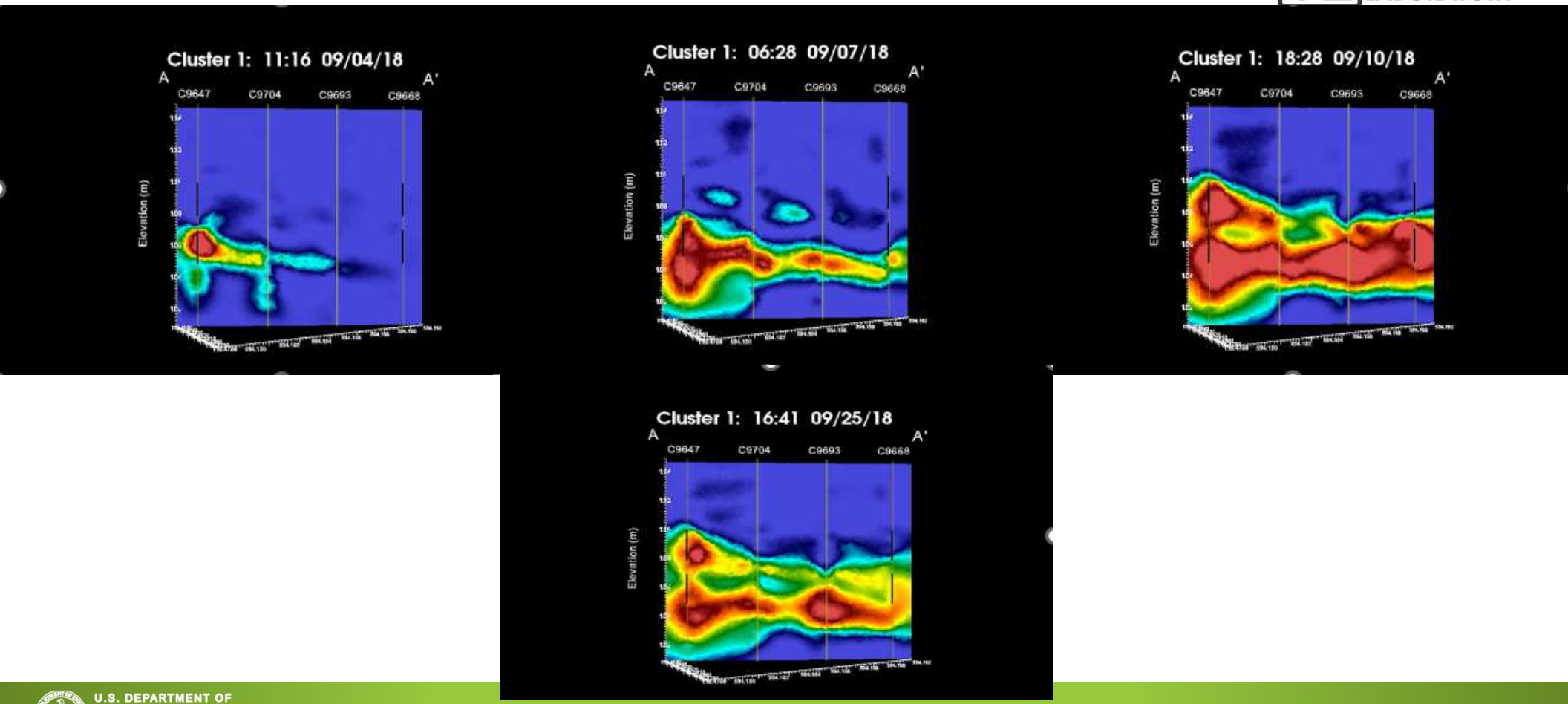
- *Objective*: develop and demonstrate autonomous real-time joint inversion of cross-hole electrical resistivity tomography (ERT) and seismic data
- Provide CCS operators with actionable and timely insight on reservoir behavior
- Pave a way for at-scale field demonstration

Impacts:

- Real-time inversion of seismic tomography data collected using existing autonomous seismic acquisition systems
- Joint HPC inversion of timelapse (4D) ERT and seismic data to provide actionable insights on reservoir changes in minutes, rather than months
- **Near real-time wellsite operational intelligence**

Real-time ERT Imaging of Injection




Cluster 1: 11:16 09/04/18
A
A'
C9647
C9704
C9693
C9668
Elevation (m)
Cluster 1: 06:28 09/07/18
A
A'
C9647
C9704
C9693
C9668
Elevation (m)
Cluster 1: 18:28 09/10/18
A
A'
C9647
C9704
C9693
C9668
Elevation (m)
Cluster 1: 16:41 09/25/18
A
A'
C9647
C9704
C9693
C9668
Elevation (m)

Execution plan: Tasks and Milestones

- **Task 1: Development of real-time HPC inversion of cross-hole time-lapse seismic data**

  M1: Automatic picking algorithm for first arrival travel times

  M2: Implementation of time-lapse seismic tomography inversion by leveraging/modifying open-source E4D code

- **Task 2: Development of real-time joint-inversion of autonomous time-lapse ERT and seismic tomography data**

  M3: Development of joint inversion of static ERT and seismic tomography data by leveraging the existing capabilities in E4D

  M4: Development of real-time joint inversion of time-lapse ERT and seismic tomography data

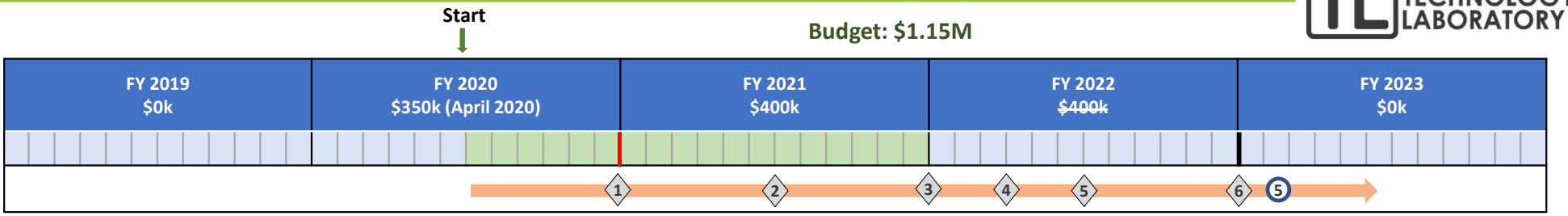
- **Task 3: Field demonstration on existing static/time-lapse ERT and seismic data**

  M5: Demonstration on existing time-lapse cross-hole seismic and ERT field data

- **Task 4: Reporting and code release**

  M6: Final report/manuscript submission and release of new capabilities in E4D code as open source

Overview of Project Timeline



Milestones:

M1: Development of algorithms for automatic picking of first arrival times in time-lapse seismic data (**GO/NO-GO**) (*complete*)

M2: Development of inversion algorithm for time-lapse seismic data within E4D (*complete*)

M3: Development of parallel joint-inversion of static ERT and seismic data within E4D (*complete*)

M4: Development of parallel real-time joint-inversion of time-lapse ERT and seismic data within E4D (*complete*)

M5: Demonstration on existing time-lapse cross-hole ERT and seismic field data (*pending*)

M6: Final report/manuscript submission and release of project-developed E4D code (*pending*)

Chart Key

(#) TRL Score | Go / No-Go Timeframe | Project Completion | Milestone

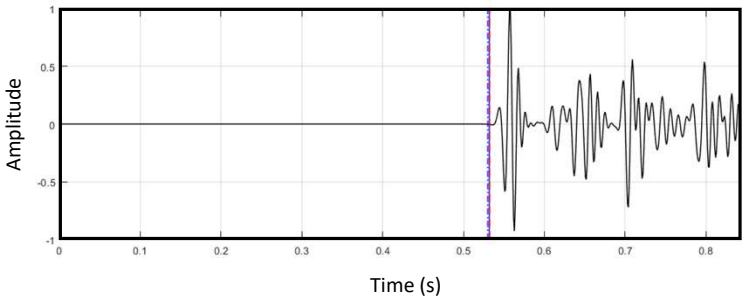
Go / No-Go

Q3: Development of algorithm to pick arrival times in time-lapse seismic data

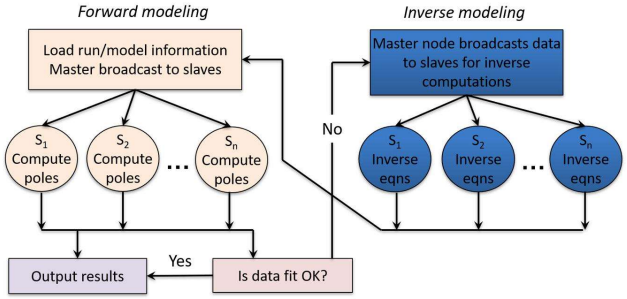
Key Accomplishments/Deliverables	Value Delivered
• Autonomous first-arrival time picking algorithm for time-lapse seismic data • Field demonstration of real-time seismic data processing/inversion and near real-time joint inversion of 4D ERT and seismic data with E4D • Public release of open-source codes for near real-time joint inversion	• Joint inversion of ERT and seismic data by utilizing HPC resources to provide actionable insights on reservoir changes in minutes rather than months, and hence allowing site operators, regulators and researchers to learn and respond more rapidly than ever before

Task 1: Development of real-time HPC inversion of cross-hole 4D seismic data

- ***Subtask 1a*: Development of algorithm for automatic picking of first arrival travel times in time-lapse seismic data**
  - Critical requirement for autonomous time-lapse and real-time inversion of seismic tomography data
  - Traditionally, has been done manually
  - **M1: Python algorithm is developed for auto picking (completed: Q4, FY20)**



- ***Subtask 1b*: Development of time-lapse seismic tomography inversion**
  - Leverage/modify existing static inversion of seismic tomography capability in open-source E4D code
  - **M2: Time-lapse inversion of seismic tomography data is developed in E4D (completed: Q2, FY21)**

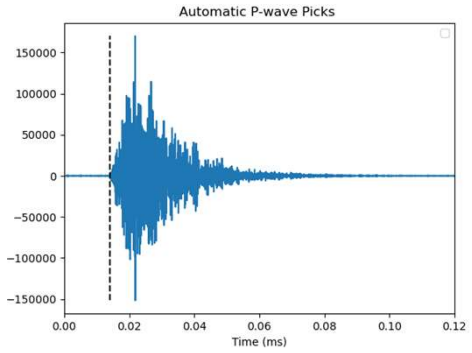


Flow chart of forward and inverse modeling in E4D

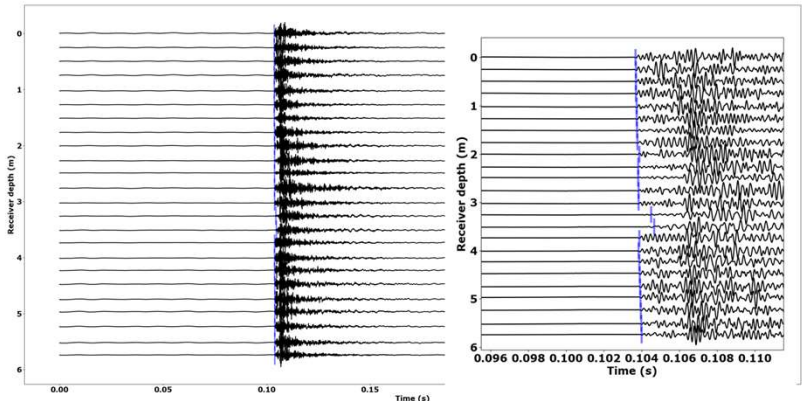
Task 1a: Algorithm for auto picking of first arrival travel time

- Implemented Akaike Information Criterion (AIC) for automatic picking of first arrival trave times
- In this approach, AIC function is computed in a part of seismogram selected by a rectangular window
- AIC function has the minimum value at the point of first arrival, which is used to pick the first arrival travel times
- Algorithm is written in python, utilizing edge computing
- Processes incoming data in real-time, finds first arrivals, and outputs E4D input file
- Tested on data from several different seismic systems
- Manuscript is being prepared for submission to a journal

M1: Developed auto picking algorithms (completed at the end of FY20)



Single channel auto-pick example (Zoomed In)

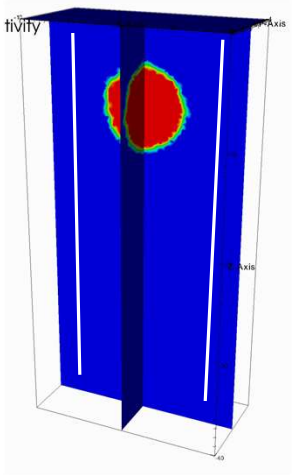


24 channel auto-pick example

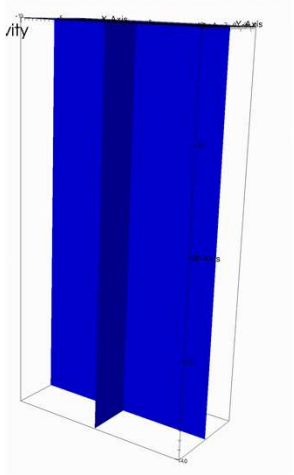
Task 1b: Development of time-lapse seismic tomography inversion

- Leverage/modify existing static inversion of seismic tomography capability in open-source E4D code
- Uses Gauss-Newton method for the inversion
- Tested the code on various synthetic cases

M2: Time-lapse inversion of seismic tomography data is developed in E4D (completed: Q2, FY21)



True velocity models: sinking plum (low velocity)



Inverted velocity models: sinking plum

Task 2: Development of real-time joint-inversion of 4D ERT and seismic data

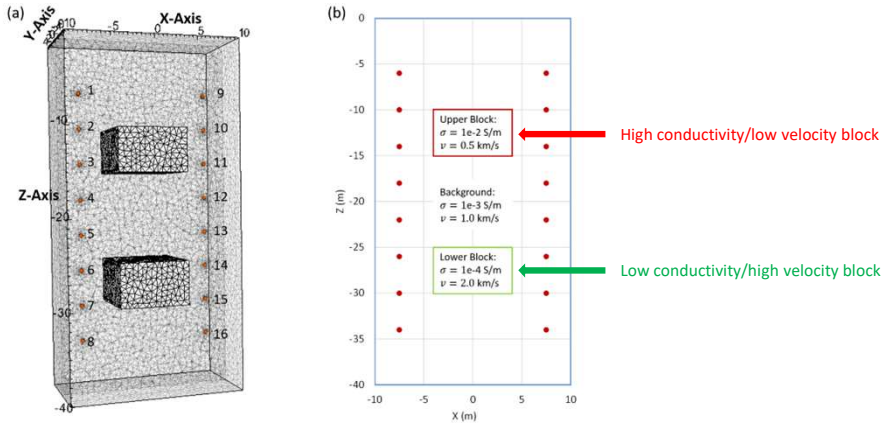
- ***Subtask 2a*: Development of joint-inversion of *static* ERT and seismic data**
  - Most challenging step toward achieving time-lapse joint inversion
  - Leverage the existing capabilities in E4D: inversion of ERT and seismic tomography data
  - Use cross-gradient approach to jointly invert ERT and seismic data
  - **M3: Developed the joint inversion capability in E4D (completed: Q4, FY21)**

- ***Subtask 2b*: Development of *real-time* joint-inversion of *time-lapse* ERT and seismic data**
  - Using the capability developed in Subtask 2a, develop real-time joint inversion of time-lapse ERT and seismic tomography data
  - **M4: Developed the real-time joint inversion capability for time-lapse ERT and seismic data in E4D (completed: Q1, FY22)**

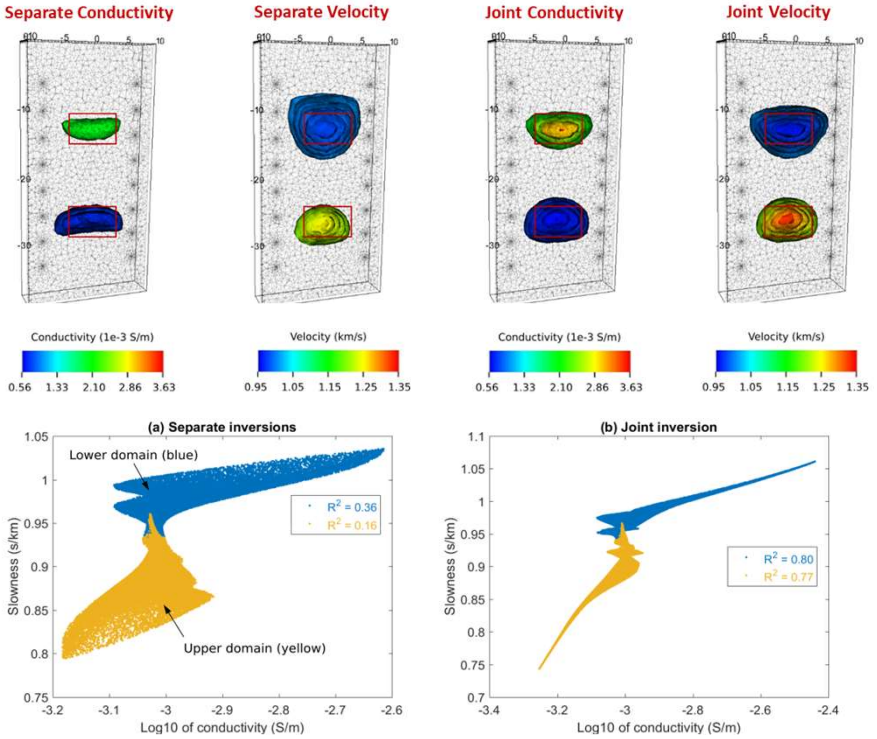
Task 2a: Synthetic example of joint-inversion of static ERT and seismic data

Static Joint Inversion:

- New HPC capability in E4D enables massive scalability
- Submitted a paper to ***Computers & Geosciences*** on algorithm and code



True model showing two anomalous blocks and electrode/seismic sensor positions



Cross plots of conductivity versus slowness (reverse of velocity): blue and yellow dots represent upper and lower anomalies and their surround areas

Task 3: Field demonstration on existing static/time-lapse ERT and seismic data

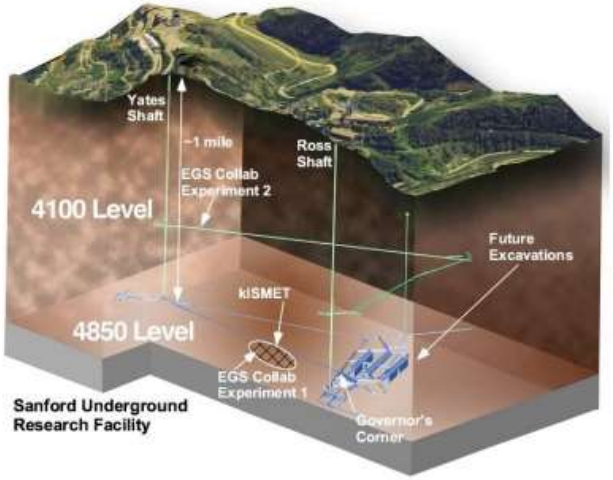
- **Identified two sites where the new capability could be demonstrated**

Enhanced Geothermal System multi-national laboratories (EGS Collab) sites at Sanford Underground Research Facility (SURF) located in Lead, South Dakota

- A series of tests are being performed to increase understanding of responses of crystalline rock to stimulations and fluid flow
- To efficiently implement enhanced geothermal systems (EGS) technologies

These tests also include time-lapse ERT and seismic data

- EGS-Collab testbed #1: located at 4850 ft (~1500 m) depth
  - to examine hydraulic fracturing
- EGS-Collab testbed #2: located at 4100 ft (~1250 m) depth
  - to examine hydraulic shearing



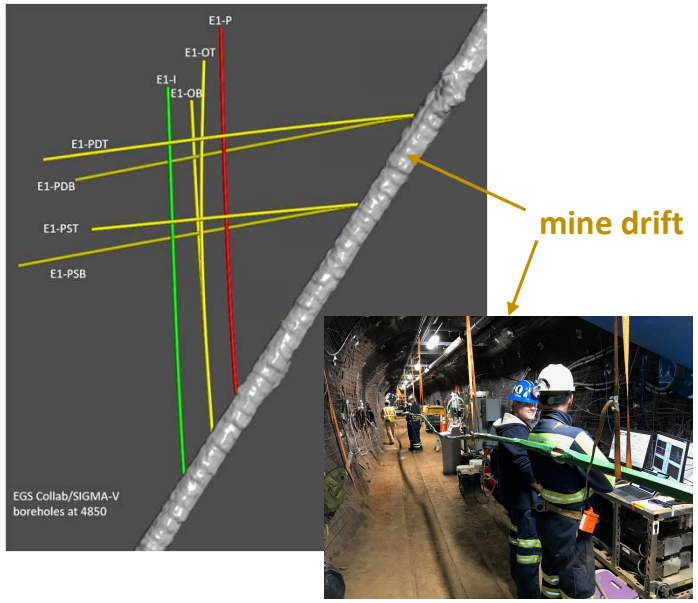
https://gdr.openei.org/egs_collab

Task 3: Field demonstration on static seismic/ERT joint inversion

EGS-Collab testbed #1: located at 4850 ft (~1500 m) depth at SURF

ERT electrodes in all monitoring boreholes

cross-hole seismic between injector and producer boreholes

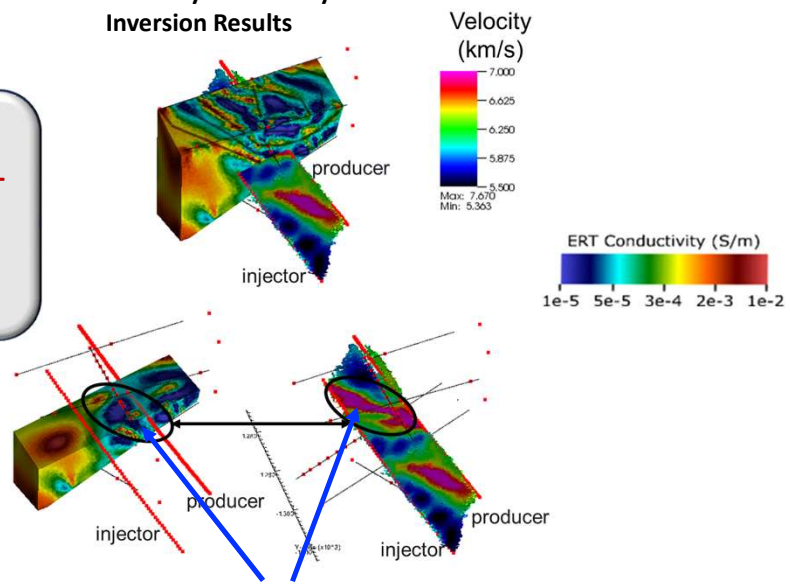


1 Injection (green), 1 production (red), and 6 monitoring (yellow) boreholes of ~60 m length

This site has good quality ERT and seismic data for characterization before stimulation of fractures

However, no good quality co-collected time-lapse ERT and seismic data

Bulk Conductivity vs. Velocity Joint Inversion Results

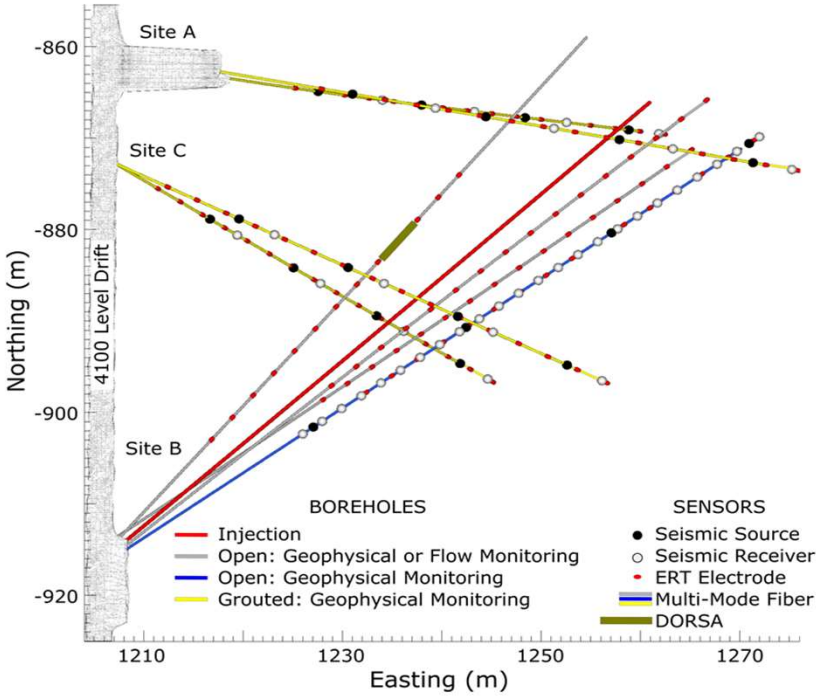


Joint inversion identifies high velocity – low conductivity correlation in overlapping region, indicative of intact, poorly fracture rock.

M5: Demonstration on existing time-lapse cross-hole seismic and ERT field data (partially complete)

Task 3: Field demonstration on static seismic/ERT joint inversion

EGS-Collab testbed #2: located at 4100 ft (~1250 m) depth at SURF



- Highly instrumented and controlled flow and transport system with high pressure packers in the red injection well
- All yellow wells are instrumented with autonomous ERT and cross-hole seismic (ML-CASSM: multi-level continuous active source seismic monitoring) systems

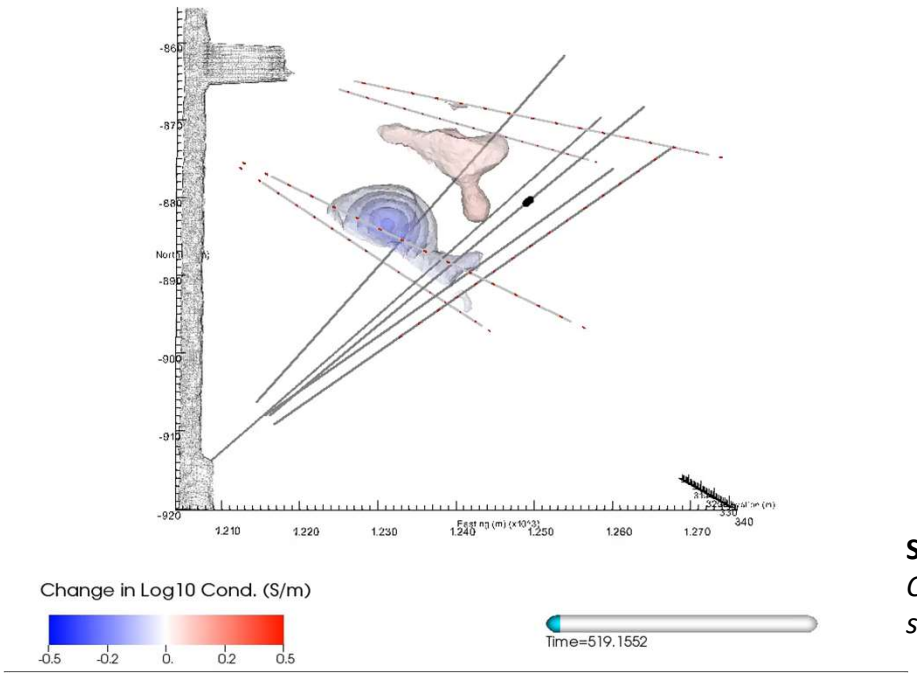
Why this data set?

Autonomous 4D ERT and cross-hole seismic data sets collected during fracture stimulation and flow testing provide a (rare) data set needed to demonstrate near real-time operational intelligence provided by joint time-lapse difference inversion capability developed in this project.

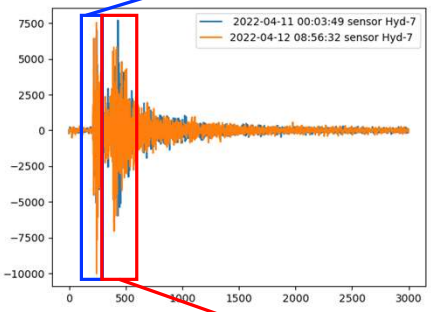
Task 3: Field demonstration on static seismic/ERT joint inversion

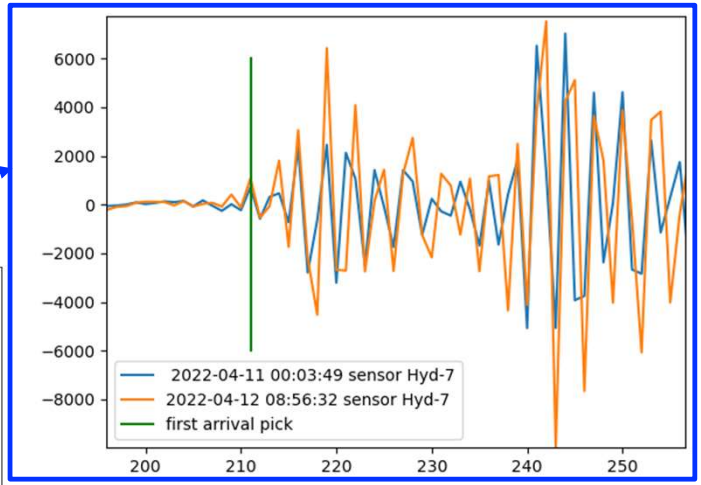
EGS-Collab testbed #2: located at 4100 ft (~1250 m) depth at SURF

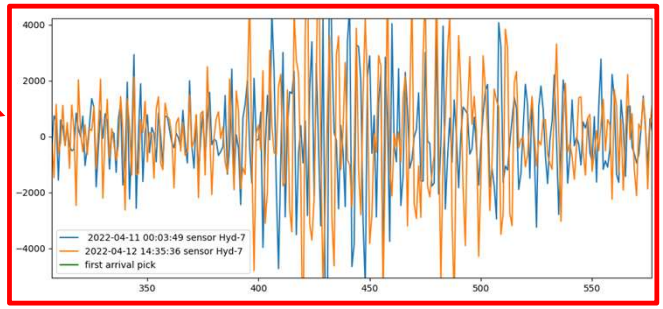
Time-Lapse ERT During 4000 PSI Injection



No change in first arrival times





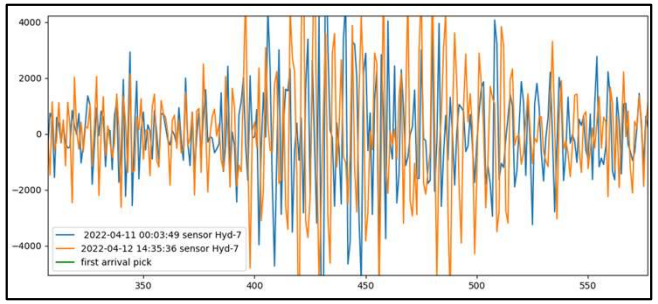


Significant change in coda

Conclusion: most/all of the time-lapse seismic info is in the coda

Next Steps?

- Utilize information in coda wave by implementing time-lapse seismic interferometry
- Would replace time-lapse travel time tomography in joint inversion code, but joint inversion code infrastructure would not have to change
- Would *not require additional funding*, but would require more time to implement
- Well studied approach and well-prepared field data set for demonstration
- *Deliverables*:
  - Open source HPC code (E4D) with autonomous **4D ERT**, **seismic tomography**, and **seismic interferometry** joint inversion capability
  - Manuscript with highly instrumented field data demonstration
  - Target completion by Q2, FY25



Summary

- **Developed advanced autonomous inversion of time-lapse seismic data**
  - Capabilities and impacts need to be demonstrated on field datasets
- **Developed joint inversion of ERT and seismic data**
- **Field demonstration on existing data is partially complete**
  - Successfully demonstrated static joint inversion capability on field data
  - No suitable time-lapse ERT and seismic data to demonstrate time-lapse joint inversion capability
    - First arrival travel times do not change during stimulation and flow, however
    - Seismic coda demonstrate significant changes due to scattering (***can be exploited***)
- **Recommendation going forward:**
  - Re-scope and implement coda wave analysis in time-lapse joint inversion
  - No cost time extension required

Questions?