Advances in Large-N Seismic Measurements to Monitor Reservoir Behavior

Project Number (FWP-FEW0191)

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National Energy Technology Laboratory

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Project Overview

Goals and Objectives

The cost of monitoring to ensure the plume is safely stored in the reservoir is a challenge to the commercialization of CO_2 storage.

- Large seismic or fiber arrays combined with novel analyses will allow for inexpensive monitoring of plume stabilization and leakage at CO_2 storage sites.
- We want to understand of the behavior of CO_2 injected underground for permanent storage, and detect it's effects.
- Need to ensure that CO_2 sequestered in the ground will remain there, can be monitored over time and that changes in the pressure field don't fracture the seal or trigger induced events.

Technical Methods/Tasks

Objective: apply three novel monitoring techniques to image CO_2 plume migration and leakage using seismic, electromagnetic and fiber optic detectors.

Tasks:

1) (ANC): use background seismic wavefield to passively monitor changes in the subsurface
2) (VSM): use localized microearthquakes to measure changes in the pressure field in response to large seismic events.
3) (SEE) : and both seismic and electric effects to resolve fluid phase properties and constrain subsurface permeability measurements.
4) (Fiber-Geophone comparison): We will address challenges and illustrate the power of applying these three techniques to large number of data made possible through the deployment of seismic and fiber optic sensors.

What is “Large-N”?

N :

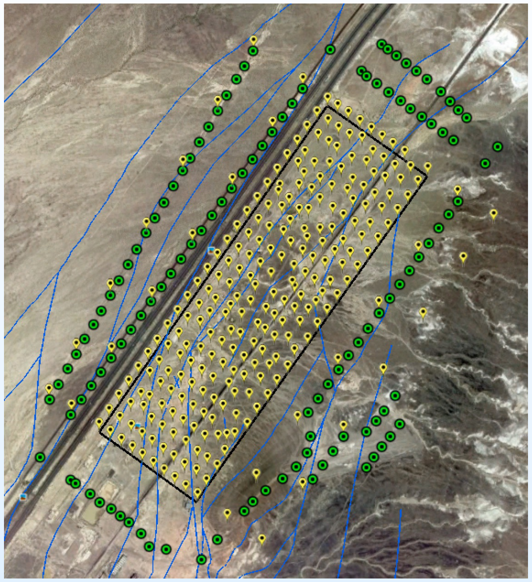
number of seismometers
or
number of microquakes
at a site

Large:

Newberry (25) : 300 correlations
Brady (239) : > 28,000
Long Beach (5200) : > 13 million

Differences in resolution

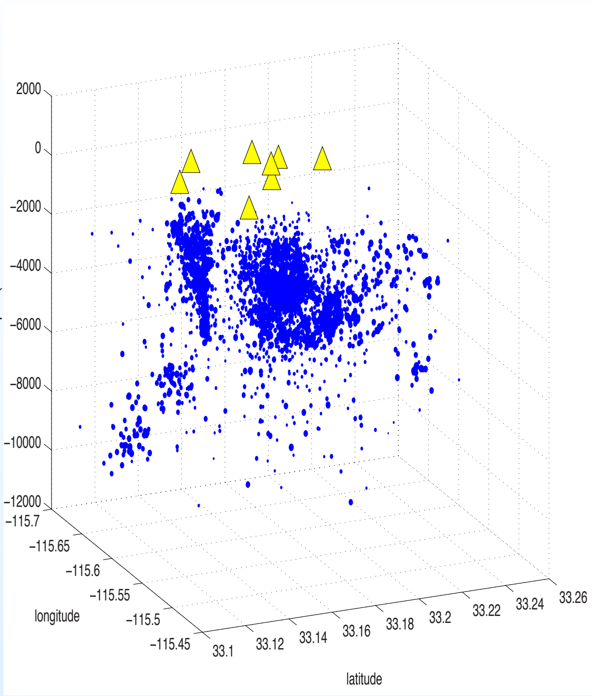
100’s to 1000’s of microquakes at active sites.



PoroTomo experiment at Brady

- Large-N network
- Mix of instrument types including fiber
- Defined changes in subsurface fluid and pressure
- Terabytes of data in-house

(PI Feigl; Livermore lead Morency)

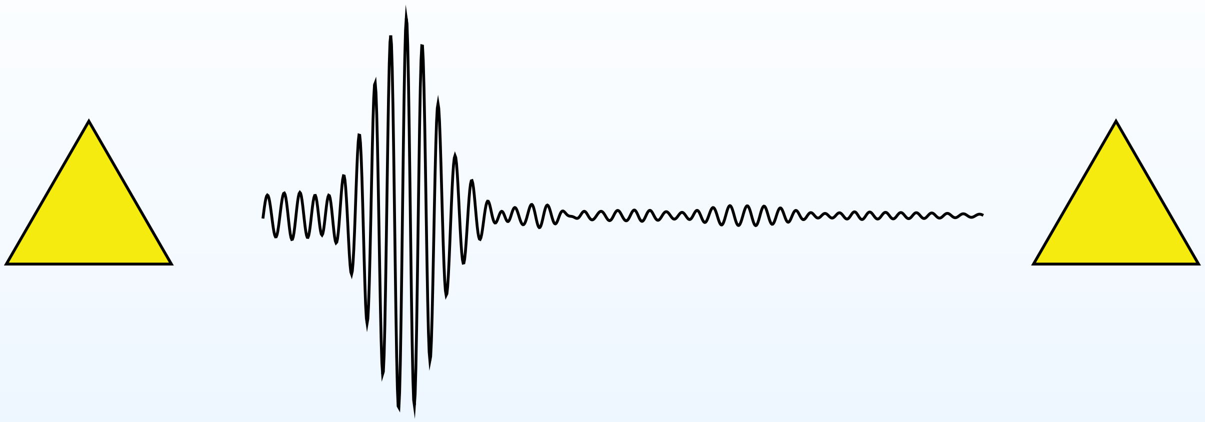


Salton Sea geothermal region

- Long term monitoring
- Thousands of cataloged microquakes
- Leverages work done for location identification 3D modeling, etc.
- Continuous and event data in-house

(Wang, Templeton, Rhode and others)

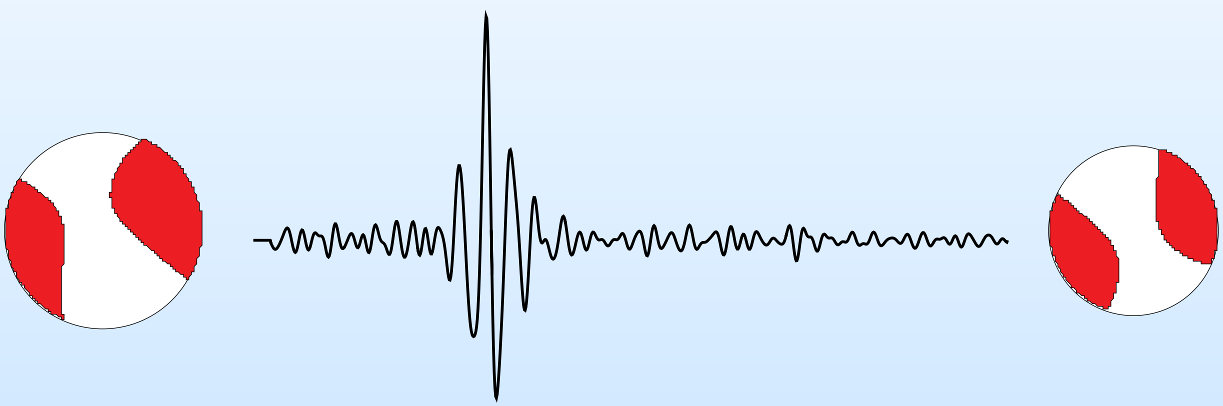
Seismic Interferometry: Virtual Earthquakes and Virtual Seismometers



ANC, CWI

"virtual earthquake"

$CC = GF_{AB}$



VSM

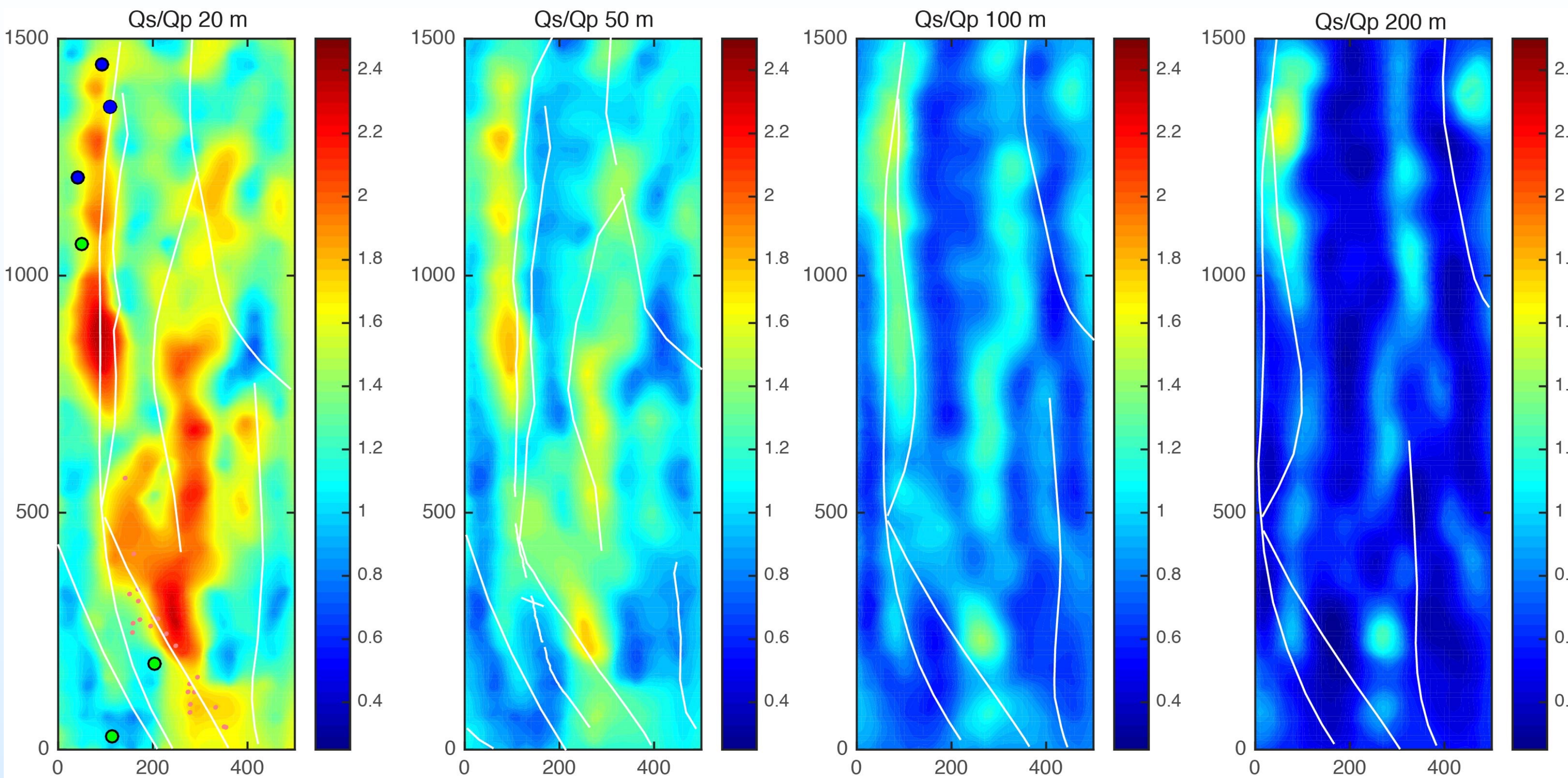
"virtual seismometer"

$CC = M_1 M_2 GF_{12}$

reference: Curtis et al. 2009

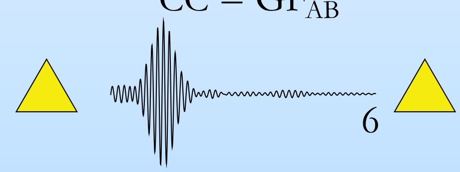
Both methods: Ncorrelations = N*(N-1)/2

Seismic Interferometry: Qs/Qp illuminates fluid pathways

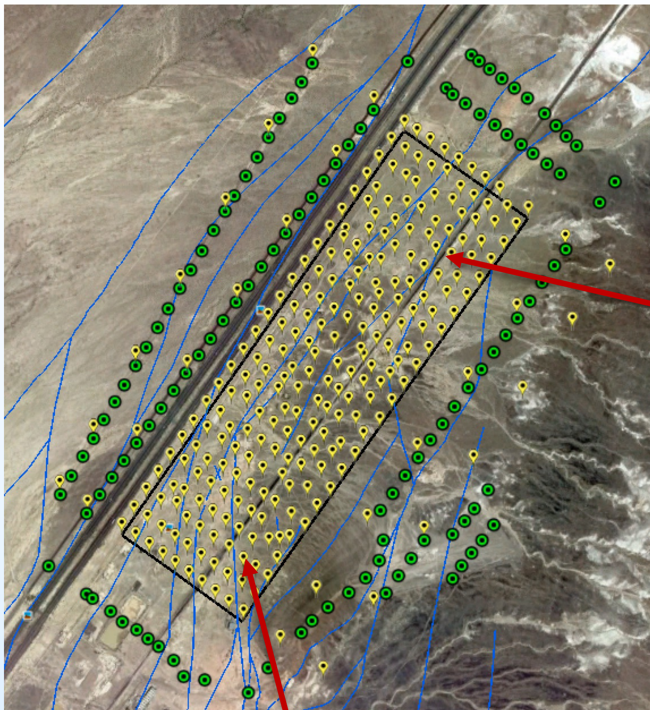


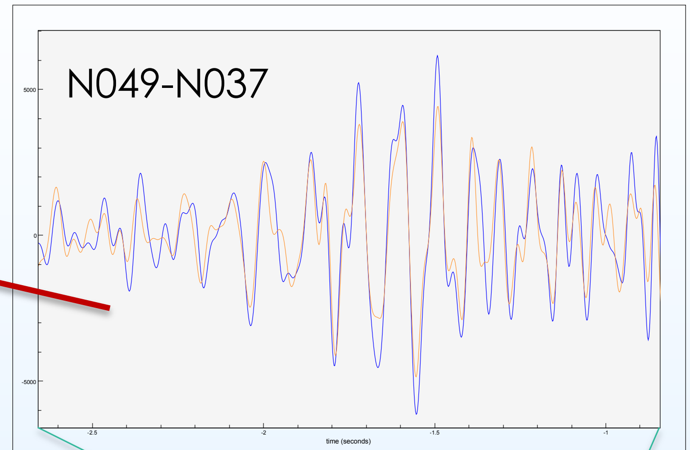
- 238 geophones result in > 28,000 independent measurable waveforms.
- We are able to resolve the elastic properties (Vs, Vp, Qs, Qp) in high detail.
- P-waves and S-waves have distinctly different sensitivity to the presence of fluid filled pore spaces. Ratios are used to identify fluid contacts.

ANC
"virtual earthquake"
$CC = GF_{AB}$



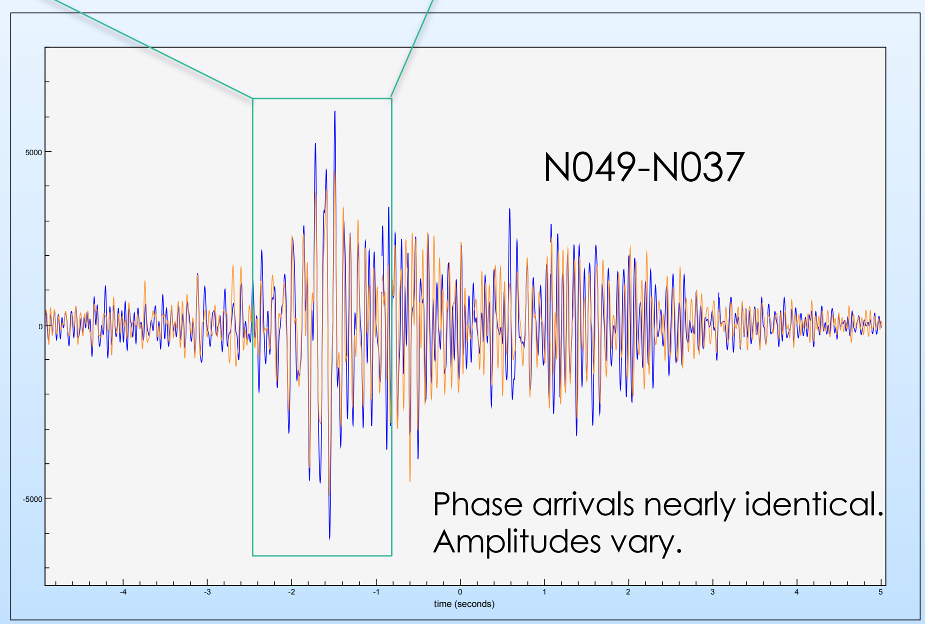
Phase arrival times are nearly identical, but amplitudes changed measurably after site shutdown

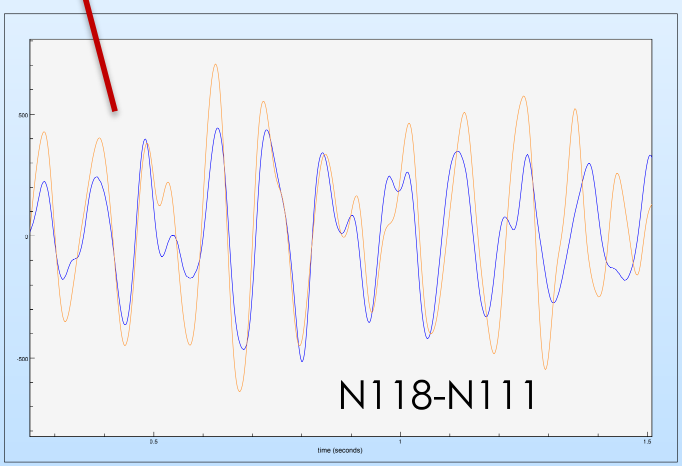




Amplitudes in the North decreased after shutdown

Normal Ops: Blue
Site Shutdown: Orange

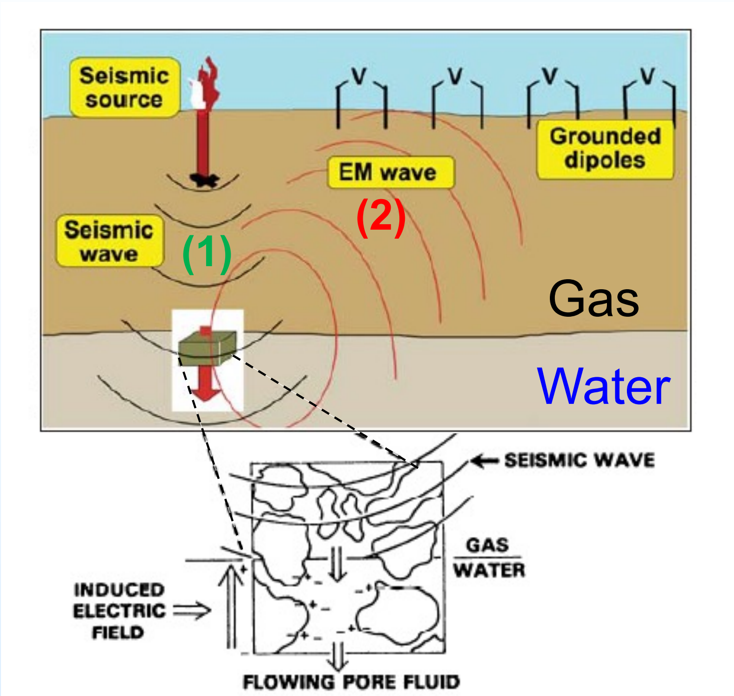




Amplitudes in the South increased after shutdown

Seismoelectric effects (SEE) for CO_2 monitoring

- SEE are pore scale phenomena, relying on charge separation created by streaming currents generated by pressure gradient occurring when a seismic wave propagates.
- SEE correspond to a seismic (1) -to-electric (2) conversion.
- SEE are sensitive to heterogeneities (e.g., difference in conductivity between CO_2, brine).



Field test of Texas Gulf Coast by Thompson & Gist (1993)
=> They detected gas-water interface due to seismoelectric effects (~500m).

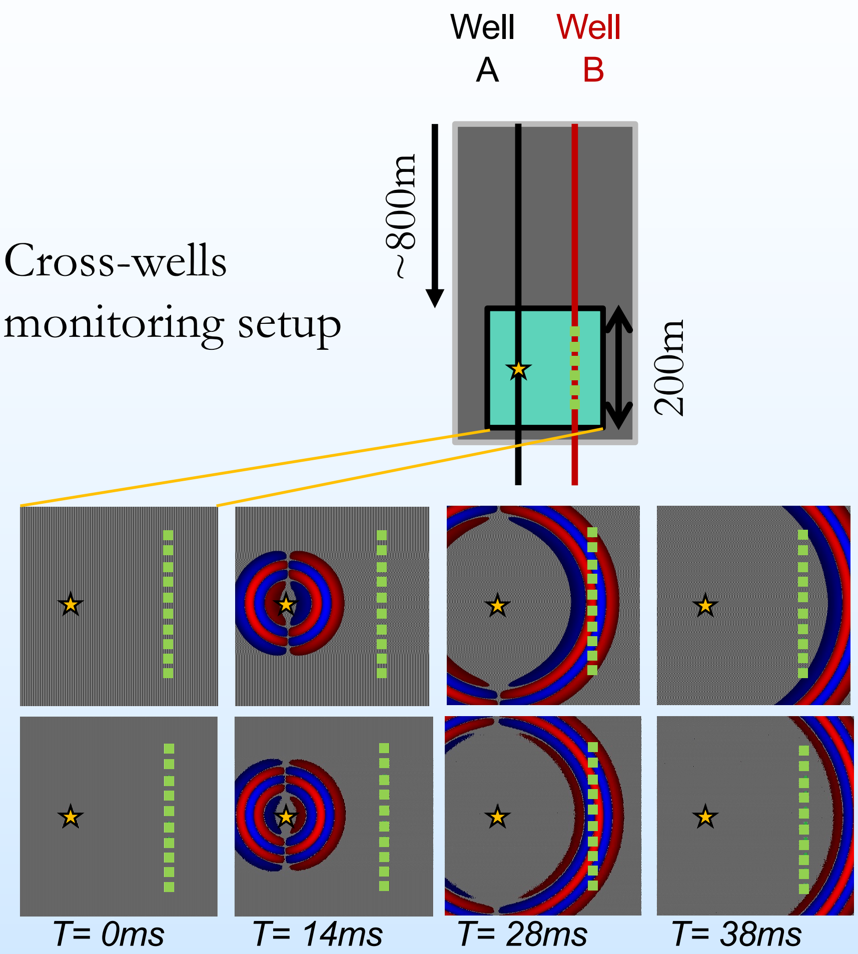
We have developed in-house new software to model SEE

We have developed codes to calculate SEE through a 3D system

Synthetic validation of SEE calculation

- SEE offer unique signals compared to seismic technique only
- SEE are specifically sensitive to fluid (e.g. brine versus CO_2)

Cross-wells monitoring setup



Solid seismic displacement

Triggered coseismic electric field

Coseismic transient electric field accompanying the seismic wave is properly recovered

SEE can directly detect the brine/CO_2 interface

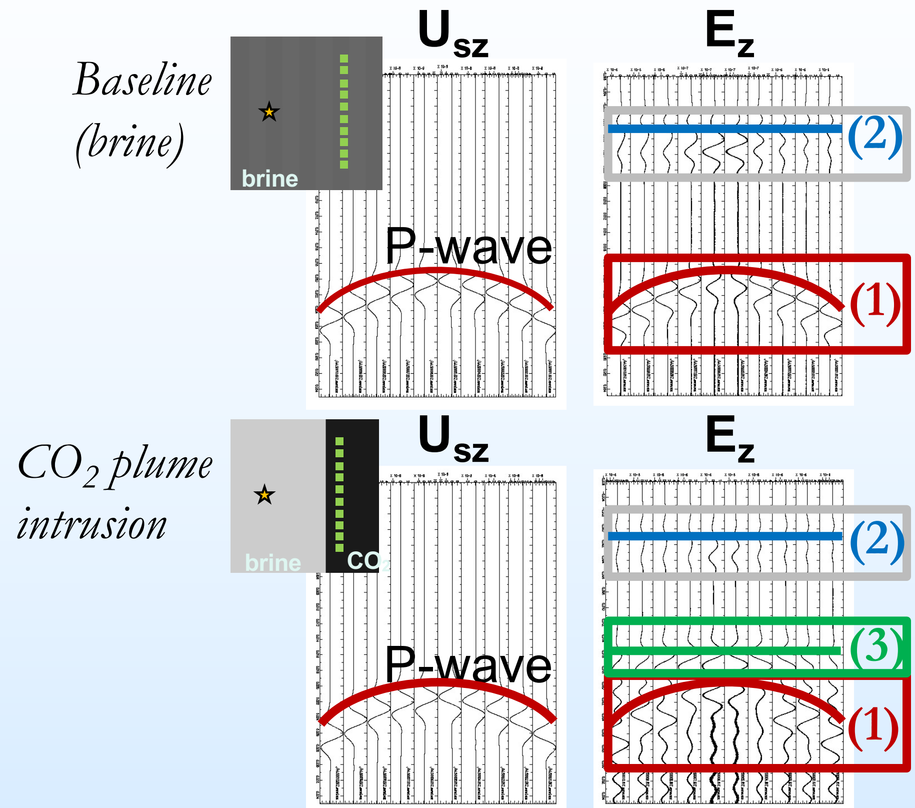
Our in-house software accurately detects 3 types of seismic-to-electric conversions:

(1) the coseismic electric signal

(2) the quasi-instantaneous electric signal generated when the seismic source occurs, and

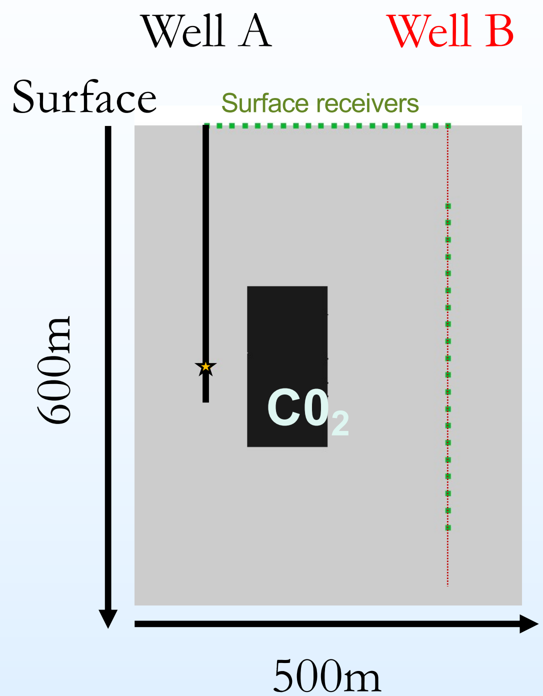
(3) the quasi-instantaneous seismo-to-electric conversion at material discontinuity.

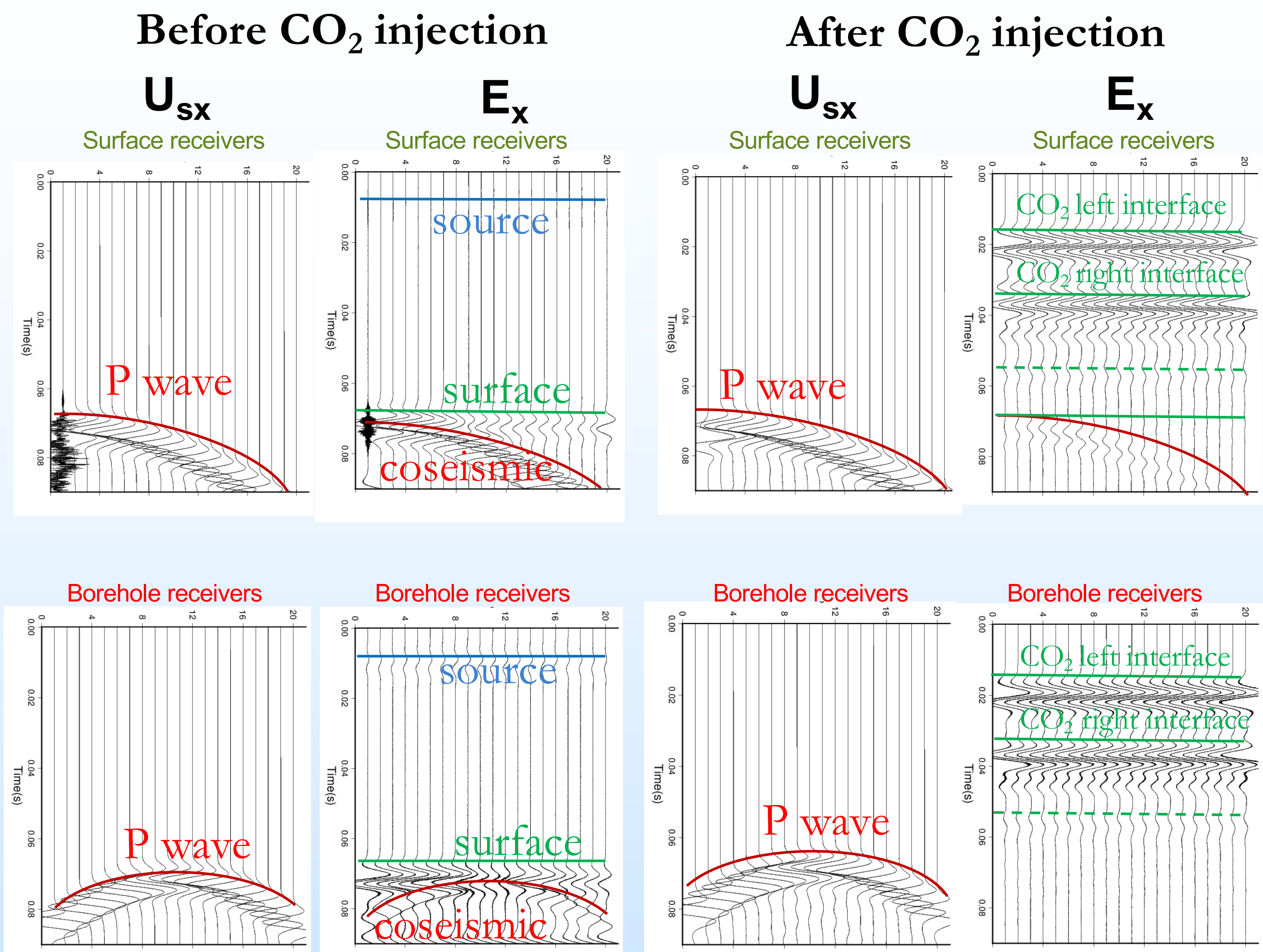
SEE can directly detect brine/CO_2 interface
Seismic alone cannot.



Seismograms (left) & electrograms (right)

Idealized setup for SEE monitoring of CO_2





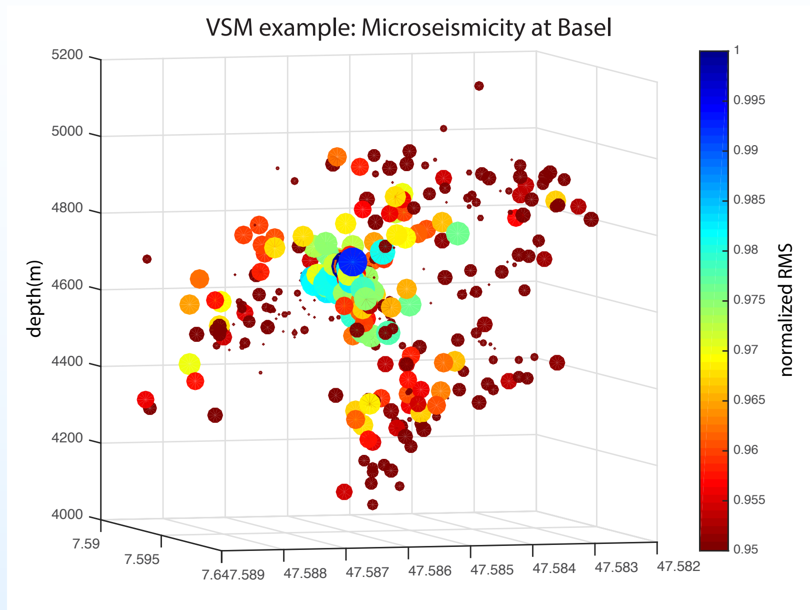
20 surface geophones and antennas
20 borehole geophones and antennas

Resistivity ($1/\sigma$) increases with CO_2 replacing brine

Surface & interface SEE signals are quasi instantaneous with amplitude variations

VSM significantly increases the resolution of tectonically active features

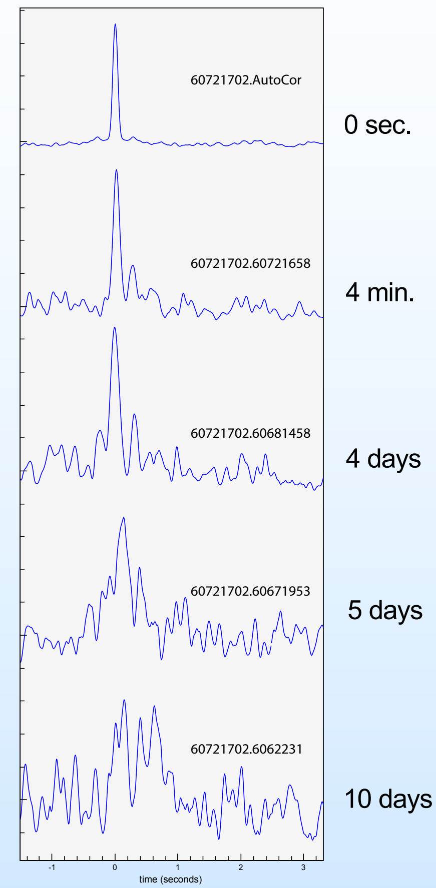
- **Objective**: Measure changes in the state of stress at tectonically active sites.
- **Objective**: Identify changes in the fluid properties over time.
- Focus – state of subsurface before and after large seismic events.
- We are in the eartly stages of this task.
- Status: we have calculated tens of thousands of virtual seismograms for tectonically active sites near fluid injection.



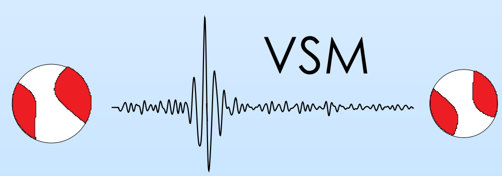
(Basel):

- VSM amplitudes and similarity functions are highly sensitive to relative 3D locations

Virtual Seismograms at Blue Mountain



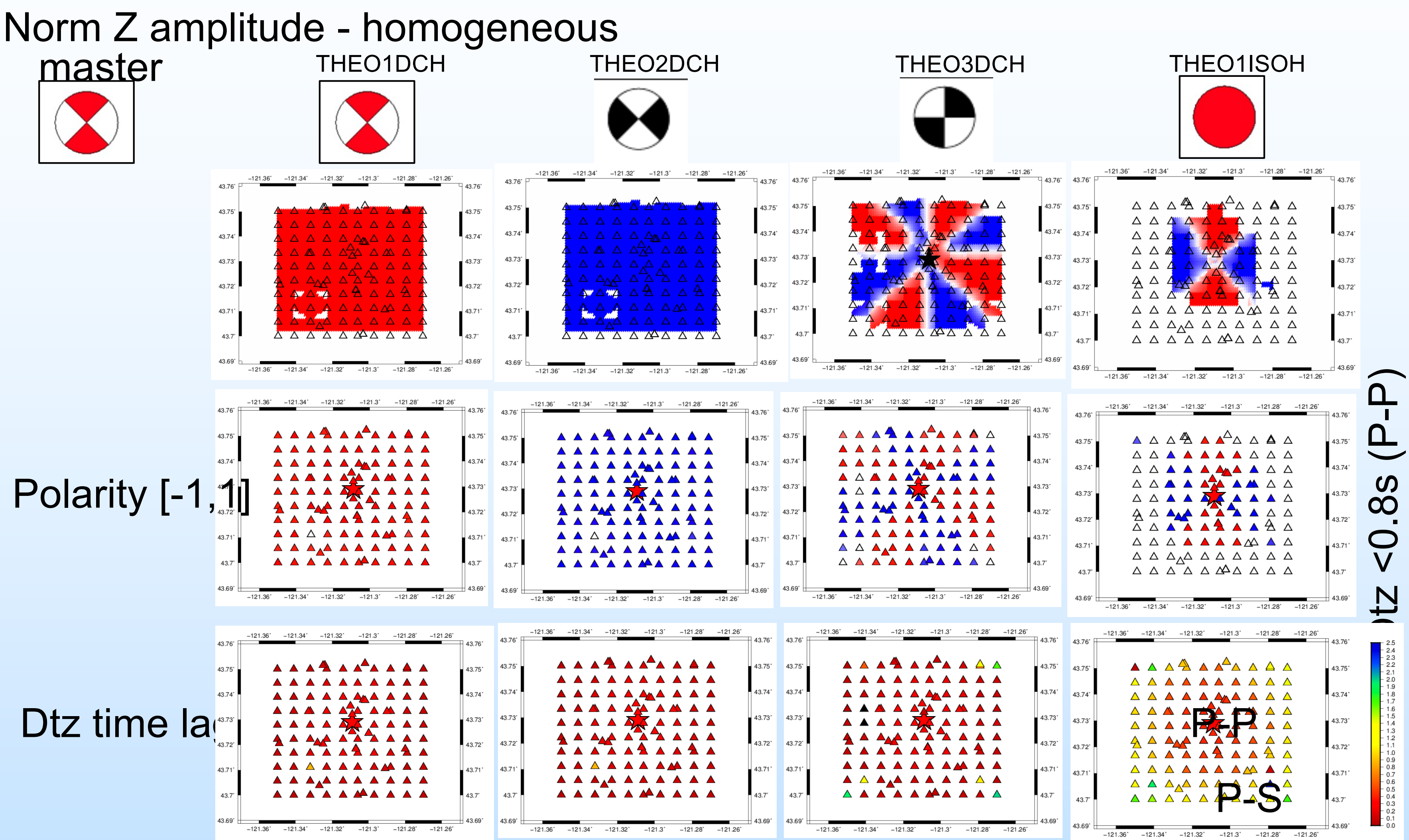
Above: the evolution of the VSM envelopes over time suggests an evolving pressure field.



"virtual seismometer"

$$CC = M_1 \; M_2 \; GF_{12}$$

VSM allows retrieval of moment tensor components from both events



Accomplishments to Date

Seismic Interferometry

- Provide high-resolution characterization of the subsurface and allow precise measurements on the evolving state of the storage reservoir
- High resolution of seismic velocities and attenuation can be used to infer porosity, permeability and fluid saturation.
- Qs/Qp illuminates fluid pathways.
- Changing fluid pressures appear immediately in the seismic amplitudes, best identified by changes in the attenuation of seismic energy.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The PoroTomo project was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Numbers DE-EE0006760 and DE-EE0005510.

Accomplishments to Date

Seismoelectric Effects

- We have created capability to numerically calculate seismic-to-electric conversion to capture seismoelectric effects, coupling Biot poroelastic seismic and electromagnetic wave propagation
- Demonstrated the sensitivity of SEE to electric (resistivity) contrasts, which can be used to monitor CO_2 .
- SEE captures more detail of these structures than purely seismic recordings.
- Although the signal-to-noise ratio of the converted seismic-to-electric signals can be critical, a well-designed network using both seismic and EM instruments would enable better monitoring of CO_2 by combining the advantages of both deep-probing seismic signals and fluid-sensitive EM signals.

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Accomplishments to Date

Seismoelectric Effects

- Full waveform adjoint capabilities for SEE to fully characterize subsurface properties (CO_2, brine)
- Validation of SEE in-house code with experimental data through a collaboration with University of Pau and Pays de l'Adour (France) in Spring 2020

Fiber Optic comparison to Geophone data

- Can be used in place of individual geophones, significantly reducing the associated costs.
- Notable differences in sensitivity need to be understood to adapt the new technology.

Network Design:

- Develop a protocol for the deployment and analysis of large-N data sets to track the movement of fluids in a storage reservoir, allowing it to be documented in the field over time.

Synergy Opportunities

We have been involved in several multi-lab and multi-institution partnerships to advance our research and technologies.

- Validation of SEE in-house code with experimental data through a collaboration with University of Pau and Pays de l'Adour (France) in Spring 2020
- University of Wisconsin, Lawrence Berkeley Lab, Ormat and Silixa as part of the "Poroelastic Tomography" (PoroTomo) experiment at Brady geothermal field.
- LANL, University of Utah, and MIT, as part of the ongoing "Fracture and Permeability Imaging" EERE project.
- Cryq and Alta Rock Energy have been partners on both the "Fracture and Permeability Imaging" project and on several projects done at Newberry volcano.
- Array Information Technology, Inc., about using his highly characterized Geysers microseismicity data set for VSM analysis.

Appendix

Benefit to the Program

The project will result in a set of technologies, strategies, and algorithms for monitoring the evolution of a CO_2 plume. This will include detailed description of sensitivity and capabilities of the interferometric and seismo-electric techniques, along with optimal network design and a description of the ideal combination of traditional geophone and fiber optic sensors.

- Current status of project:
  - Passive seismic methods capable of identifying and monitoring fluids in the subsurface.
  - Codes capable of calculating the seismo-electric response of a CO_2 intrusion.
  - Fiber optic and geophone networks have complimentary sensitivity to the seismic wavefield.
- End/final state of product –
  - Develop a protocol for the deployment and analysis of large-N networks to track the movement of fluids in a storage reservoir, allowing it to be documented in the field over time.

Project Overview

Award: FWP-FEW0191 (Susan Carroll PI)

Project Description

Tasks designed to advance the capabilities of analytical tools that will be needed to safely inject and store CO_2 in the subsurface.

Five tasks with specific technical focus:

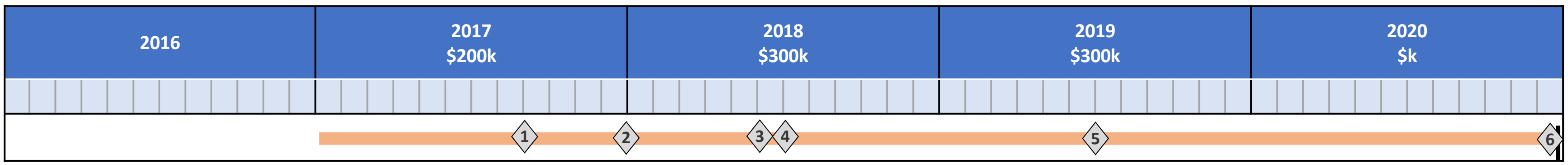
Task 1 – CO_2 Storage Carbonate Reservoirs
Task 2 – Microseismic Toolset for Fault Detection and Seismicity Mitigation
Task 3 – Implications of Stress State Uncertainty on Caprock and Well Integrity
Task 4 – Industrial CO_2 Demonstrations
Task 5 – Novel Monitoring Techniques for CO_2 Storage Using Large-N Seismic Arrays

Project Benefits

Objective: Understand of the behavior of CO_2 injected underground for permanent storage, and detect it’s effects.

- We want to be able to monitor the movement of CO_2 sequestered in the Earth.
- Need to ensure that CO2 sequestered in the ground will remain there, can be monitored over time and that the pressure field changes created don't fracture the seal or trigger induced events.

Gantt Chart



Milestones

1. Demonstrated that fluids can be mapped using passive seismic arrays
2. Were able to observe changes over time as fluids traveled through the subsurface.
3. Developed in-house software to calculate the seismo-electric wavefield.
4. Calculated the seismo-electric response of a CO_2 intrusion.
5. VSM methodology used to image fault structure.
6. Complete analysis comparing the capability of geophone and fiber optic data sets

Chart Key

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

Key Accomplishments/Deliverables	Value Delivered
2017: Demonstrated capability using passive seismic methods to identify fluids in the subsurface, map their migration paths and monitor changes over time. **2018**: Developed new software for SEE and confirmed ability to detect brine/CO_2 interface. **2019**: High resolution imagery using VSM. **2020**: Fiber optic/ geophone analysis. Note: dates reflect the funding year.	• High resolution of seismic velocities and attenuation can be used to infer porosity, permeability and fluid saturation. • Seismic attenuation illuminates fluid pathways. • Changing fluid pressures appear immediately in the seismic amplitudes, enabling us to track fluid movement. • Completed development of new software for coupled seismo-electric calculations. • Demonstrated that SEE can detect the brine/CO_2 interface.