Task 5: Large N Seismic Arrays

Project Number (FEW0191)

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National Energy Technology Laboratory

Carbon Capture Front End Engineering Design Studies and CarbonSafe
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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: develop three novel monitoring techniques for imaging 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) : use both seismic-to-electric effects to resolve fluid phase properties and constrain subsurface permeability measurements.
4) (Fiber-Geophone comparison): address challenges and illustrate the power of applying these three techniques to large data sets made possible through the deployment of seismic and fiber optic sensors.

What is "Large-N"?

N : number of unique measurements

number of seismometers
or
number of earthquakes

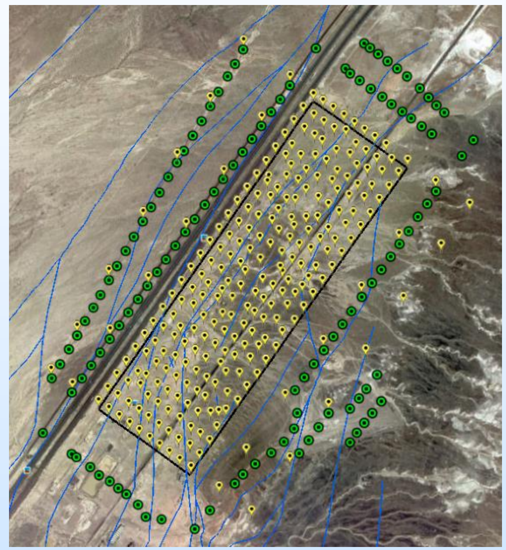
Ncorrelations = N*(N-1)/2

Large:

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

Differences in resolution

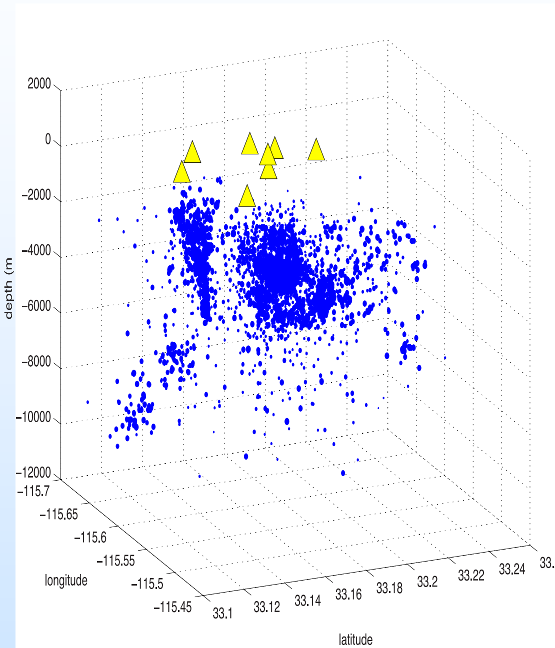
100's to 1000's of microquakes at active sites.



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)



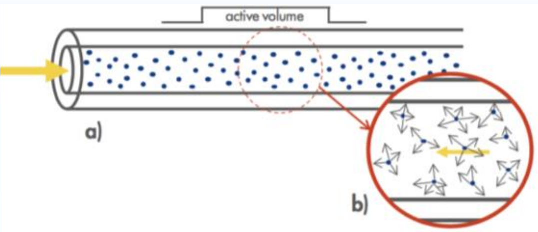
Salton Sea geothermal region

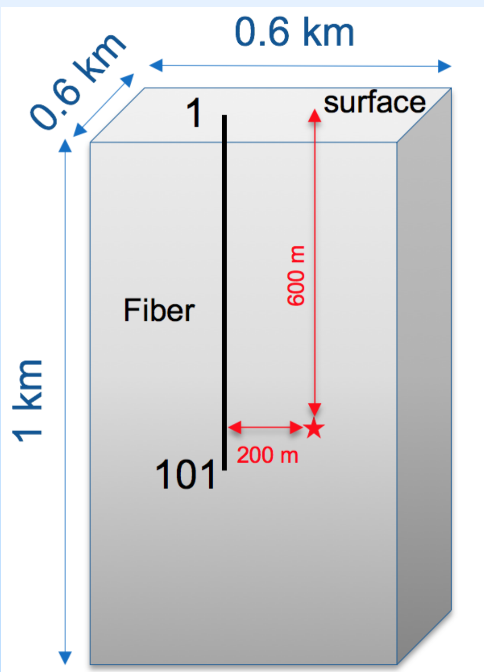
- Long term monitoring
- Thousands of cataloged microquakes
- Leverages work done for location identification 3D modeling, etc.
- Continuous and event data in-house

(Wang, Templeton, Rhode and others)

Fiber Optic sensors: An inherently Large-N technology

[Lumens, 2014]

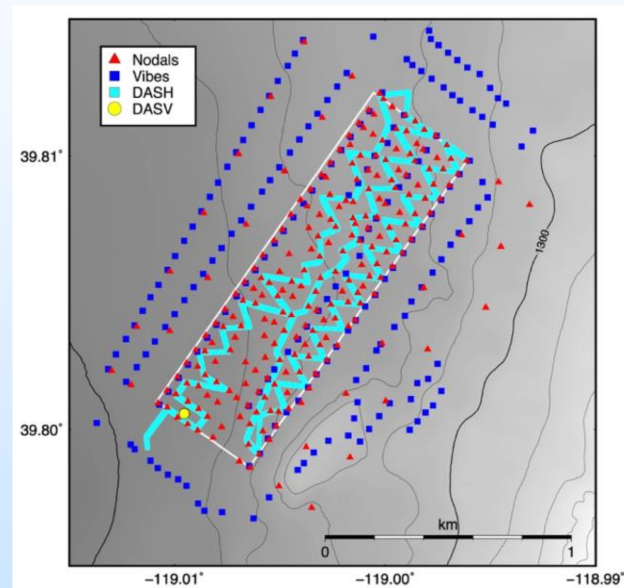




Fiber can be easily deployed downhole

- Fiber-optic sensors offer high spatial resolution (~1m) over large distances (~km)
- Sensitive to axial strain
- Single component, highly sensitive to geometry of the system (unlike 3D geophones)

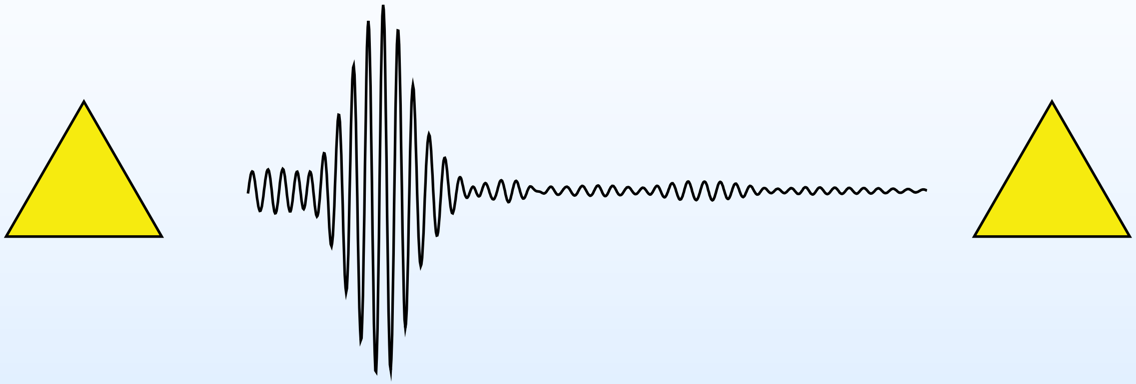
Fiber at Porotomo (cyan) was interspersed with geophones (red)



- Fiber-optic data can be used for subsurface characterization and moment tensor inversion

We have developed codes to calculate the fiber response and inversion routines for moment tensor analysis.

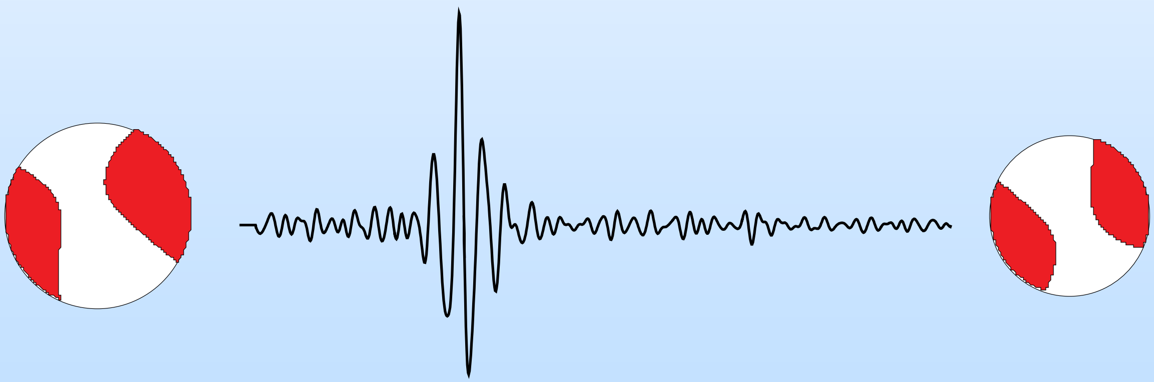
Seismic Interferometry: Virtual Earthquakes and Virtual Seismometers



ANC, CWI

"virtual earthquake"

$CC = GF_{AB}$



VSM

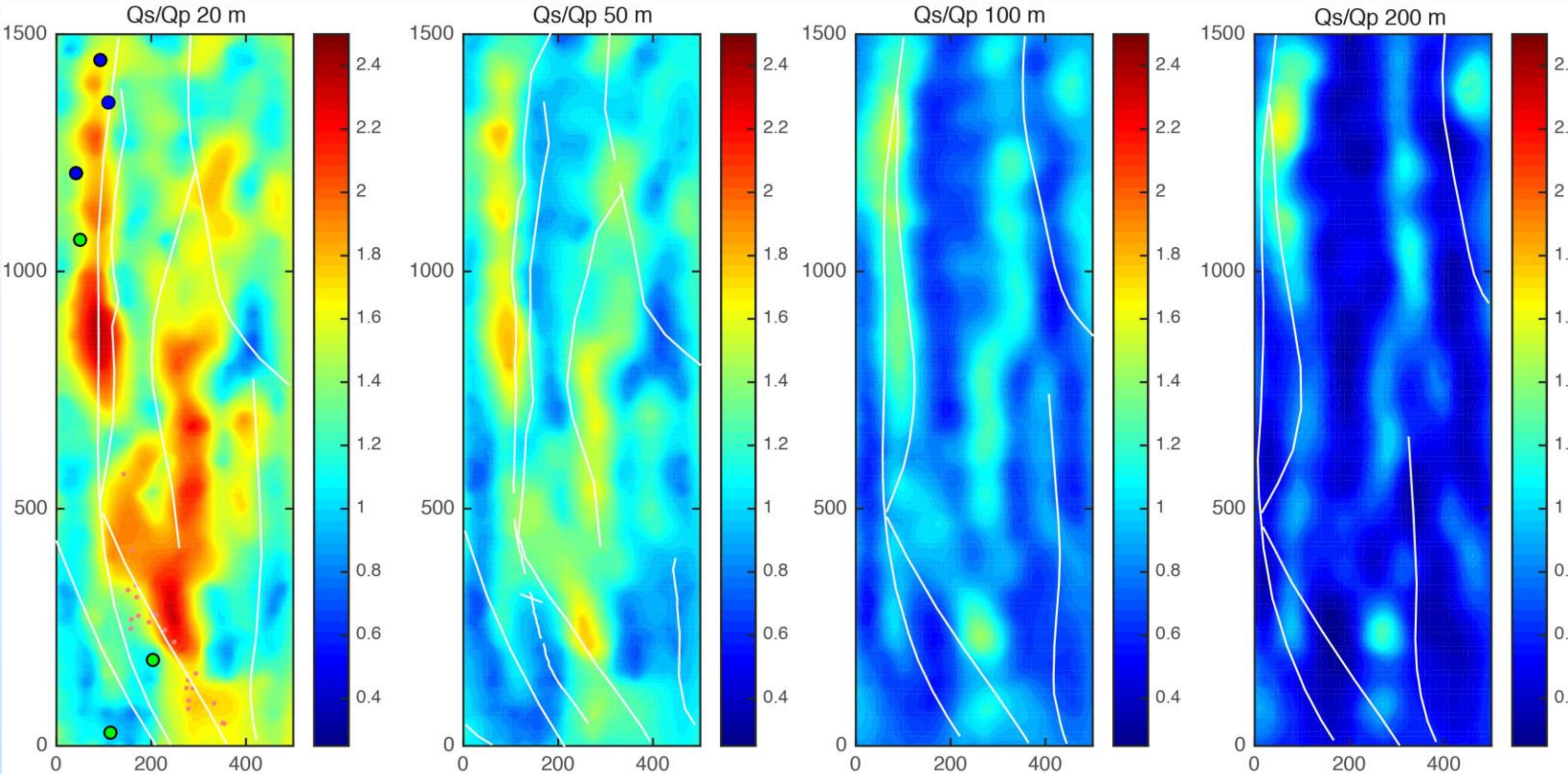
"virtual seismometer"

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

reference: Curtis et al. 2009

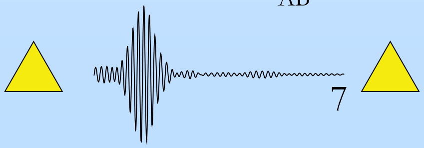
Both methods: Ncorrelations = N*(N-1)/2

Seismic Interferometry: Qs/Qp illuminates fluid pathways

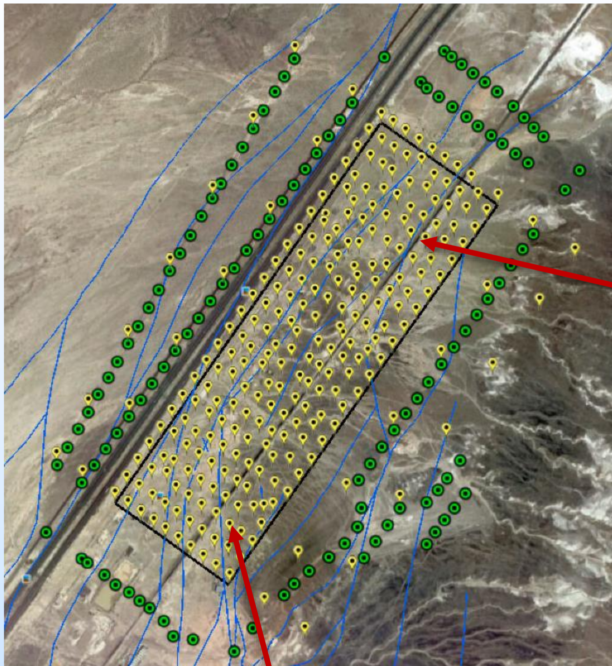


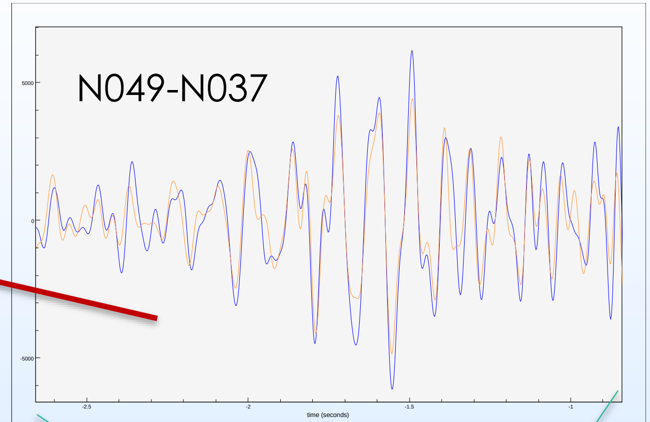
- 238 geophones result in > 28,000 independent measurable waveforms.
- We are able to resolve the elastic properties (Vs, Vp, Qs, Qp) in high detail.
- P-waves and S-waves have distinctly different sensitivity to the presence of fluid filled pore spaces. Ratios are used to identify fluid contacts.

ANC
"virtual earthquake"
CC = GF_{AB}



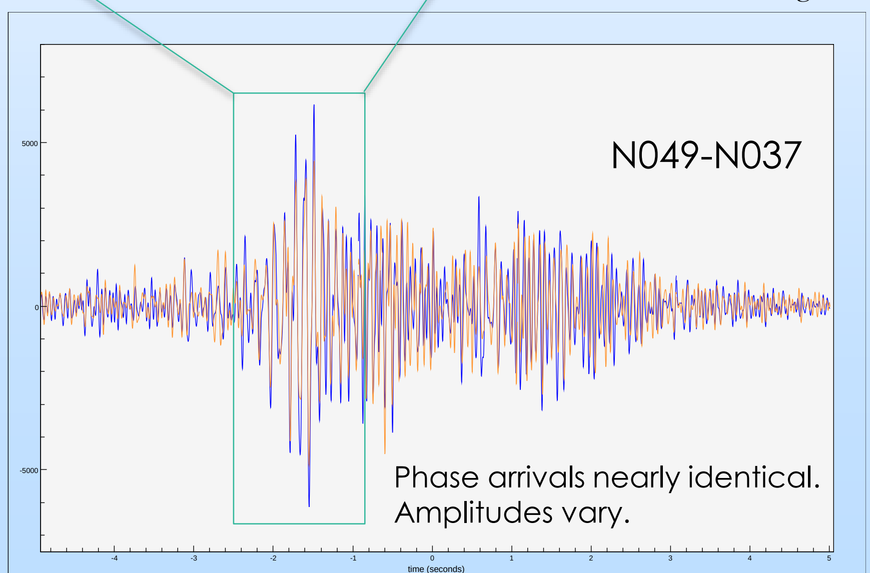
Phase arrival times are nearly identical, but amplitudes changed measurably after site shutdown

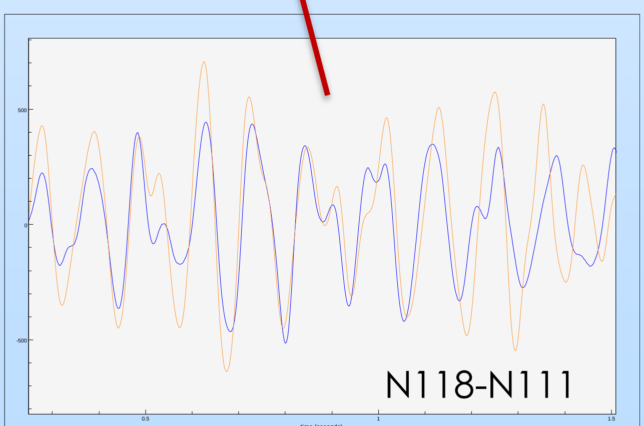




Seismic amplitudes reacted differently across the site in response to changing fluid pressures: increasing in the South and decreasing in the North after injection was stopped.

Normal Ops: Blue
Site Shutdown: Orange

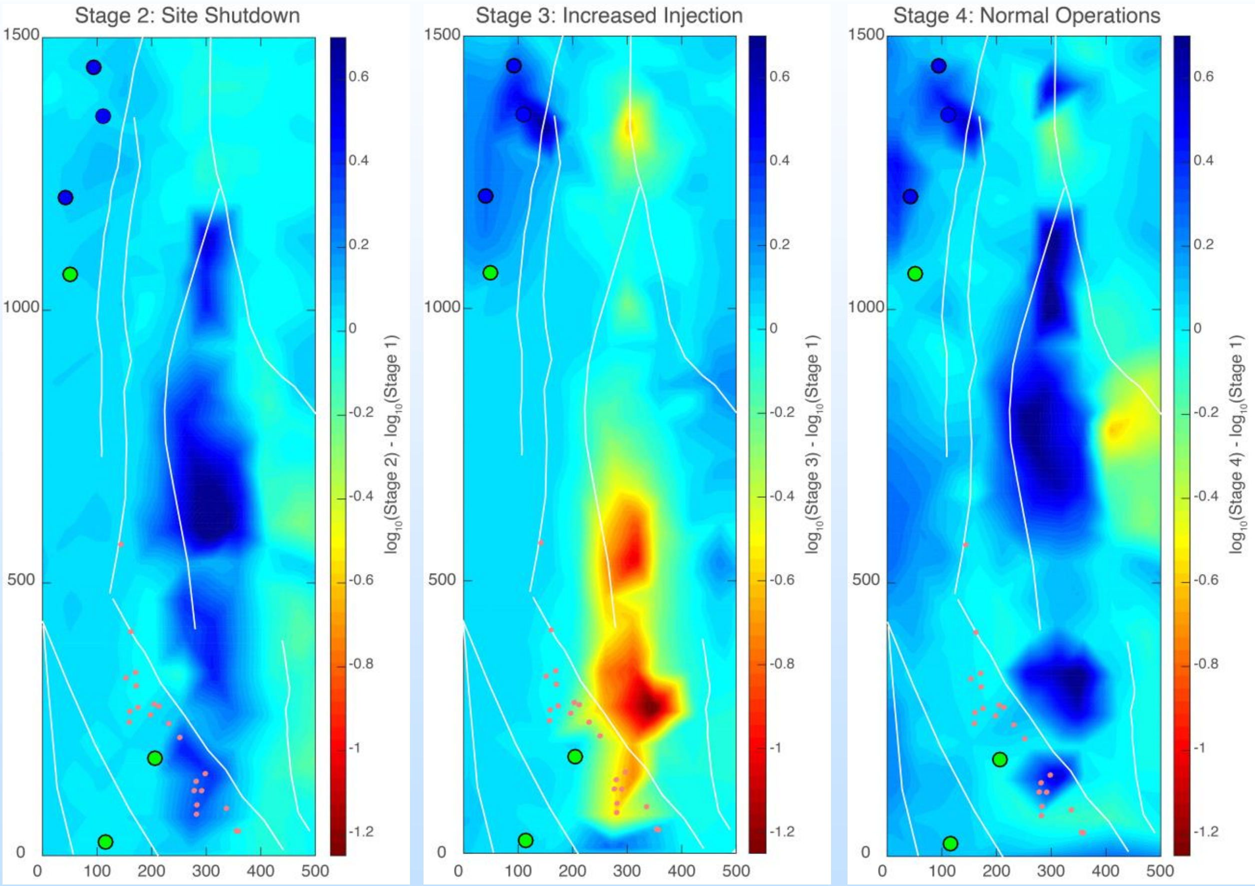




Seismic Interferometry: can rapidly indentify changes in subsurface

Seismic amplitudes changed measurably and immediately as fluids moved through the system.

We see spatial variations across the site in response to changing fluid pressures: increasing in the South and decreasing in the North after injection was stopped.



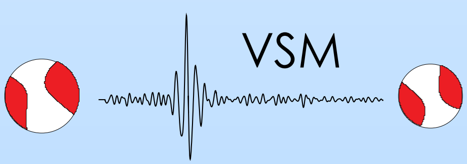
Dynamic changes in seismic amplitudes as operations changed

- blue: more efficient propagation
- red: more attenuated

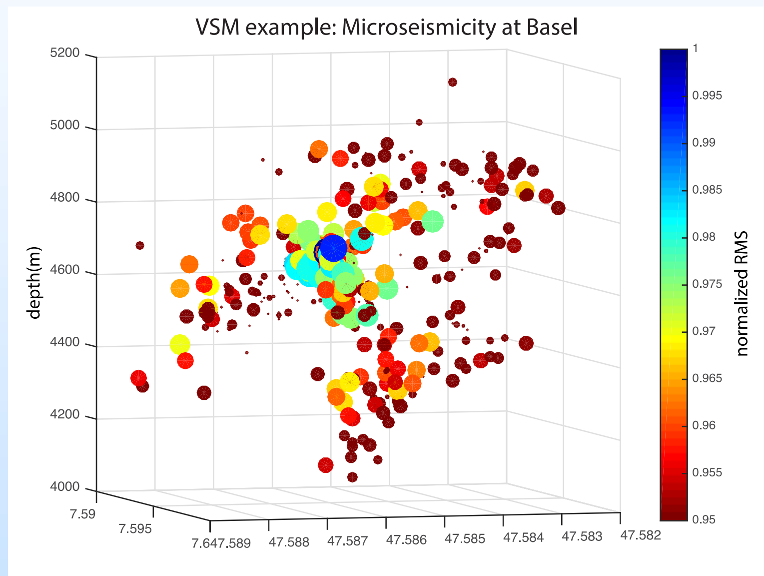
Virtual Seismometers: focusing in on the active region

VSM can increase the resolution in seismically active areas by orders of magnitude

- Focus – state of subsurface before and after large seismic events.



"virtual seismometer"
$CC = M_1\ M_2\ GF_{12}$



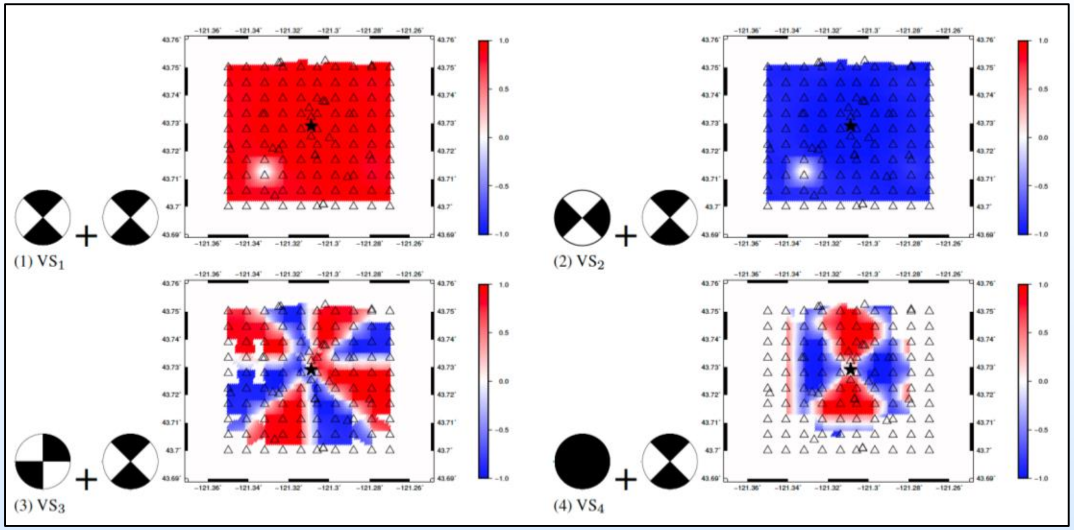
(Basel):

- 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.

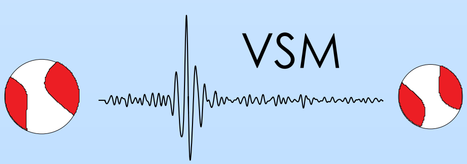
VSM allows high resolution of both structure and source characteristics



Can be used to identify the style of slip (related to the state of stress)

And to characterize the structure within and between faults (illuminating zones of weakness).

We have developed codes to measure focal mechanisms from VSM waveforms



"virtual seismometer"

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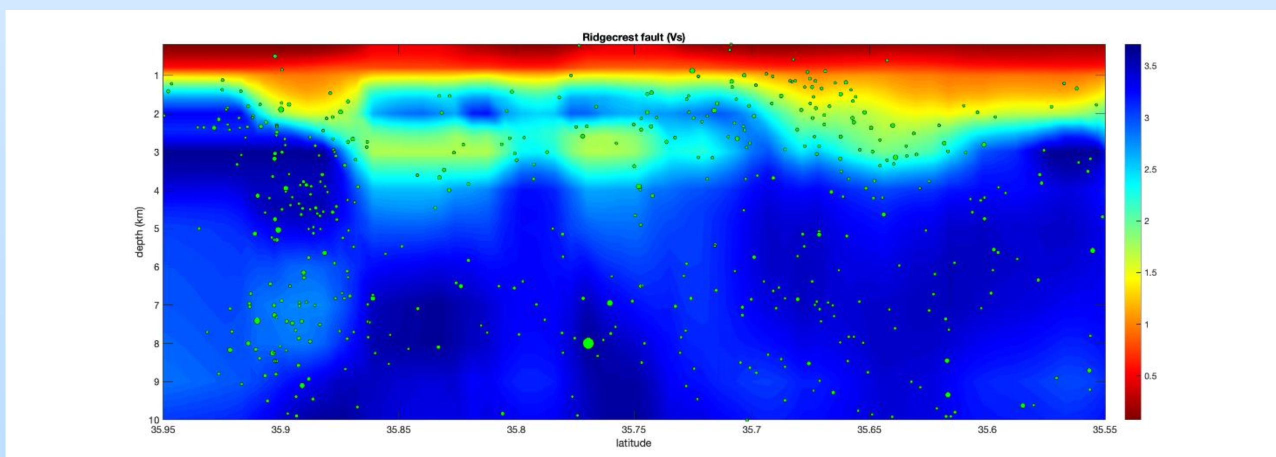
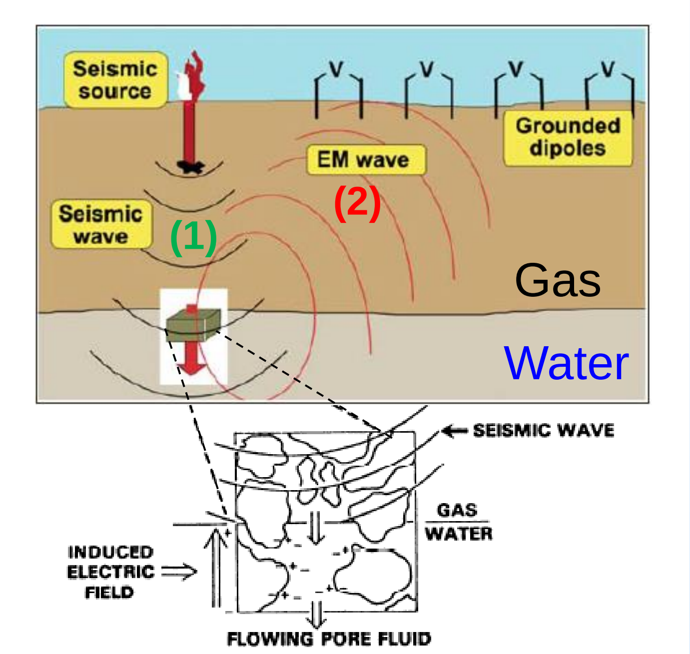


Seismoelectric effects (SEE) for CO_2 monitoring

- 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

SEE can directly detect the brine/CO_2 interface

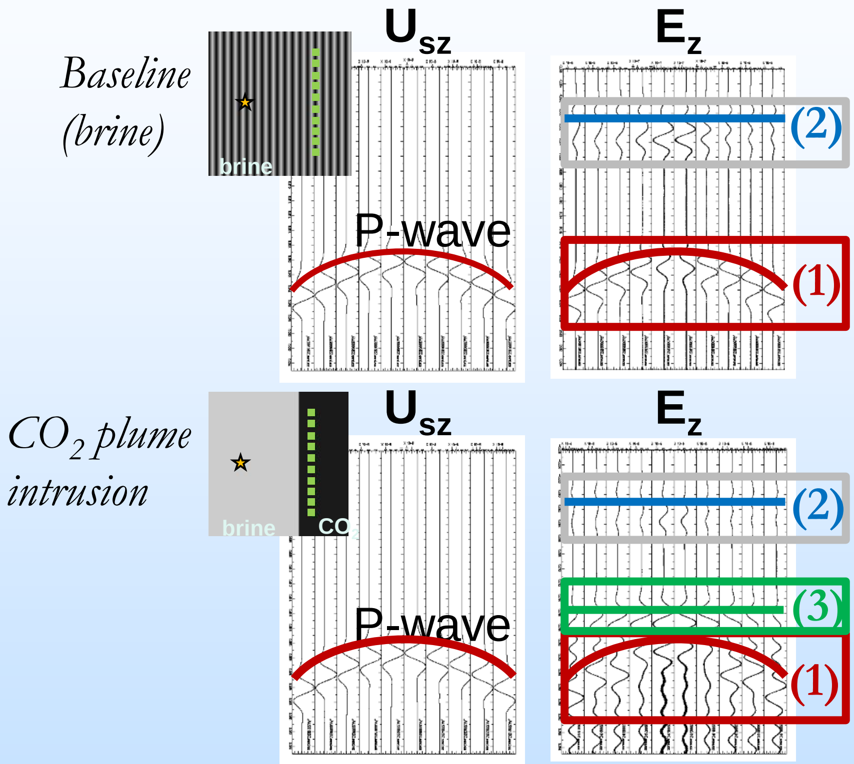
Our in-house software accurately detects 3 types of seismic-to-electric conversions:

(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.



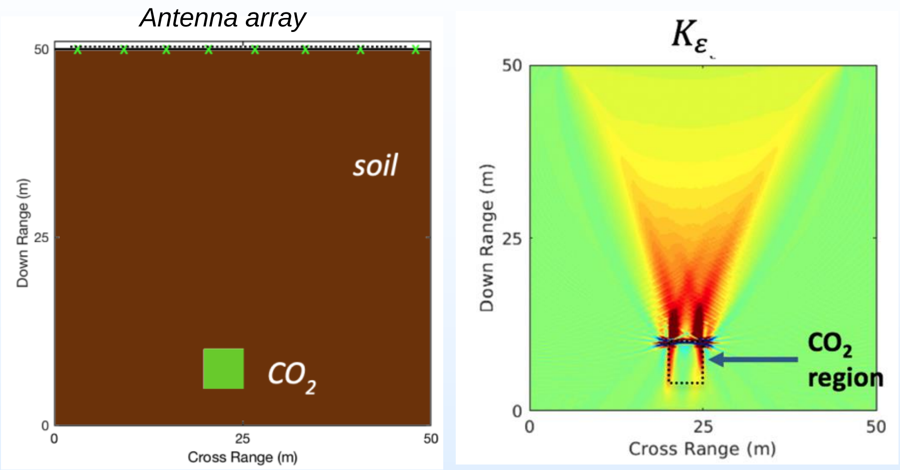
Seismograms (left) & electrograms (right)

Finite-frequency sensitivity kernels for subsurface CO_2 imaging

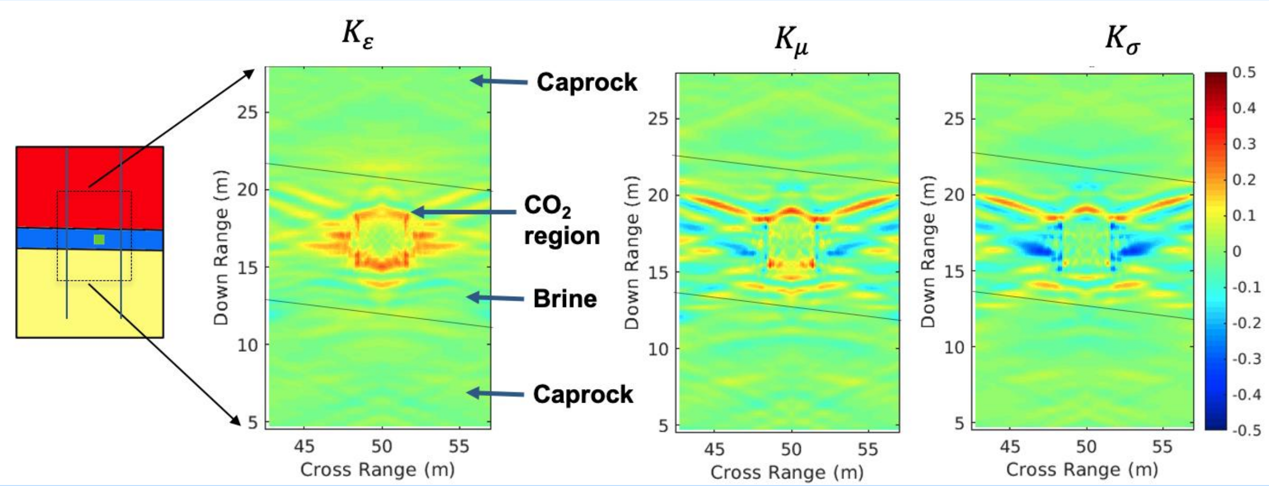
Goal: Detect CO_2 in brine saturated aquifer using radar based adjoint imaging

Status: calculation of SEE resolution kernels

Future Work: Iterative framework for inversion of electromagnetic properties, conduct feasibility studies to determine parametric limits for detection of sub-surface CO2 using this method.



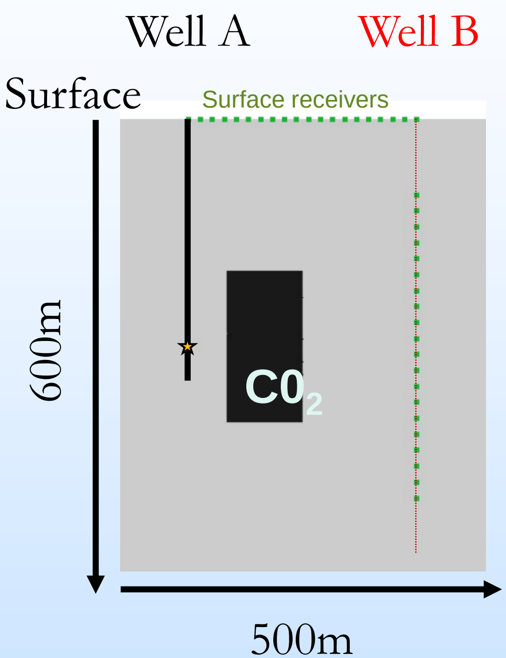
2-D TM mode ground penetrating radar setup : CO_2 close to subsurface, permittivity kernel shows detection capabilities



Preliminary results : Sensitivity kernels detect CO_2 region. Permittivity kernel shows maximum contrast.

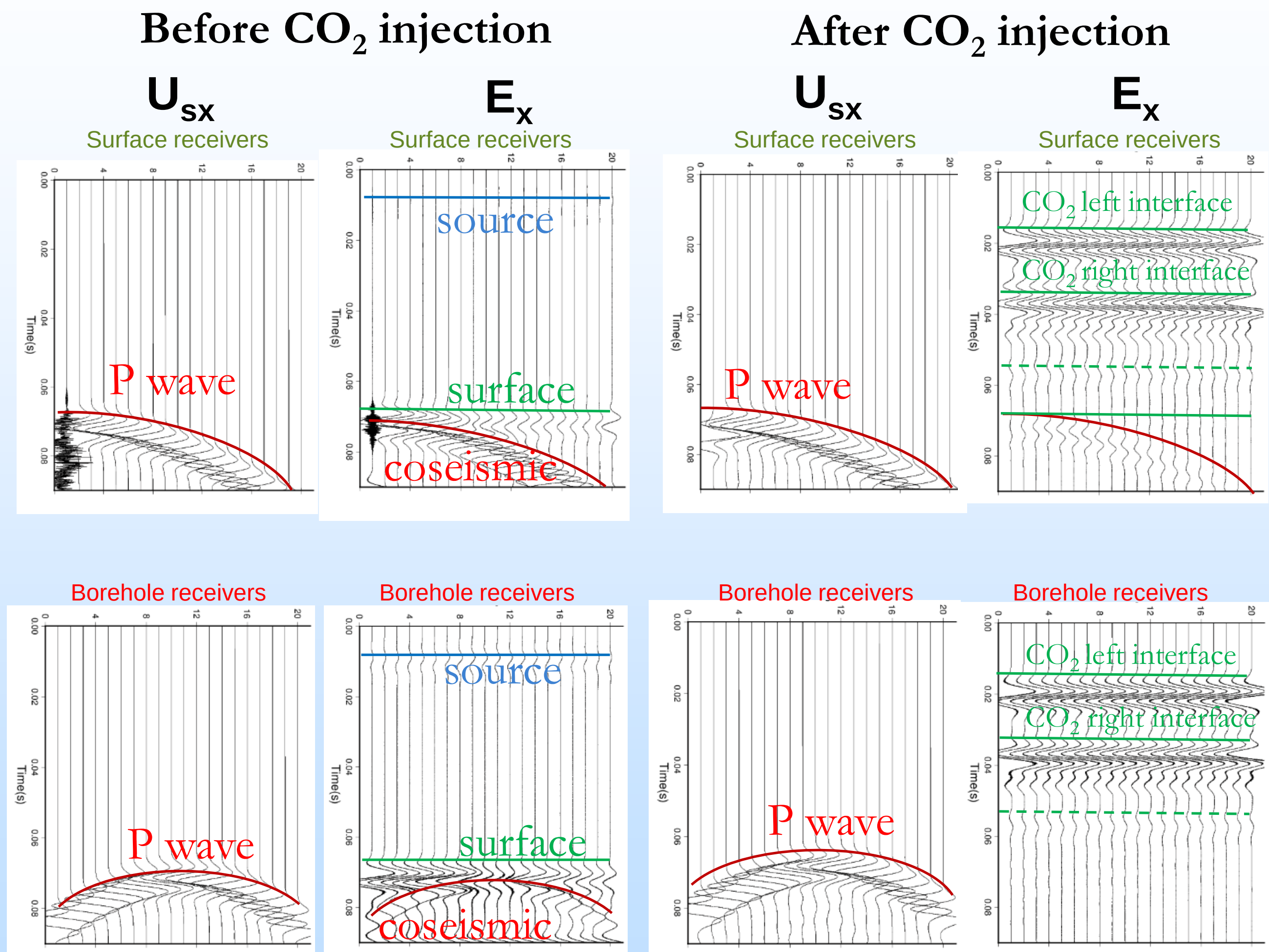
Mukherjee, S. & Morency, C., Finite-frequency sensitivity kernels based upon adjoint methods for electromagnetic wave propagation, GJI 2020. (submitted).

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

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.

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.

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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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)
- 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.

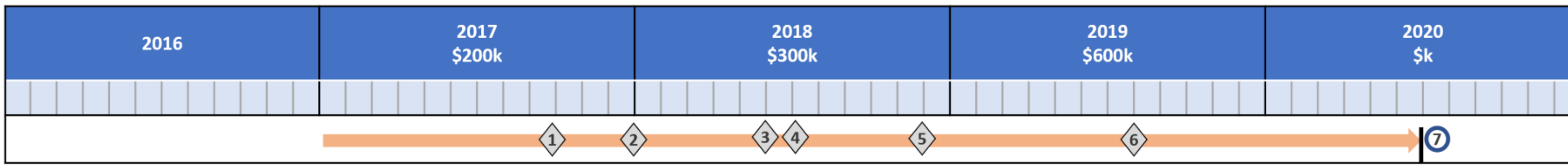
Appendix

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.
- 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.

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. Calculated 20,000 virtual seismograms to investigate post-seismic response of fluid pressures.
6. Developed codes to calculate invert focal mechanisms using virtual seismometers.
7. Complete analysis comparing capability of geophone and fiber optic data sets.

Chart Key

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

Go / No-Go

Impact

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:** Use of virtual seismometers to calculate focal mechanisms for individual events. 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. • VSM focal mechanisms can help define the stress field.

Organization Chart

- Project Team

Eric Matzel	Interferometry and waveform inversion
Christina Morency	Seismo-Electric algorithm development
Saptarshi Mukherjee	Seismo-Electric kernel calculation
Robert Mellors	Fiber Optic

- Lawrence Livermore National Laboratory
  - Atmospheric, Earth, & Energy Division

Project Overview

Award: FWP-FEW0191 (Josh White 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.

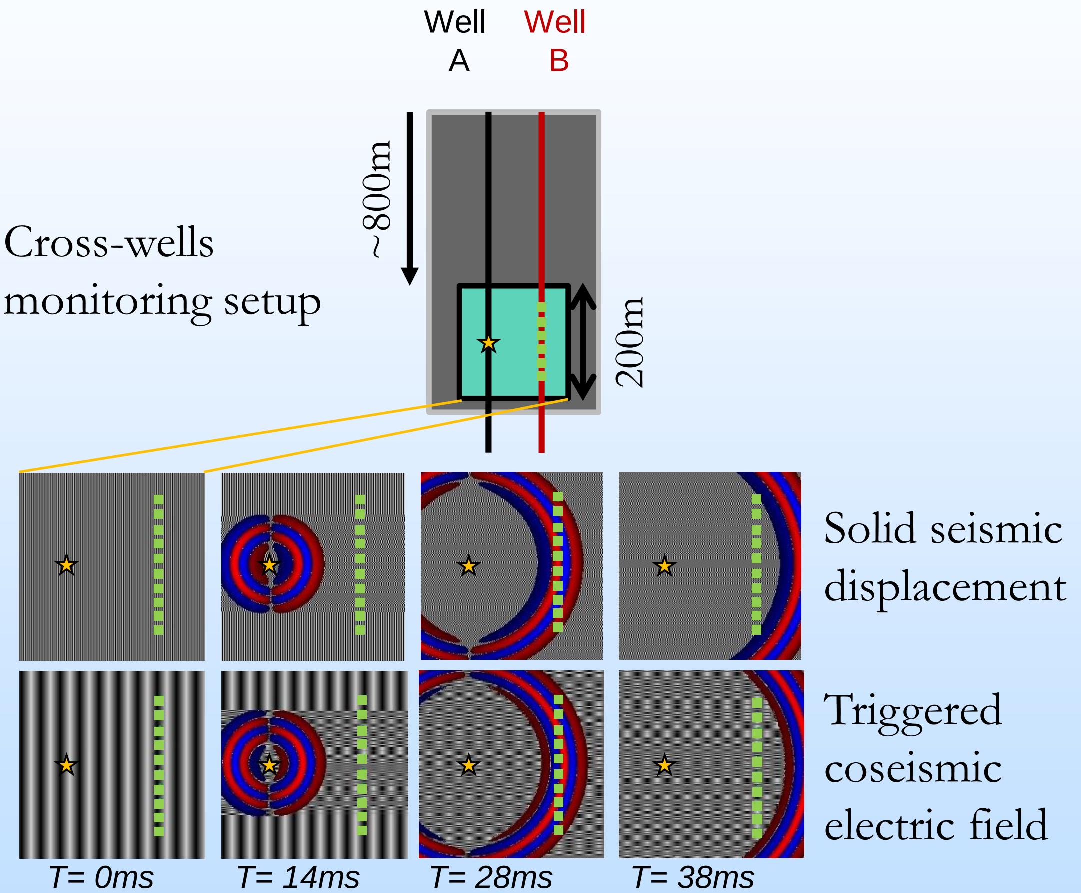
- We want to be able to monitor the movement of CO_2 sequestered in the Earth.
- Need to ensure that CO2 sequestered in the ground will remain there, can be monitored over time and that the pressure field changes created don't fracture the seal or trigger induced events.

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



Coseismic transient electric field accompanying the seismic wave is properly recovered