Advances in Large-N Seismic Measurements to Monitor Reservoir Behavior

Project Number (FWP-FEW0191)

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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.
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): use 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.

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"

$\text{CC} = G_{F_{AB}}$

VSM
"virtual seismometer"

$\text{CC} = M_1 M_2 G_{F_{12}}$

Both methods: $N_{\text{correlations}} = N(N-1)/2$

Reference: Curtis et al. 2009
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 South increased after shutdown.

Amplitudes in the North decreased after shutdown.

Phase arrivals nearly identical. Amplitudes vary.
Seismic Interferometry: can rapidly identify 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
Seismoelectric effects (SEE) for CO₂ 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 CO₂, 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 CO₂)

Coseismic transient electric field accompanying the seismic wave is properly recovered
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/CO₂ interface
Seismic alone cannot.
Idealized setup for SEE monitoring of CO₂

Before CO₂ injection

Surface receivers

P wave

Coseismic

Surface & interface SEE signals are quasi-instantaneous with amplitude variations

After CO₂ injection

Surface receivers

P wave

CO₂ left interface

CO₂ right interface

20 surface geophones and antennas
20 borehole geophones and antennas

Resistivity ($1/\sigma$) increases with CO₂ replacing brine
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 early stages of this task.
- Status: we have calculated tens of thousands of virtual seismograms for tectonically active sites near fluid injection.

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

"virtual seismometer"

\[ CC = M_1 M_2 G F_{12} \]
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.

• $Q_s/Q_p$ illuminates fluid pathways.

• Changing fluid pressures appear immediately in the seismic amplitudes, best identified by changes in the attenuation of seismic energy.

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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 CO₂.

• 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 CO₂ by combining the advantages of both deep-probing seismic signals and fluid-sensitive EM signals.

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Upcoming Work

Seismoelectric Effects
- Full waveform adjoint capabilities for SEE to fully characterize subsurface properties (CO₂, 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.
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 CO₂ 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 CO₂ 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 CO₂ intrusion.
5. Calculated 20,000 virtual seismograms to investigate post seismic response of fluid pressures.
6. Complete analysis comparing the capability of geophone and fiber optic data sets

Key Accomplishments/Deliverables

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/CO₂ interface.

Value Delivered
- 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/CO₂ interface.

Note: dates reflect the funding year.
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 CO₂ in the subsurface.

Five tasks with specific technical focus:

Task 1 – CO₂ 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 CO₂ Demonstrations
Task 5 – Novel Monitoring Techniques for CO₂ Storage Using Large-N Seismic Arrays

Project Benefits
Objective: Understand of the behavior of CO₂ injected underground for permanent storage, and detect it’s effects.

- We want to be able to monitor the movement of CO₂ 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.
Instrumentation

Seismo Electronics LLC (Houston, TX)

DC-4500 Features:
• Output Noise: 20VP-P at 90db gain
• Work time: 5 hours
• Work temperature: -20 to 60 degrees Celsius
• Stacking Trigger Accuracy: 0.05 of sample rate
• Operating system: Window XP
• Bundled software: data collection

Accessories include:
• Seismoelectric electrodes
• Geophone

Surface seismic source:
• Sledge Hammer
• Buffalo Gun (used to reach 2km depth)
• Weight Drop Seismic source

Some Applications:
• Fracture Aquifer, Llano Intrusive Project TX, US (2011)
• Aquifer, Haiti (2011)
• Oil, Thrail Oilfield Project, TX, US (2012)
• Oil, Lockhard Oilfield Project, TX, US (2012)
• Geothermal, Sinopec Project, TX, US (2014)

SEE commercially used for oil, gas and water survey