JOINT INVERSION OF TIME-LAPSE SEISMIC DATA
DE-FOA0001725

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U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
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PRESENTATION OUTLINE

• Interpretation of Time-Lapse Seismic Data
• Towards Improving the Certainty of CO₂ Plume Position with Seismic Joint Inversion
  a) Wave-Equation-Based (WEB) Amplitude-Variation-with-Offset (AVO)
     • Preliminary Results: Single vs. Joint Inversion
  b) Joint Impedance and Facies Inversion
• Accomplishments
• Lessons Learned
• Synergy Opportunities
• Summary

Bell Creek Field, Montana (Denbury)

CO₂ injection: May 2013

CO₂ injection: Dec 2013

Modified after Salako et al. (2018)
INTERPRETATION OF TIME-LAPSE SEISMIC DATA (2012‒2014)

- CO₂ Banking Against Permeability Barrier
- Higher Time-Lapse Response Due to Pressure
- Fluid and Pressure Communication Between Two Production Phases
- Pressure Buildup Due to Water Injection
- Southeastern Extension of the Permeability Barrier

Modified after Salako et al. (2017)
SEISMIC INVERSION

**Inverse Problem**

**Forward Problem**

**ELASTIC PROPERTIES**

Source $\rightarrow$ Distance $\rightarrow$ Receiver

- Layer 1: $A_1, S_1, \rho_1$
- Layer 2: $A_2, S_2, \rho_2$
- Layer 3: $A_3, S_3, \rho_3$

**SEISMIC DATA** + WELL LOGS + GEOLOGIC INFORMATION

Distance $\downarrow$ Time $\downarrow$ Depth
**JOINT INVERSION**

Inverse Problem

**ELASTIC PROPERTIES**

Source -> Distance -> Receiver

Layer 1: AI 1, SI 1, \( \rho_1 \)
Layer 2: AI 2, SI 2, \( \rho_2 \)
Layer 3: AI 3, SI 3, \( \rho_3 \)

**Baseline**

**Monitor**

TIME-LAPSE SEISMIC DATA + WELL LOGS + GEOLOGIC INFORMATION
Inverse Problem

Joint Impedance and Facies Inversion (Ikon Science)

Baseline

Monitor

TIME-LAPSE SEISMIC DATA
+ WELL LOGS + GEOLOGIC INFORMATION

CO₂ SATURATION MODELS & AMOUNT OF STORED CO₂

ELASTIC PROPERTIES

Rock Physics

Source Receiver

Layer 1
AI 1, SI 1, ρ₁

Layer 2
AI 2, SI 2, ρ₂

Layer 3
AI 3, SI 3, ρ₃

Depth

Distance

Time
WEB-AVO

- Target-oriented full-waveform elastic inversion of seismic data.
  - Wider bandwidth and less noise
- Directly inverts for compressibility (1/bulk modulus) and shear compliance (1/shear modulus).
  - More sensitivity to changes in pore fill => highly suitable for time-lapse monitoring
- Inversion of migrated data in time and output in depth.
  - Avoid prone-error postinversion depth conversions

Gisolf et al. (2017)
INPUT DATA

3-D Seismic Data Baseline (2012)

3-D Seismic Data Monitor (2014)

Well Logs and Horizons

Seismic Velocities
BACKGROUND MODEL

P Velocity

S Velocity

Density
DATA PRECONDITIONING I

Common Offset Gather

Ray Parameter Gather
DATA PRECONDITIONING II


After Preconditioning

- Dip Filtering
- Offset Amplitude Balancing
WAVELET ESTIMATION FROM SEISMIC-TO-WELL TIE – EXAMPLE
INVERSION ALONG AN ARBITRARY LINE

Modified after Salako et al. (2017)
SEISMIC DATA – BASELINE (2012)
SEISMIC DATA – MONITOR (2014)
TIME-LAPSE DIFFERENCE (MONITOR – BASELINE)
SINGLE INVERSION: COMPRESSIBILITY BASELINE
SINGLE INVERSION: COMPRESSIBILITY MONITOR
SINGLE INVERSION: TIME-LAPSE DIFFERENCE OF COMPRESSIBILITY
SINGLE INVERSION: SHEAR COMPLIANCE BASELINE
SINGLE INVERSION: SHEAR COMPLIANCE MONITOR
SINGLE INVERSION: TIME-LAPSE DIFFERENCE OF SHEAR COMPLIANCE
JOINT INVERSION: COMPRESSIBILITY BASELINE
JOINT INVERSION: COMPRESSIBILITY MONITOR
JOINT INVERSION: TIME-LAPSE DIFFERENCE OF COMPRESSIBILITY
JOINT INVERSION: SHEAR COMPLIANCE BASELINE
JOINT INVERSION: SHEAR COMPLIANCE MONITOR
JOINT INVERSION: TIME-LAPSE DIFFERENCE OF SHEAR COMPLIANCE
TIME-LAPSE DIFFERENCE OF COMPRESSIBILITY

Wells along line

SINGLE INVERSION

JOINT INVERSION
TIME-LAPSE DIFFERENCE OF SHEAR COMPLIANCE

Wells along line

Critical Challenges.  Practical Solutions.
JOINT IMPEDANCE AND FACIES INVERSION

• Different low-frequency models for each defined facies.
  – Bayesian analysis within the inversion to choose low-frequency model.
  – Multiple facies-based low-frequency models => Better quality of inverted elastic parameters than conventional inversions.
• Rock physics constrained by geologic facies => representative of subsurface geology.
• Time-lapse difference from single or joint inversion => high-quality images of the dynamic changes in reservoir.

(www.ikonscience.com/software/ji-fi-introduction)
ACCOMPLISHMENTS TO DATE

Wave-Equation-Based (WEB) Amplitude-Variation-with-Offset (AVO)
• Data gathered, loaded, quality-checked.
• Created initial background model.
• First seismic data-conditioning tests completed.
• Finished well tie and estimated wavelet activities.
• Defined tests of single vs. joint inversion.
  – Line of arbitrary geometry.
  – First joint inversion with WEB-AVO accomplished.

Joint Impedance and Facies Inversion
• Defined hardware to be used in the project.
• Arranged software training.
LESSONS LEARNED

• Input data require detailed analysis before using in inversion.
• A multidisciplinary approach is required from the beginning of the project.
• Results of the joint inversion should be validated with detailed analysis of engineering data.
• Land seismic data present more challenges than marine data.
• Seismic data conditioning may require several iterations for WEB-AVO single inversion.
• Arbitrary lines can be used to conduct rapid tests before three-dimensional tests.
SYNERGY OPPORTUNITIES

- Any CO₂ storage project with conventional time-lapse seismic data.
- Joint inversion projects with conventional surface seismic and controlled source electromagnetic data.
PROJECT SUMMARY

• Key findings
  – Encouraging results of WEB-AVO joint inversion.

• Next steps
  – Wave-Equation-Based Amplitude-Variation-with-Offset
    ◆ More tests using an arbitrary line that consider geophysical, geological, and reservoir engineering information.
    ◆ Define new seismic data-conditioning tests.
    ◆ Thorough validation of joint inversion option.

  – Joint Impedance and Facies Inversion
    ◆ Complete software training, and start rock physics tests.
CONTACT INFORMATION

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THANK YOU!
Program Goals Addressed

1. Develop methods that improve the certainty about the position of the CO₂ plume over time, within various geologic formations and depositional environments.
2. Detect stored CO₂ and assess the CO₂ plume boundaries over time.
3. Quantify the limits of detection and thresholds of uncertainty.
4. Account for the qualities of the fluids and types of storage reservoirs (formations, depositional environments, depths) during and after injection.
5. Associate the monitoring technique with plume extent and location.
6. Apply data from multiple monitoring sources. The approach employs both Bayesian techniques and joint inversion.
7. Validation is required. This will be done by using existing software historical monitoring data (a time-lapse seismic data set from 2012 and 2014).
8. Continue development of technologies that have been validated at the proof-of-concept level, or TRL3.
9. Technologies should progress through TRL4 such that components are integrated and tested in a laboratory environment to ensure that performance is consistent with updated performance attributes and requirements.
10. Supports goals 1, 2, and 4 of DOE’s Carbon Storage Program goals.

Benefits Statement

The proposed project will develop and apply new modeling and monitoring tools in the form of two promising joint inversion techniques. The tools will be applied to a time-lapse 4-D seismic data set to address and resolve shortcomings of current inversion technology and time-lapse amplitude difference interpretation. WEB time-lapse joint inversion offers the ability to separate the effects of CO₂ saturation from pressure by inverting directly for compressibility and by outputting a CO₂ saturation model in depth, which will better define the extent and position of the CO₂ saturation plume and provide an independent means of determining the mass of stored CO₂. Joint impedance and facies inversion are expected to improve the resolution of facies and their effect on the distribution of CO₂. Incorporating the inversion results into predictive simulations could lead to better understanding of the subsurface behavior, position, and boundaries of the CO₂ plume over time. The proposed research supports the DOE Carbon Storage Program’s goals to 1) develop and validate technologies to ensure 99% storage permanence and 2) develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness. 3) Information produced will be useful for inclusion in DOE’s Carbon Storage best practices manuals for monitoring, verification, and accounting.
PROJECT OVERVIEW: GOALS AND OBJECTIVES

1. Develop a workflow (tool) to quantitatively estimate reservoir properties and the amount of CO₂ stored in the reservoir from time-lapse seismic inverted parameters, calibrated and validated with a rock physics model and geologic information.

2. Reduce the uncertainty in detecting and assessing the location of the CO₂ plume boundaries using Bayesian techniques in the joint inversion of seismic parameters and sedimentary facies.

3. Validate by comparing the results to conventional inversion and previous qualitative reservoir characterization.

4. Use the results from (1) and (2) to update the static geologic model and dynamic simulation model.

• Anticipated Outcome: Advancement of two state-of-the-art CO₂ monitoring methods from the current TRL3 to TRL4.
## PROJECT MILESTONES

<table>
<thead>
<tr>
<th>Task/Subtask</th>
<th>Milestone Title</th>
<th>Planned Completion Date</th>
<th>Verification Method</th>
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<tbody>
<tr>
<td>1.0 – Project Management, Planning, and Reporting</td>
<td>M1 – Hold DOE NETL Kickoff Meeting</td>
<td>2/28/18</td>
<td>Presentation file submitted to DOE</td>
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<tr>
<td>1.0 – Project Management, Planning, and Reporting</td>
<td>M2 – Finalize Contracts with Project Partners</td>
<td>7/31/18</td>
<td>Reported in subsequent quarterly report</td>
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<td>2.4 – WEB Inversion to Reservoir Properties</td>
<td>M3 – Complete WEB Time-Lapse Joint Inversion</td>
<td>2/28/19</td>
<td>Reported in subsequent quarterly report</td>
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<td>3.3 – Joint Inversion to Reservoir Properties</td>
<td>M4 – Complete Joint Impedence and Facies Inversion</td>
<td>7/31/19</td>
<td>Reported in subsequent quarterly report</td>
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<tr>
<td>4.3 – Analysis of Results</td>
<td>M5 – Complete Predictive Simulations and Comparisons</td>
<td>10/31/19</td>
<td>Reported in subsequent quarterly report</td>
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</tbody>
</table>
ORGANIZATION CHART

Senior Oversight
Charles Gorecki

Project Advisor
Nick Azzolina

Lead Organization
EERC

Project Director/
Principal Investigator
Shaughn Burnison

Project Partners
DOE NETL
Denbury Resources
Delft Inversion
Ikon Science
Computer Modelling Group

Task 1.0
Project Management, Planning, and Reporting
Lead
Shaughn Burnison

Task 2.0
WEB Time-Lapse Joint Inversion
Lead
Cesar Barajas-Olalde

Task 3.0
Joint Impedence and Facies Time-Lapse Inversion
Lead
Olarinre Salako

Task 4.0
Integration and Validation
Lead
Lu Jin
2-year project
One budget period

PROPOSED SCHEDULE

<table>
<thead>
<tr>
<th>Task/Subtask</th>
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<th>End Date</th>
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<td>1.0 - Project Management, Planning, and Reporting</td>
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<td>12/31/19</td>
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<tr>
<td>1.1 - Project Management</td>
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<td>12/31/19</td>
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<tr>
<td>1.2 - Project Reporting</td>
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<td>2.0 - WEB Time-Lapse Joint Inversion</td>
<td>1/1/18</td>
<td>2/28/19</td>
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<tr>
<td>2.1 - Data Gathering, Loading, and Quality Check</td>
<td>1/1/18</td>
<td>3/31/18</td>
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<td>2.2 - Compressibility Effects and Background Model</td>
<td>4/1/18</td>
<td>8/31/18</td>
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<tr>
<td>2.3 - Seismic Conditioning and Well Tie</td>
<td>8/1/18</td>
<td>9/30/18</td>
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<td>3.0 - Joint Impedence and Facies Time-Lapse Inversion</td>
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<td>3.1 - Log Conditioning and Rock Physics Modeling</td>
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<td>8/31/18</td>
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<td>3.2 - Seismic AVO Conditioning</td>
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<td>12/31/19</td>
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<td>4.1 - Geomodel Refinement</td>
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<td>3/31/19</td>
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<td>4.2 - Predictive Simulations and Comparisons</td>
<td>2/1/19</td>
<td>6/30/19</td>
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**Milestones**

- M1 – Hold DOE NETL Kickoff Meeting
- M2 – Finalize Contracts with Project Partners
- M3 – Complete WEB Time-Lapse Joint Inversion
- M4 – Complete Joint Impedence and Facies Inversion
- M5 – Complete Predictive Simulations and Comparisons

**Deliverables**

- D1 – Project Management Plan (updated)
- D2 – Technology Maturation Plan (updated)
- D3 – Data Management Plan (updated)
- D4 – Interim Report on WEB Time-Lapse Joint Inversion
- D5 – Interim Report on Joint Impedence and Facies Inversion
- D6 – Final Technical Report
- D7 – Data Submitted to NETL EDX
- D8 – Journal Article or Technical Paper Draft
The following publications were referenced in the presentation:

- Doulgeris, P., 2017, Personal communication.


SINGLE INVERSION AT ONE OF THE WELLS

Single Inversion

Background, Well logs (smoothed), Inverted

Seismic input

Predicted synthetics

Residual
JOINT INVERSION AT ONE OF THE WELLS

Simultaneous Joint Inversion (baseline and monitor)

Background, Well logs (smoothed), Inverted

Seismic input

Predicted synthetics

Residual

2012

2014

4D