Robust CO₂ Plume Imaging using Joint Tomographic Inversion of Seismic Onset Time and Distributed Pressure and Temperature Measurements

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Presentation Outline

• Why are we doing this?
  – Benefits to the program
• How are we doing this?
  – Project overview and methodologies
• Accomplishments to date
  – Application to a post-combustion CO2 WAG Pilot: Petra Nova Parish CCUS Project
  – Application to the Midwest Regional Carbon Sequestration Partnership Project: Chester 16 Reef
• Summary and next steps
Benefit to the Program

• Program goals being addressed
  – Development of modeling and monitoring methods, tools, technologies that improve the certainty about the position of the CO$_2$ plume over time

• Project benefits statement
  – Provide a practical & cost-effective methodology for CO$_2$ plume delineation using routine pressure/temperature measurements + geophysical monitoring
  – Facilitate (near) real-time monitoring of CO$_2$ plume migration in field projects needed to meet current regulatory requirements
Project Overview:
Goals and Objectives

• Develop and demonstrate a rapid and cost-effective methodology for spatio-temporal tracking of CO$_2$ plumes during geologic sequestration
  – *Pressure and temperature tomography*: Use pressure & temperature arrival time data to infer spatial distributions of CO$_2$ plume
  – *Integration of seismic onset time*: Improve the seismic monitoring workflow through the integration of ‘onset’ times
  – *Joint Bayesian inversion and field validation*: Efficient Bayesian framework for probabilistic data integration validated using data from ongoing field projects (Petra Nova Parrish CCUS project, Texas)
Methodology

CO$_2$ Plume Imaging: Key Elements

- Recasting Fluid Flow Equations as Tomographic Equations
  - High frequency asymptotic solution
- Utilization of the Seismic Onset Time Concept
- Parsimonious Representation of Geologic Heterogeneity
  - Ill-posed inverse problem, needs regularization
  - Image compression via basis functions
- Data Integration and Image Updating
  - Multi-objective optimization and Inverse Modeling
Methodology

Asymptotic Approach: Fluid Fronts vs. Wave Fronts *

* Fatemi and Osher, 1995; Vasco and Datta-Gupta, 1999; 2016

- High frequency solution to the flow and transport equation mimics the one usually found in wave propagation
- We can exploit the analogy between the propagating fluid front and a propagating wave
- The trajectories or flow paths associated with the fluid front are similar to rays in seismology/optics
- Provides an efficient formalism for plume imaging using reservoir dynamic response
Accomplishments to Date: Year 1

• Developed a Formalism for CO2 Plume Tracking Using Pressure Tomography
• CO₂ Plume Tracking at Petra Nova CCUS Pilot – Project
• Saturation Imaging Seismic Onset Time: Impact of Survey Frequency
Accomplishments to Date: Year 2

- Developed a Formalism for CO$_2$ Plume Tracking Using Temperature Tomography
- Application of Seismic Onset Time to Saturation Imaging at the Peace River Project, Canada (Collaboration with Shell)
  - *Geophysical Journal International (Published, December 2020)*
  - *First Break (Published, February 2021)*
- Analytical Approaches to Quantitative Analysis of Bottom Hole Pressure and Temperature Data
  - *AEP Mountaineer CO2 Injection Project*
Accomplishments to Date: Year 3

- Field Application of Pressure and Temperature Tomography for CO2 Plume Imaging
  - Pressure and DTS Data at the Chester-16 Reef CO2 Injection Project (MRCSP) (Published 2021, SPE 206249)

- Battelle developed a screening model for predicting pressure buildup at CO2 injection wells
  - The model can assist project developers during the early days of project planning
Methodology

Asymptotic Solution: Diffusivity Equation

- Diffusivity equation in heterogeneous medium

\[
\phi(x) \mu c_t \frac{\partial P(x, t)}{\partial t} = \nabla \cdot (k(x) \nabla P(x, t))
\]

- Transform to Fourier domain

\[
\phi(x) \mu c_t (-i \omega) \tilde{P}(x, \omega) = k(x) \nabla^2 \tilde{P}(x, \omega) + \nabla k(x) \cdot \nabla \tilde{P}(x, \omega)
\]

- High frequency asymptotic solution leads to a propagation equation for pressure ‘front’:

\[
\sqrt{\alpha(x)} |\nabla \tau(x)| = 1 \quad \text{where} \quad \alpha(x) = \frac{k(x)}{\phi(x) \mu c_t}
\]

Eikonal Equation

The Eikonal equation can be solved efficiently using the Fast Marching Method (Sethian, 1996)
Methodology
Pressure ‘Front’ Propagation

0.01 Day
West Ranch Field 98-A CO2 Pilot: CO₂ Plume Profile Comparison

Day 0

INITIAL

CO₂ ZMF = 0.3

UPDATED

CO₂ ZMF = 0.3, Top View
Methodology
Temperature Tomography

- Analogous Approach to Pressure Tomography
- **Assumption** – Thermal Transport is Dominated by Advection
- Transport Equation is Transformed into Eikonal Equation using the Asymptotic Approach
- Streamlines are Used to Develop a Formalism for Thermal Tracer Tomography
Asymptotic Solution: Transport Equation
(Fatemi and Osher, 1995; Vasco and Datta-Gupta, 1999, 2016)

\[ \tilde{C}(x, \omega) = e^{-i \omega \tau(x)} \sum_{k=0}^{\infty} \frac{A_k(x)}{(-i \omega)^k} \]

- \( \tau(x) \), the phase of the wave, represents the geometry of the propagating front
- High frequency asymptotic solution leads to the Eikonal Equation:
  \[ \vec{v} \cdot \nabla \tau = 1 \]

The Eikonal equation can be solved efficiently using the streamline approach
Streamline Time of Flight and Fluid Front Propagation

Permeability Distribution

Streamline Distribution

Time-of-Flight

Front Propagation (1000 Days)

\[ \tau = \int_{0}^{\xi} \frac{\phi}{|\vec{u}|} \, d\xi. \]
Propagation Time of Thermal Tracer

- Travel Time of Thermal Tracer (Somogyvari et al., 2016; Somogyvari and Bayer, 2017):

\[
\tau_T = \int_0^\infty \frac{\phi}{R |\vec{u}|} d\xi
\]

Thermal Retardation Factor = \( R = \frac{\phi(x)C_f}{C_m} \)

Heat capacity of the matrix

Heat capacity of the fluid

**Travel Time of the Thermal Tracer Represents the Propagating Thermal Front**
Chester-16 Project Overview

- Chester-16 Pinnacle Reef located in Otsego county, Michigan
- Large scale CO2 storage test, Midwest Regional Carbon Sequestration Partnership (MRCSP)
- CO2 arrival tracked at the monitoring well via DTS
- Infer distribution of CO2 inflow at different zones using Pressure and DTS
Chester-16: Observed Data (Pressure and DTS)

Pressure

Bottom-Hole Pressure of Injection Well

Behind-casing Pressure of four sensors at Monitoring Well

Location of behind-casing sensors

Temperature

DTS (Injection Well)

DTS (Monitoring Well)
Simulation Model Description

- Grid: $50 \times 28 \times 79 = 110600$ cells
- Todd-Longstaff Miscible Model
- 2 Wells: One Injector, one monitoring well
- Heterogeneous Property:
  - Permeability range: $[1e-10, 129]$ md
  - Porosity range: $[0, 0.275]$
## CO2 Injection History

### CO2 Injection Period: January 2017 – December 2018

<table>
<thead>
<tr>
<th>Injection Period</th>
<th>Date Range</th>
<th>Days Injected</th>
<th>Target Formation</th>
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<tbody>
<tr>
<td>1</td>
<td>01/11/2017 - 01/14/2017</td>
<td>4</td>
<td>A1 Carbonate</td>
</tr>
<tr>
<td>2</td>
<td>02/22/2017 - 04/06/2017</td>
<td>44</td>
<td>A1 Carbonate</td>
</tr>
<tr>
<td>3</td>
<td>04/22/2017 - 07/24/2017</td>
<td>94</td>
<td>A1 Carbonate</td>
</tr>
<tr>
<td>4</td>
<td>09/29/2017 - 11/27/2017</td>
<td>60</td>
<td>Brown Niagara</td>
</tr>
<tr>
<td>5</td>
<td>12/16/2017 - 1/16/2018</td>
<td>32</td>
<td>A1 Carbonate</td>
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<tr>
<td>6</td>
<td>02/05/2018 - 03/21/2018</td>
<td>45</td>
<td>A1 Carbonate and Brown Niagara</td>
</tr>
<tr>
<td>7</td>
<td>05/26/2018 - 08/14/2018</td>
<td>81</td>
<td>A1 Carbonate and Brown Niagara</td>
</tr>
<tr>
<td>8</td>
<td>10/20/2018 – 12/31/2018</td>
<td>73</td>
<td>A1 Carbonate and Brown Niagara</td>
</tr>
</tbody>
</table>

The chart on the right illustrates the daily CO2 flow rate (MT/day) and cumulative CO2 injection (MT) for different injection periods and formations.
Data Integration and Model Updating: Challenges

- Diverse Data Types
  - Scale, resolution and precision
- Poorly constrained
  - Sparse data, large parameter space
- Multiscale, Multiobjective Inverse Problem
  - Large scale update using genetic algorithm to match pressure data
  - Fine-scale updates using streamlines to match DTS data
Large-scale Updates: Region Definition by Spectral Clustering (Kang et al., 2014)

- Spectral Decomposition of the Grid Laplacian Matrix with Adjacency Information
- Region Definition by Clustering Analysis of the 2nd Smallest Eigen Vector (Ratio Cut Partitioning)
- Five Regions Identified for Pressure Updating
Large-Scale Updates: Parameter Sensitivity Analysis

\[
\Delta J = f(X) = \sum_i^{Timestep} \left[ \ln | \Delta BHP_{\text{Injector}} |_i \right] + \sum_{j=1,2,3,4} \ln | \Delta \text{Pressure}_{\text{Sensor}_j} |_i \right]
\]

\[
sensitivity_i = \frac{\Delta J}{\Delta x_i} x_i^{\text{Base}}
\]
Pressure Updating Using Genetic Algorithm

\[ \Delta J = f(X) = \sum_{i}^{Timestep} \ln | \Delta BHP_{Injector} |_i + \sum_{j=1,2,3,4} \ln | \Delta Pressure_{Sensor_j} |_i \]

- Genetic Algorithm Setups
  - # of Generations: 10
  - # of Populations: 30

- Multiple history-matched models
  - Select best 7 realizations
Pressure Matching Results

- : observed,  - : Initial Model,  - : 7 Selected Models,  - : Best

Behind Casing Pressure Sensors

Sensor 1
Sensor 2
Sensor 3
Sensor 4

Injector BHP
DTS Matching via Fine Scale Updating

Minimize a Penalized Misfit Function

Data Misfit: \[ \| \delta d - S \delta k \| = \sum_{i=1}^{M} \left( \delta d_i - \sum_{j=1}^{N} S_{ij} \delta k_j \right)^2 \]

Model Norm: \[ \| \delta k \| = \sum_{j=1}^{N} \left( \delta k_j \right)^2 \]

Model Roughness: \[ \| L \delta k \| = \sum_{j=1}^{N} \left( \nabla \delta k_j \right)^2 \]

Streamlines allow analytic computation of the sensitivity of the arrival times to reservoir properties
DTS Matching at the Monitoring Well

- Matching data: DTS data of Monitoring Well

\[ T_{\text{threshold}} = 103^\circ F \]

DTS data is matched in terms of arrival time of a threshold temperature (onset time)
DTS Matching: Temperature Response at Selected Depths

No change in T

- B Salt
- A2 Carbonate
- A2 Evaporite
- A1 Carbonate
- Brown Niagaran

Graphs showing temperature response over time for different depths.
Permeability Changes After Local Updating with DTS Data

Before DTS

After DTS

Perm Change (Updated - Initial)
Flow Field and Temperature Update: Pressure + DTS Matching

Best-matched model from GA

After Local Match (final model)

Streamline
Time of Flight

Temperature along Streamlines
CO2 Plume Tracking

- Gas saturation comparison at 12/31/2018
- CO₂ moves further after model updates using observed pressure and DTS data
- Vertical movement of CO2 is limited and CO2 mostly stays in the zone of injection
Summary

- Developed novel approaches to CO2 plume tracking using tomographic inversion of pressure, temperature and seismic data.
- Our approach exploits the analogy between a propagating fluid front and a propagating wave-front to develop a formalism for flow and transport tomography.
- Field applications at Petra Nova CCUS CO2 pilot project and Chester-16 Midwestern Regional Sequestration Project demonstrate the practical viability of our approach.
- CO2 plume movement results are consistent with independent warmback analysis of the temperature data.
Next Steps

- Field validation of the numerical tomographic inversion using data from ongoing CO₂ injection project at the West Ranch Field, TX (Petra Nova Parish CCUS)
Appendix

– These slides will not be discussed during the presentation, but are mandatory.
## Gantt Chart

<table>
<thead>
<tr>
<th>TASK NAME</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>BP1</th>
<th>BP2</th>
<th>BP3</th>
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<td>Task 1.0  Project Management and Planning</td>
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<td>Update Project Management Plan</td>
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<td>Update Technology Maturation / Data Management Plans</td>
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<td>Complete quarterly progress reports</td>
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<td>Complete annual and final reports</td>
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<td>Task 2.0  CO2 Plume Tracking Using Pressure and Temperature Tomography</td>
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<td>Task 3.0  Time-lapse ‘Onset’ Times for CO2 Plume Imaging</td>
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<td>Task 5.0  Field Validation of CO2 Plume Tracking via Tomographic Inversion</td>
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