Robust CO_2 Plume Imaging using Joint Tomographic Inversion of Seismic Onset Time and Distributed Pressure and Temperature Measurements

Project Number **DE-FE0031625**

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U.S. Department of Energy

National Energy Technology Laboratory

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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
- CO_2 Plume Tracking at Petra Nova CCUS Pilot – Project
  - *Fuel* 255 (2019); *SPE Res. Eval. and Engg*. (2019)
- Saturation Imaging Seismic Onset Time: Impact of Survey Frequency
  - *Journal of Petroleum Science and Engineering (2020)*

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

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

- Transform to Fourier domain

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

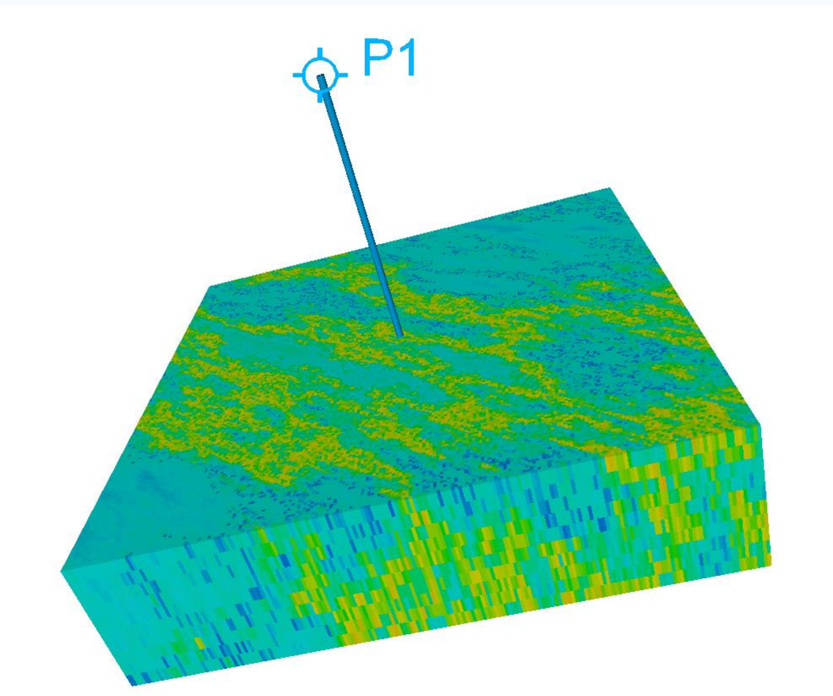
- High frequency asymptotic solution leads to a propagation equation for pressure 'front':

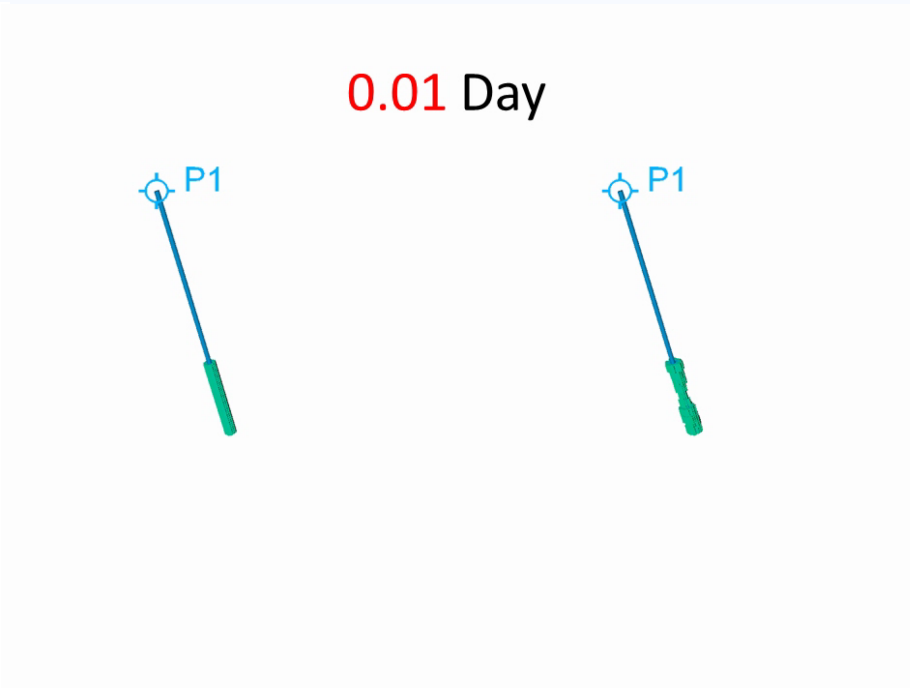
$$\sqrt{\alpha(\mathbf{x})}\left|\nabla\tau(\mathbf{x})\right| = 1 \quad \text{where} \quad \alpha(\mathbf{x}) = \frac{k(\mathbf{x})}{\phi(\mathbf{x})\mu c_t}$$

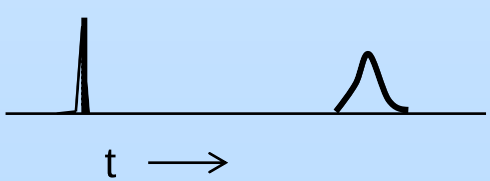
Eikonal Equation

The Eikonal equation can be solved efficiently using the Fast Marching Method (Sethian, 1996)

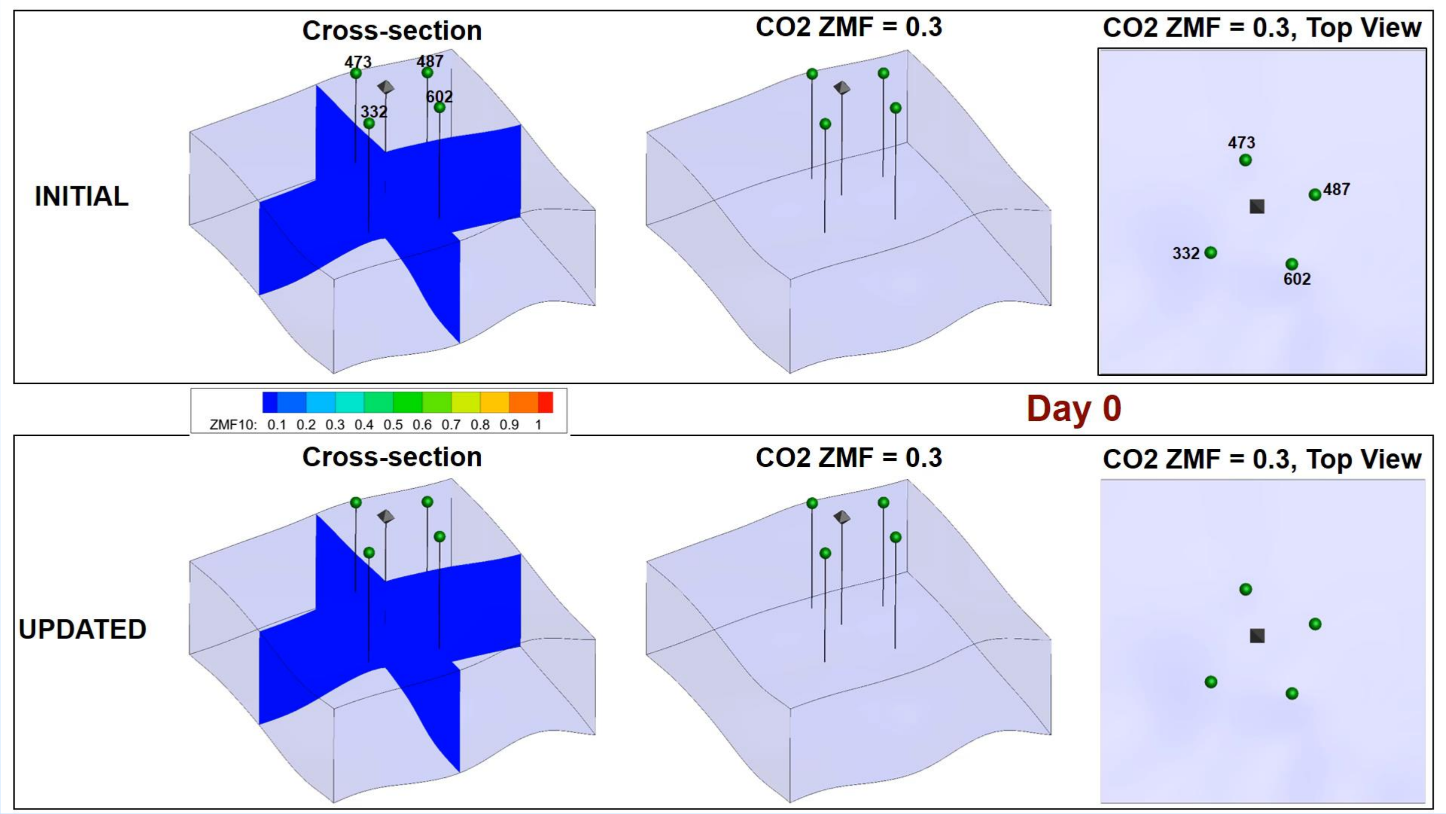
Methodology
Pressure ‘Front’ Propagation







West Ranch Field 98-A CO2 Pilot : CO_2 Plume Profile Comparison



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)

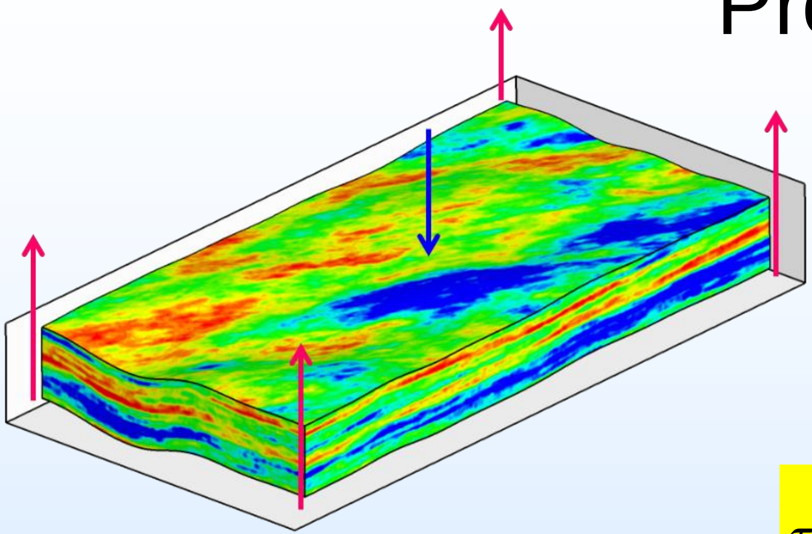
$$\tilde{C}(\mathbf{x},\omega) = e^{-i\omega\tau(\mathbf{x})} \sum_{k=0}^{\infty} \frac{A_k(\mathbf{x})}{(-i\omega)^k}$$

- $\tau(x)$, the phase of the wave, represents the geometry of the propagating front
- High frequency asymptotic solution leads to the Eikonal Equation:

$$\vec{v} \cdot \nabla \tau = 1$$

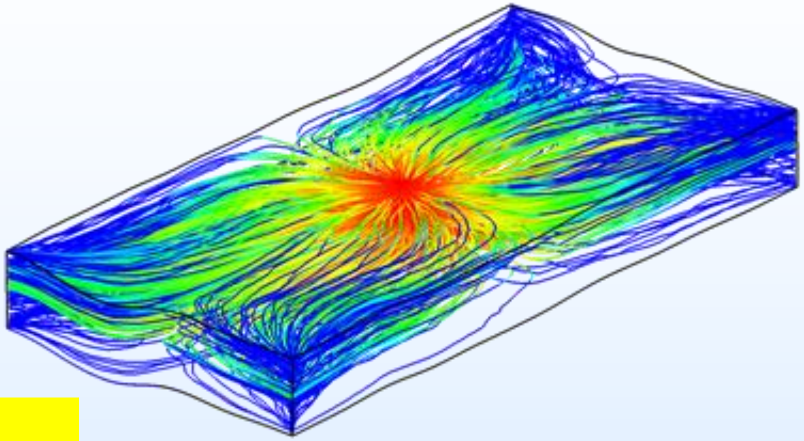
The Eikonal equation can be solved efficiently using the streamline approach

Streamline Time of Flight and Fluid Front Propagation

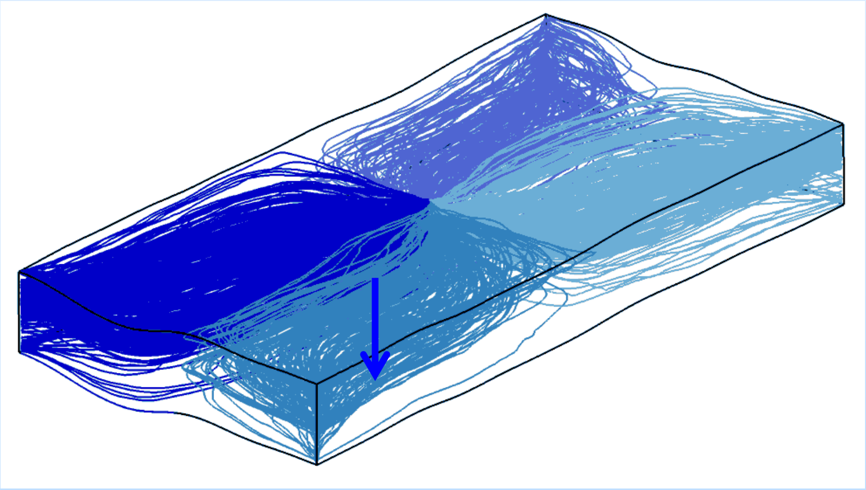


Permeability Distribution

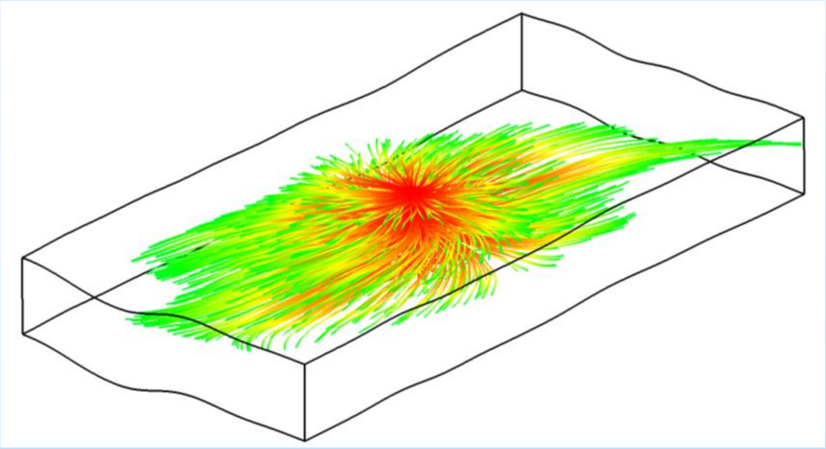
$$\tau = \int_0 \frac{\phi}{|\vec{u}|} \mathrm{d}\xi.$$



Time-of-Flight



Streamline Distribution



Front Propagation (1000 Days)

Propagation Time of Thermal Tracer

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

$$\tau_T = \int_0 \frac{\phi}{R|\vec{u}|} \mathrm{d}\xi$$

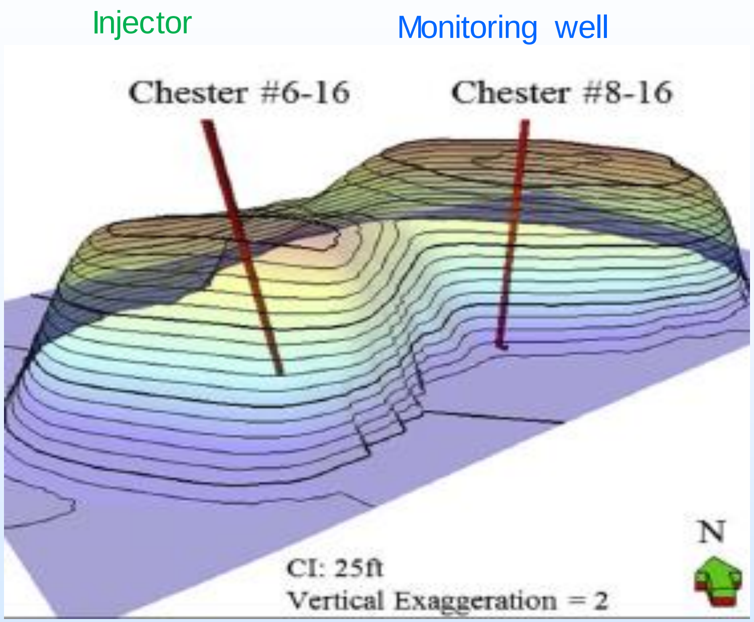
Thermal Retardation Factor = $R = \frac{\phi(x)C_f}{C_m}$

Heat capacity of the matrix

Heat capacity of the fluid

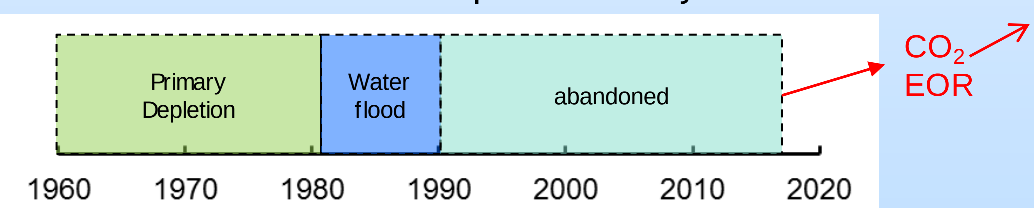
Travel Time of the Thermal Tracer Represents the Propagating Thermal Front

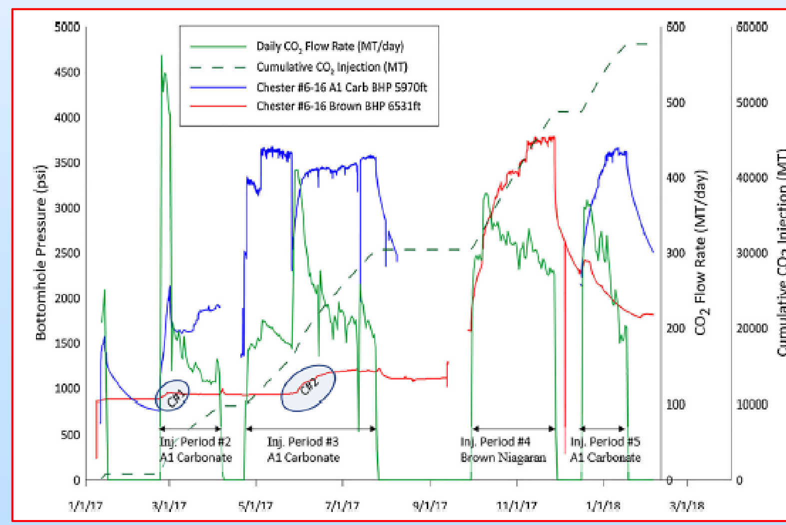
Chester-16 Project Overview



- Chester-16 Pinnacle Reef located in Otsego county, Michigan
- Large scale CO2 storage test, Midwest Regional Carbon Sequestration Partnership (MRCSP)
- CO_2 arrival tracked at the monitoring well via DTS
- Infer distribution of CO_2 inflow at different zones using Pressure and DTS

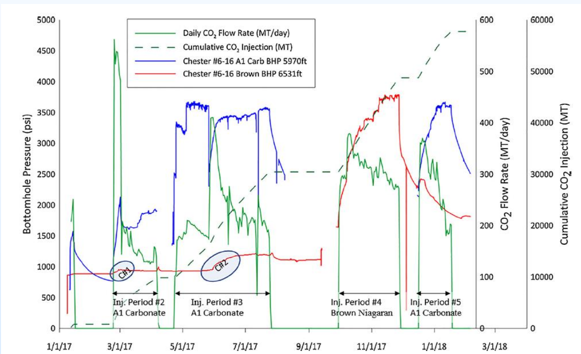
Field Development History



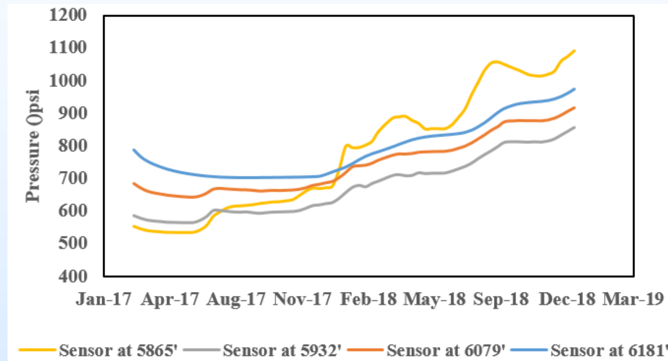


Chester-16: Observed Data (Pressure and DTS)

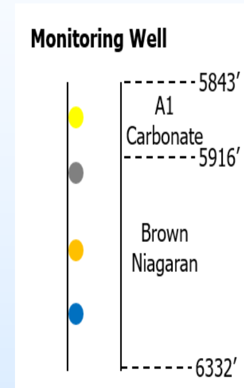
Pressure



Bottom-Hole Pressure of Injection Well

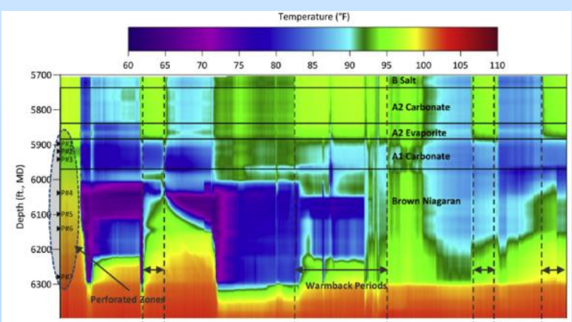


Behind-casing Pressure of four sensors at Monitoring Well

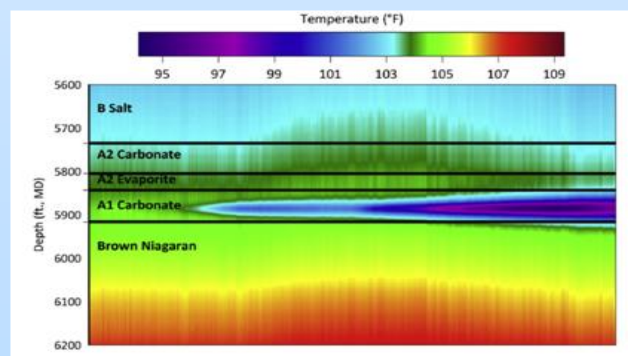


Location of behind-casing sensors

Temperature

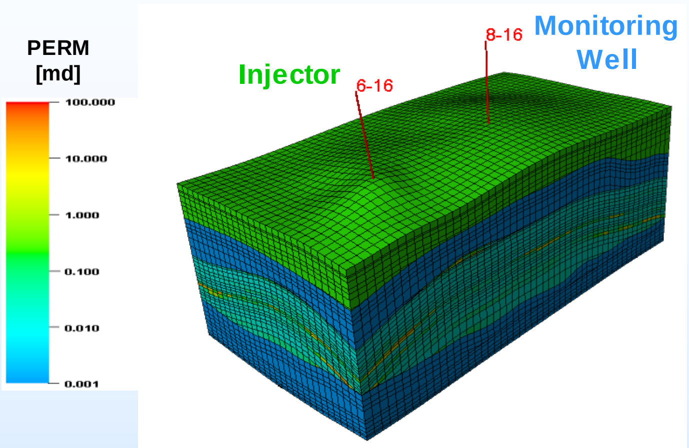


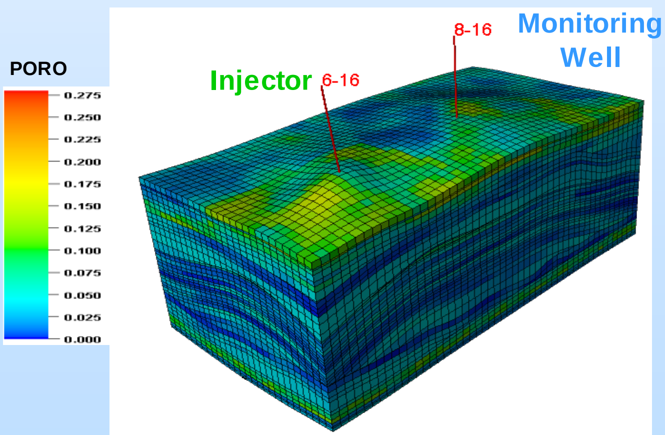
DTS (Injection Well)

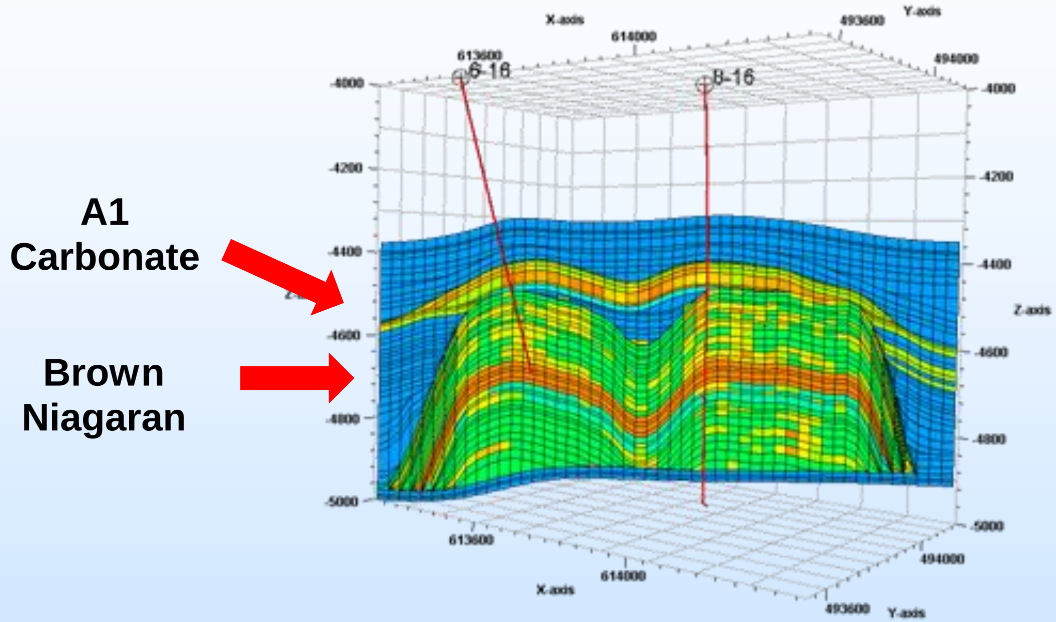


DTS (Monitoring Well)

Simulation Model Description



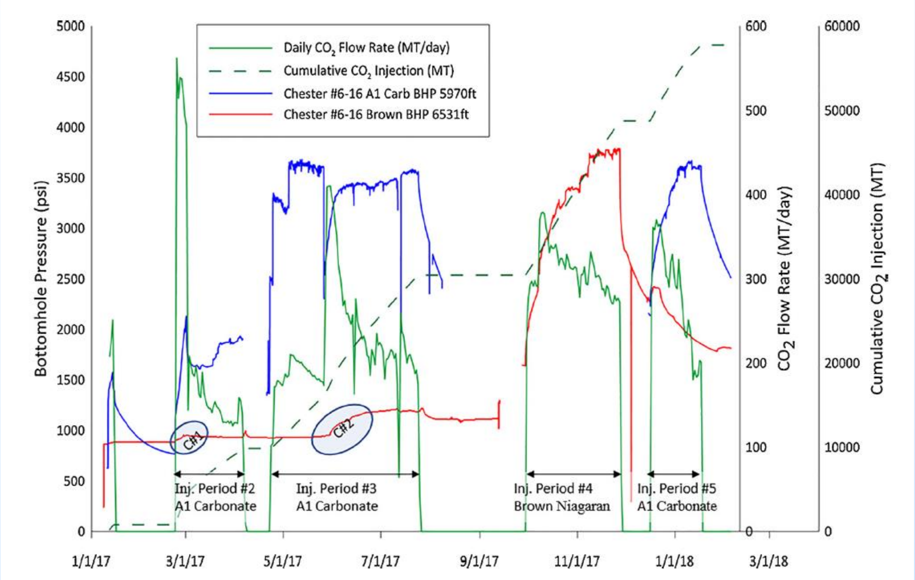




- Grid: 50 x 28 x 79 = 110600 cells
- Todd-Longstaff Miscible Model
- 2 Wells: One Injector, one monitoring well
- Heterogeneous Property:
  - Permeability range: [1e-10,129] md
  - Porosity range: [0,0.275]

CO2 Injection History

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

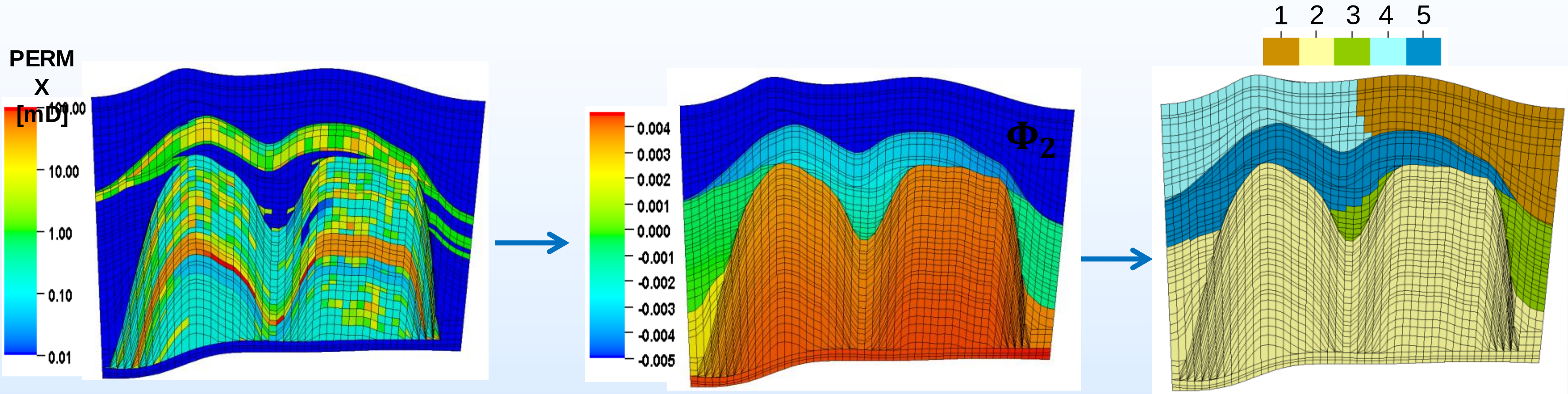


CO2 Injection Period: January 2017 –December 2018

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)



Grid Property

2nd smallest basis

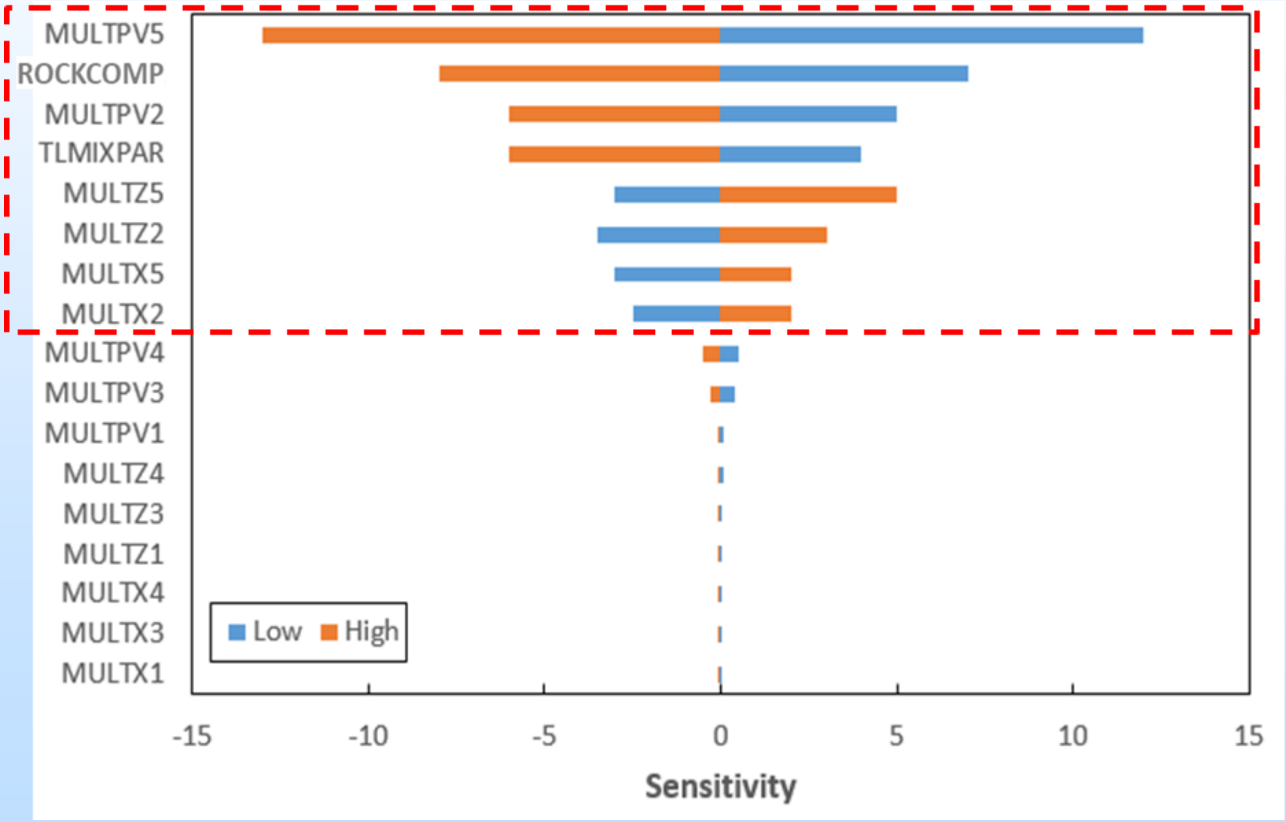
Regions/Clusters

– 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

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

$$sensitivity_i = \frac{\Delta J}{\Delta x_i} x_i^{Base}$$

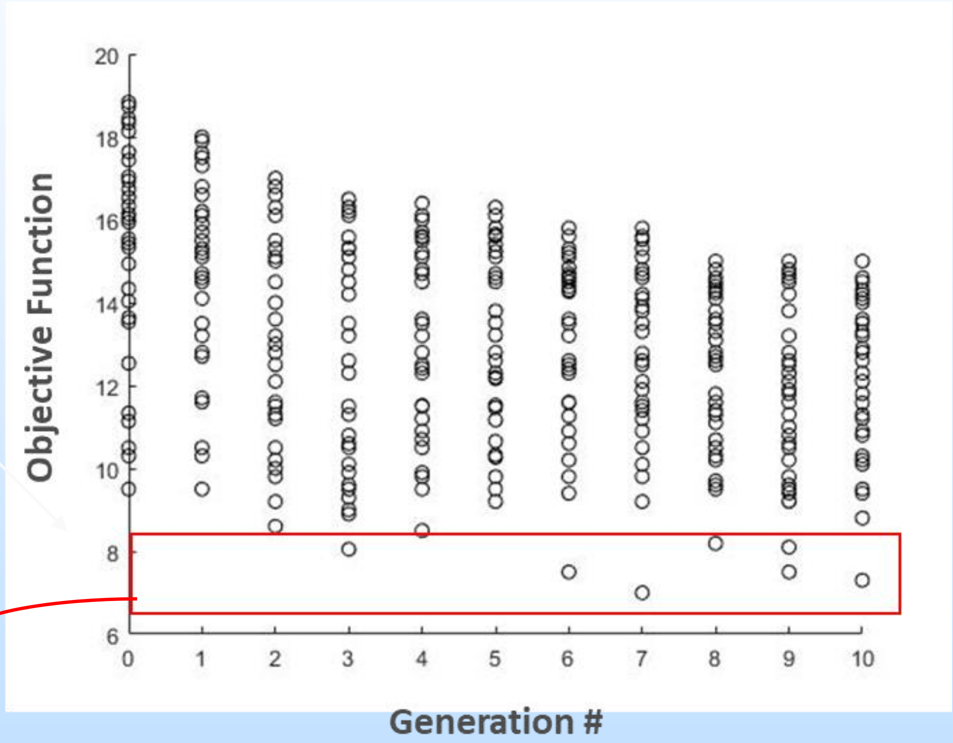


Pressure Updating Using Genetic Algorithm

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

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

- Multiple history-matched models
  - Select best 7 realizations

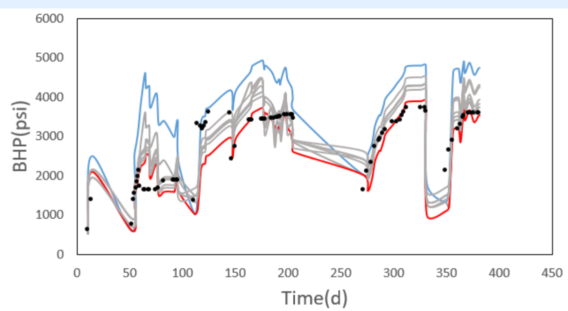


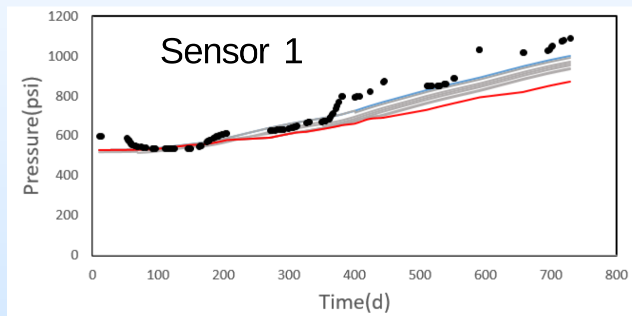
Pressure Matching Results

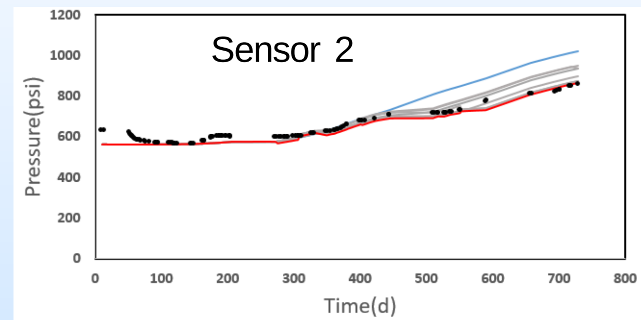
● : observed, :Initial Model, : 7 Selected Models, : Best

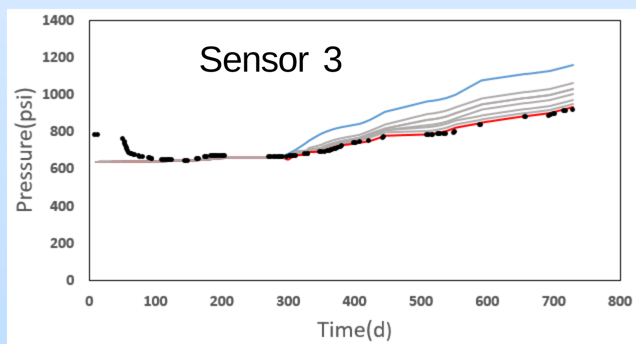
Behind Casing Pressure Sensors

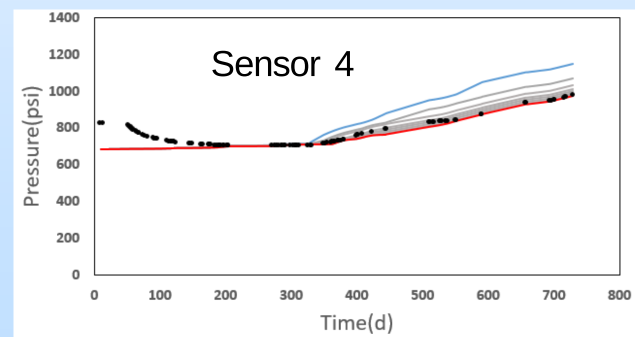
Injector BHP











DTS Matching via Fine Scale Updating

Minimize a Penalized Misfit Function

Data Misfit:

$$\left\|\delta\mathbf{d} - \mathbf{S}\delta\mathbf{k}\right\| = \sum_{i=1}^{M}\left(\delta d_i - \sum_{j=1}^{N} S_{ij}\delta k_j\right)^2$$

Model Norm:

$$\left\|\delta\mathbf{k}\right\| = \sum_{j=1}^{N}\left(\delta k_j\right)^2$$

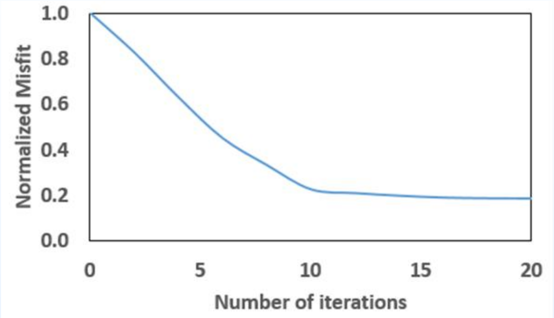
Model Roughness:

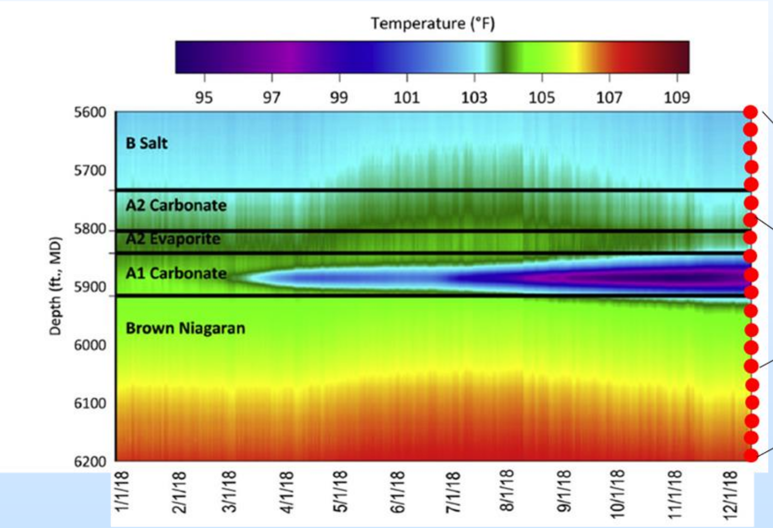
$$\left\|\mathbf{L}\delta\mathbf{k}\right\| = \sum_{j=1}^{N}\left(\nabla\delta k_j\right)^2$$

Streamlines allow analytic computation of the sensitivity of the arrival times to reservoir properties

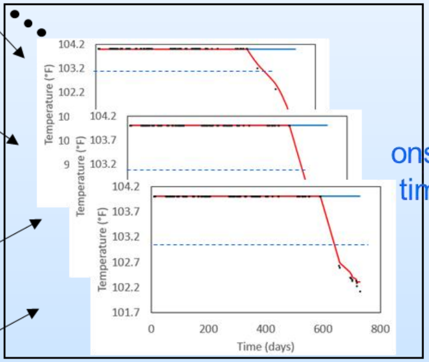
DTS Matching at the Monitoring Well

- Matching data: DTS data of Monitoring Well

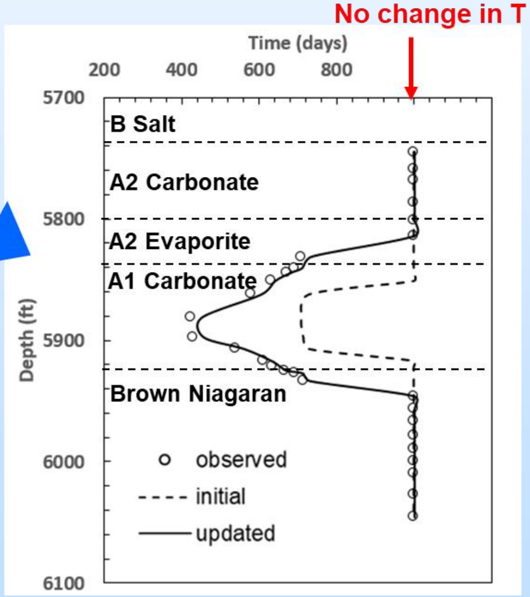




$$T_{threshold} = 103°F$$

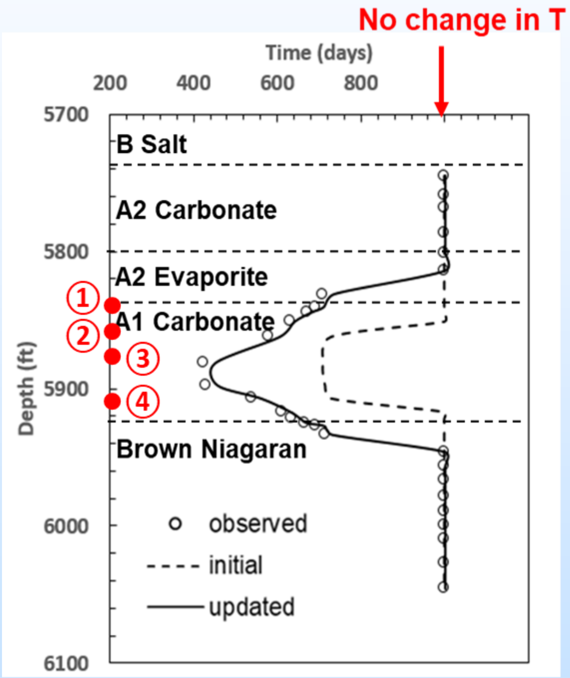


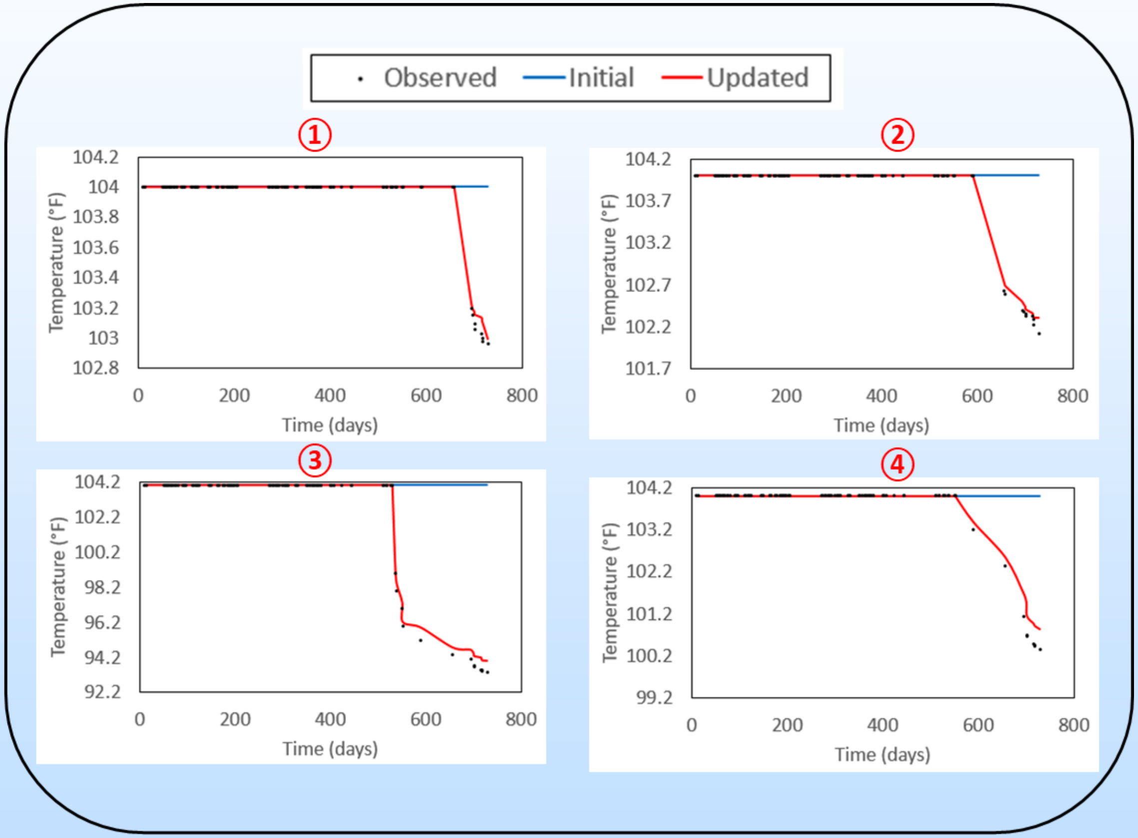
onset time



DTS data is matched in terms of arrival time of a threshold temperature (onset time)

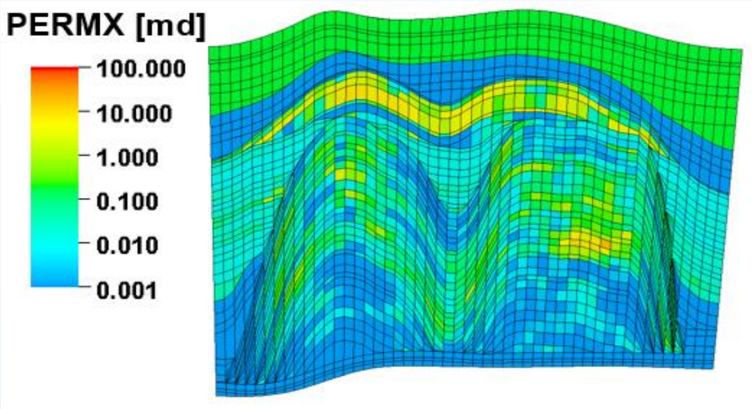
DTS Matching: Temperature Response at Selected Depths



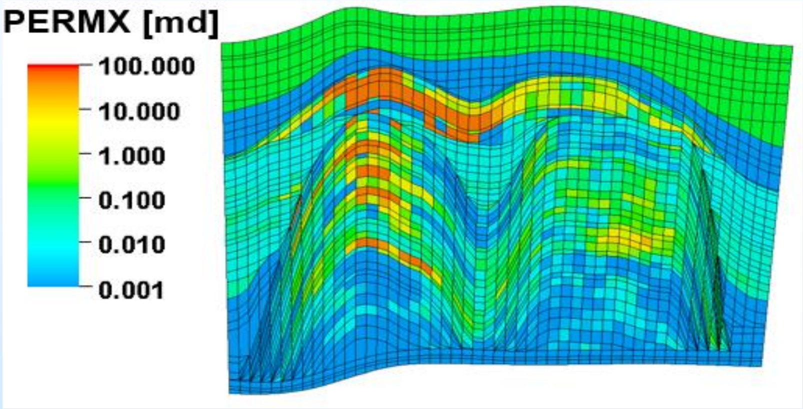


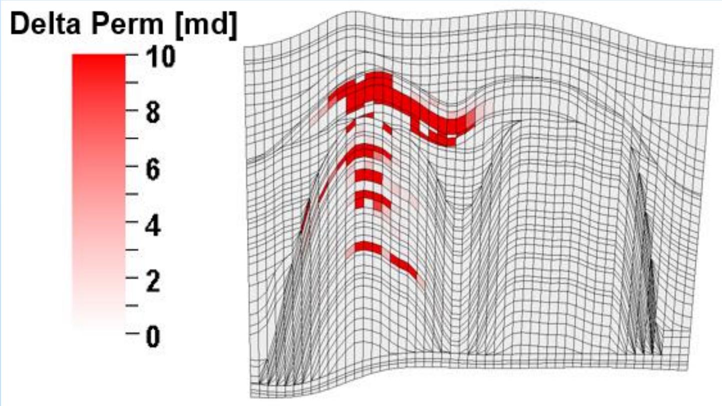
Permeability Changes After Local Updating with DTS Data

Before DTS



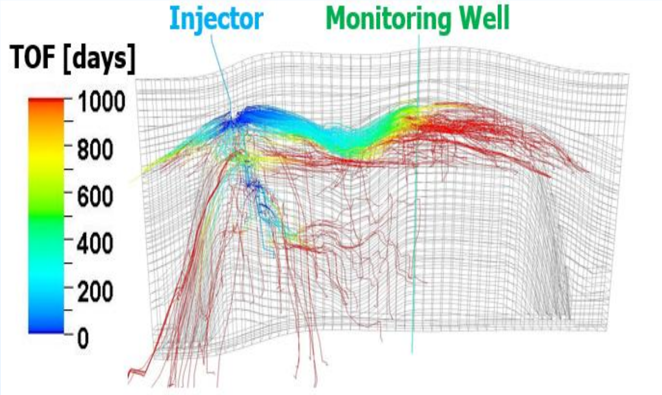
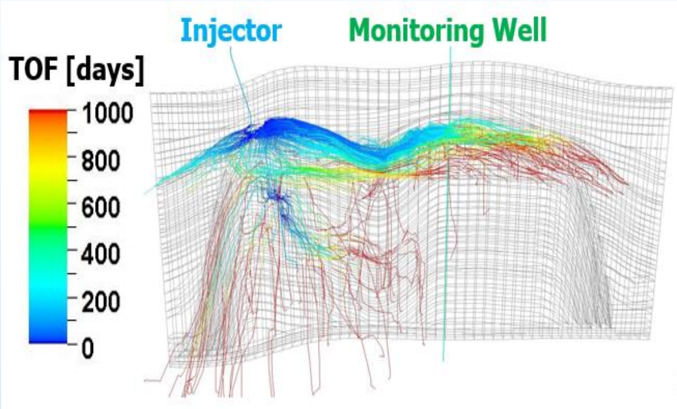
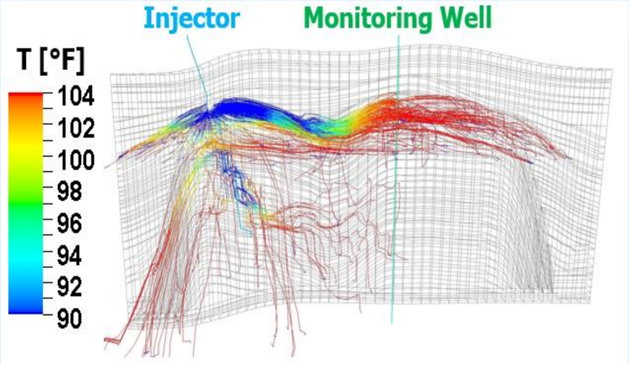
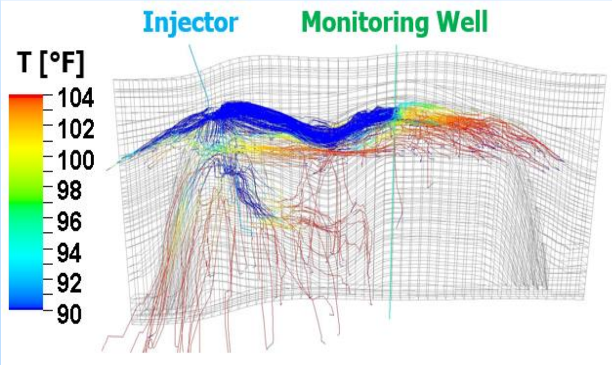
After DTS





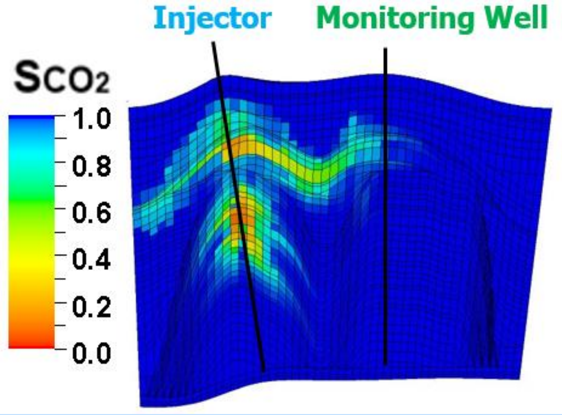
Perm Change (Updated - Initial)

Flow Field and Temperature Update: Pressure +DTS Matching

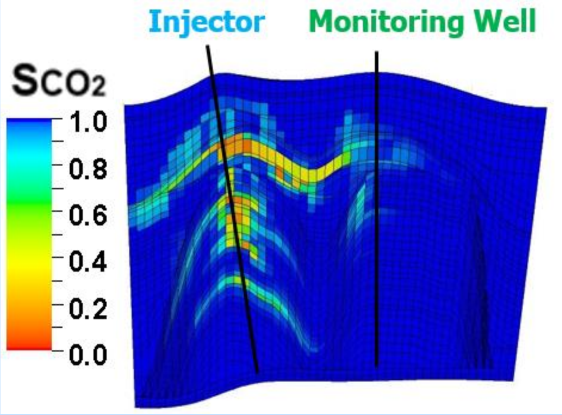
	Best-matched model from GA	**After Local Match (final model)**
Streamline Time of Flight		
Temperature along Streamlines		

CO_2 Plume Tracking

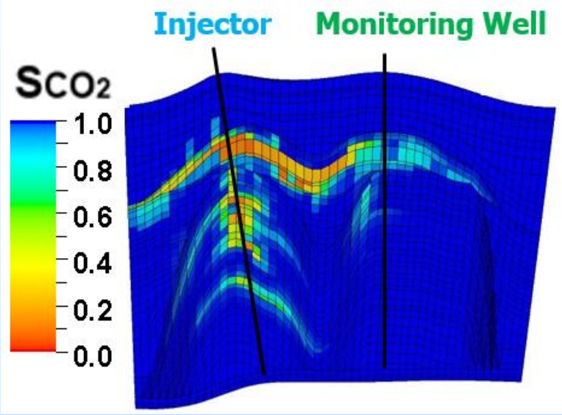
- Gas saturation comparison at 12/31/2018
- CO_2 moves further after model updates using observed pressure and DTS data
- Vertical movement of CO2 is limited and CO2 mostly stays in the zone of injection



Initial



Pressure Match



Pressure + DTS Match

Summary

- Developed novel approaches to CO_2 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 CO_2 pilot project and Chester-16 Midwestern Regional Sequestration Project demonstrate the practical viability of our approach
- CO_2 plume movement results are consistent with independent warmback analysis of the temperature data

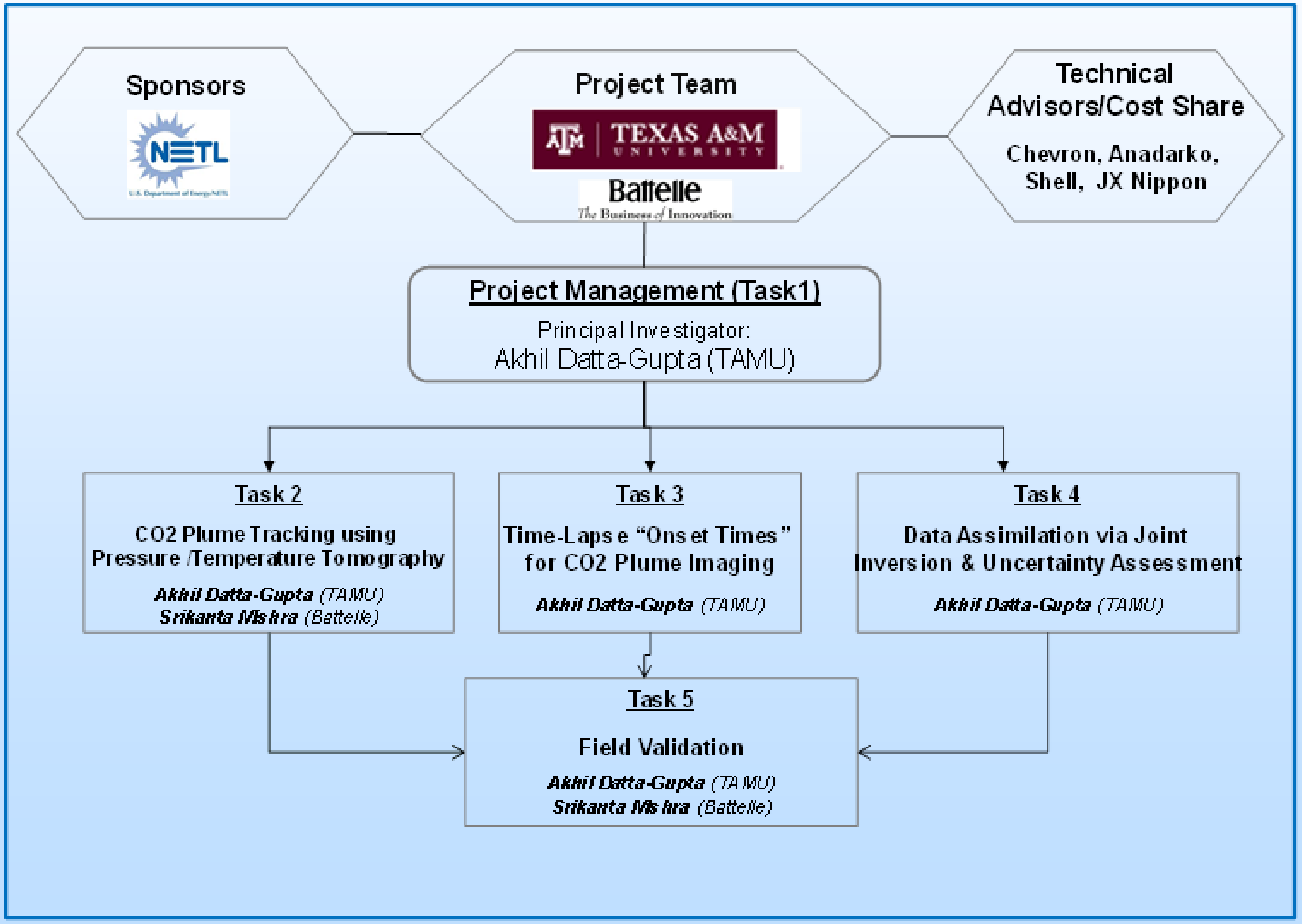
Next Steps

- Field validation of the numerical tomographic inversion using data from ongoing CO_2 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.

Organization Chart



Gantt Chart

	BP1				BP2				BP3			
TASK NAME	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Task 1.0 Project Management and Planning	♦			♦				♦				♦
Update Project Management Plan	♦											
Update Technology Maturation / Data Management Plans	♦											
Complete quarterly progress reports	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦
Complete annual and final reports				♦				♦				♦
Task 2.0 CO2 Plume Tracking Using Pressure and Temperature Tomography								♦				
Subtask 2.1 Rapid forward modeling of pressure and temperature transmission				♦								
Subtask 2.2 Tomographic inversion of pressure and temperature data						♦						
Subtask 2.3 Testing with synthetic data sets								♦				
Task 3.0 Time-lapse 'Onset' Times for CO2 Plume Imaging						♦						
Subtask 3.1 Impact of CO2 saturation on the 'onset' times of seismic attributes				♦								
Subtask 3.2 Integration of seismic onset time for CO2 saturation front detection						♦						
Task 4.0 Data Assimilation via Joint Inversion and Uncertainty Assessments								♦				
Subtask 4.1 Geologic model parameterization								♦				
Subtask 4.2 Integration of fluid flow and geophysical data/uncertainty quantification								♦				
Task 5.0 Field Validation of CO2 Plume Tracking via Tomographic Inversion												♦
Subtask 5.1 Application to the Petronova Parish Holdings CCUS Project											♦	
Subtask 5.2 Application to Peace River site data											♦	