Integration of seismic-pressure-petrophysics inversion of continuous active-source seismic monitoring data for monitoring and quantifying CO_2 plume

Project Number: FE0031544

Phase I: 01/24/2018 – 07/01/2020

Phase II: 07/01/2020 – 06/30/2022

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U.S. Department of Energy

National Energy Technology Laboratory

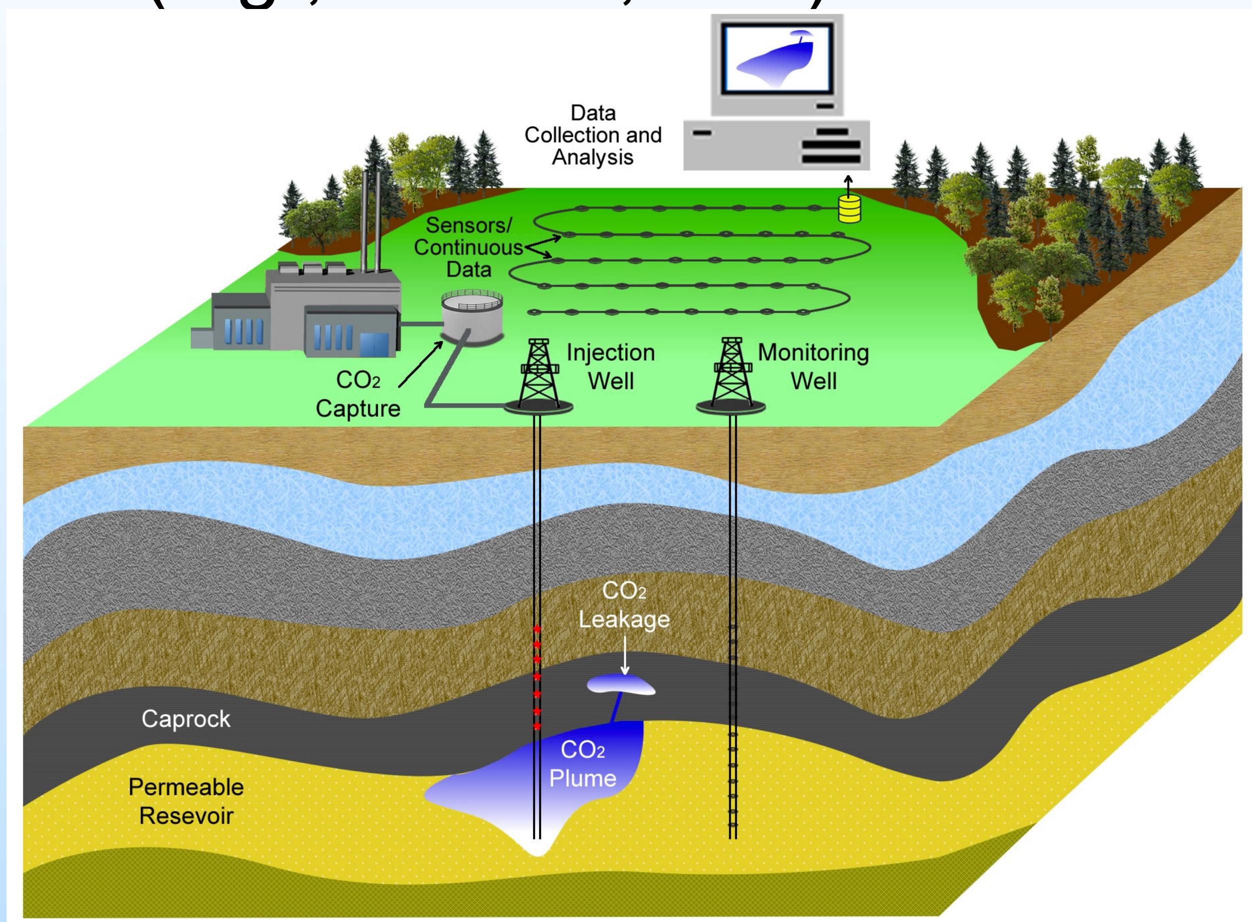
Project Review Meeting – Carbon Storage, August 9-11 2021

Presentation Outline

- Background
- Project Overview
- Technical Status/Accomplishments to date
- Project Summary
- Synergy Opportunities

Background

- Find out how much the stored CO2 is there, and quantify the uncertainty. 10 million ton plus/minus 50%, or plus/minus 5%?
- Multi-scale datasets (e.g., seismic, flow)



Project Overview:
Goals and Objectives

- develop methodologies for fast seismic full waveform inversion of CASSM datasets for simultaneously estimating velocity and attenuation, and with data assimilation; (Tasks 2 & 3)

- develop joint Bayesian petrophysical inversion of seismic models and pressure data for providing and updating CO_2 saturation models; (Task 4)

- demonstrate the methods using multiple multi-scale datasets including (surface and borehole) synthetic, laboratory, and field CASSM datasets. (Tasks 5 & 6)

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Accomplishments to Date

Guangchi Xing

Task 2.0

- Developed a simple formulation of time-domain viscoacoustic wave equation (2.1)
- Built the numerical scheme and numerical code of solving the new wave equation (2.1)
- Derived adjoint operators for further developing the algorithm of full waveform inversion (2.2)
- Developed the paralleled code of Q full waveform inversion (2.2, ongoing)
- Completed validation tests in Frio (2.3)

Milestone report was submitted in April 2020

To find a better efficient wave simulator (subtask 2.1)

$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p + \left[\eta\left(-\nabla^2\right)^{\gamma+1} - \nabla^2\right]p + \tau\frac{\partial}{\partial t}\left(-\nabla^2\right)^{\gamma+1/2} p$$

Dispersion **Loss**

Zhu and Harris (2014) *Geophysics*

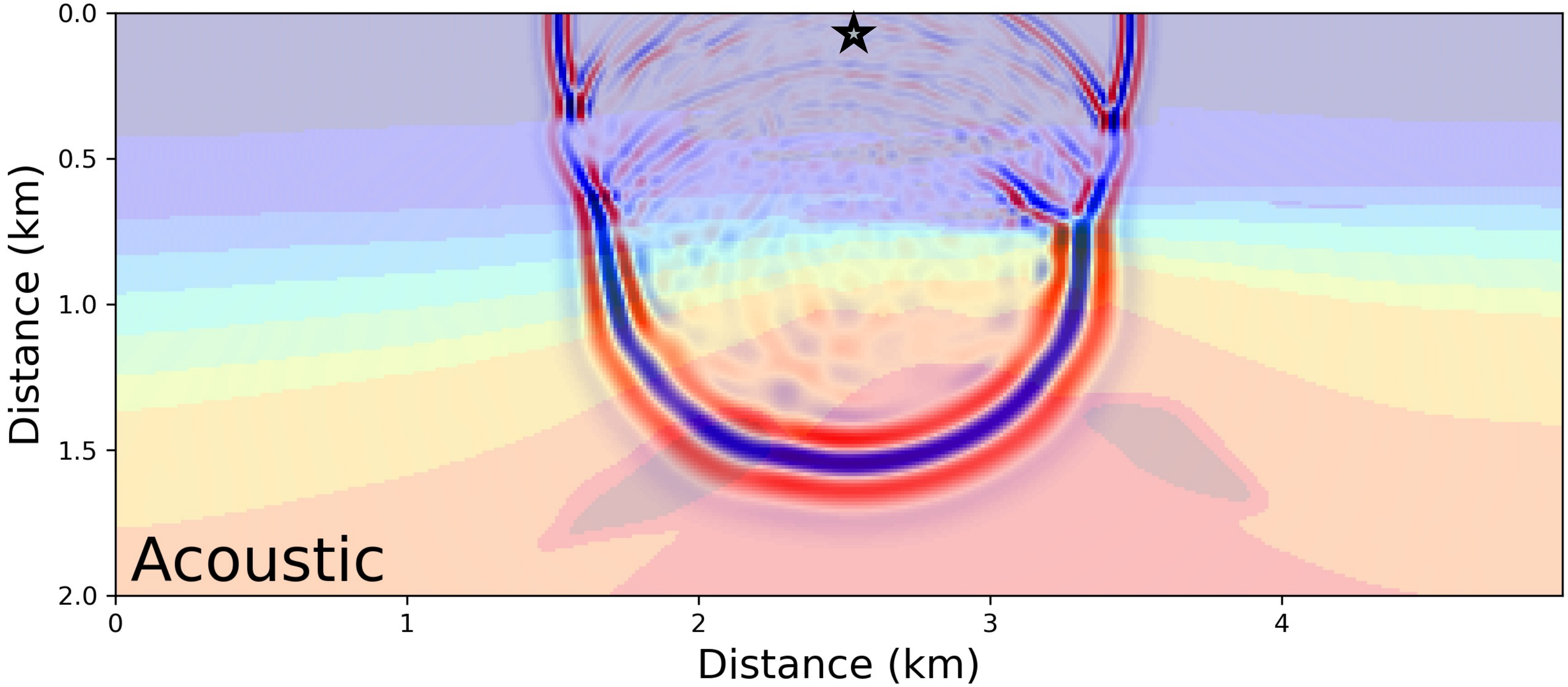
Difficulty!!! because of spatial variable $\gamma(x, y, z)$

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p + \left(\gamma\frac{\omega_0}{c}(-\nabla^2)^{\frac{1}{2}} - \gamma\frac{c}{\omega_0}(-\nabla^2)^{\frac{3}{2}}\right)p + \left(-\pi\gamma\frac{1}{c}(-\nabla^2)^{\frac{1}{2}} + \pi\gamma^2\frac{1}{\omega_0}\nabla^2\right)\frac{\partial}{\partial t}p$$

Dispersion **Loss**

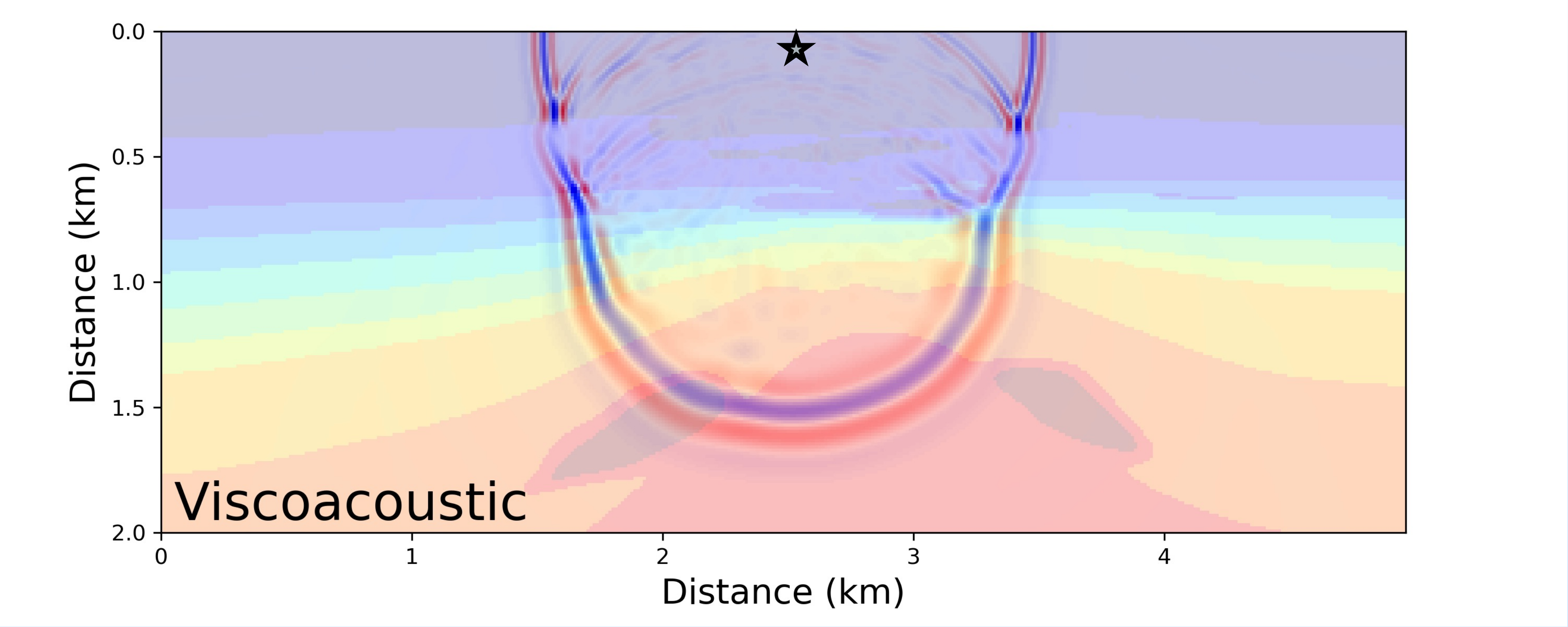
Xing and Zhu (2019) *JGR-Solid Earth*

Wavefield snapshot



Xing and Zhu (2019) *JGR-Solid Earth*

Wavefield snapshot



Xing and Zhu (2019) *JGR-Solid Earth*

Subtask 2.2: Adjoint operators for joint full waveform inversion

Forward modeling

$$\mathbf{L}u = (\mathbf{L}_0 + \mathbf{L}_1 + \mathbf{L}_2)u = f,$$

$$\mathbf{L_0} = \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2$$

Propagator

$$\mathbf{L}_1 = -\gamma\,\frac{\omega_0}{c}(-\nabla^2)^{\frac{1}{2}} + \gamma\,\frac{c}{\omega_0}(-\nabla^2)^{\frac{3}{2}}$$

Phase dispersion

$$\mathbf{L_2} = \left(\pi\gamma\,\frac{1}{c}(-\nabla^2)^{\frac{1}{2}} - \pi\gamma^2\,\frac{1}{\omega_0}\nabla^2\right)\frac{\partial}{\partial t}$$

Amplitude loss

Adjoint modeling

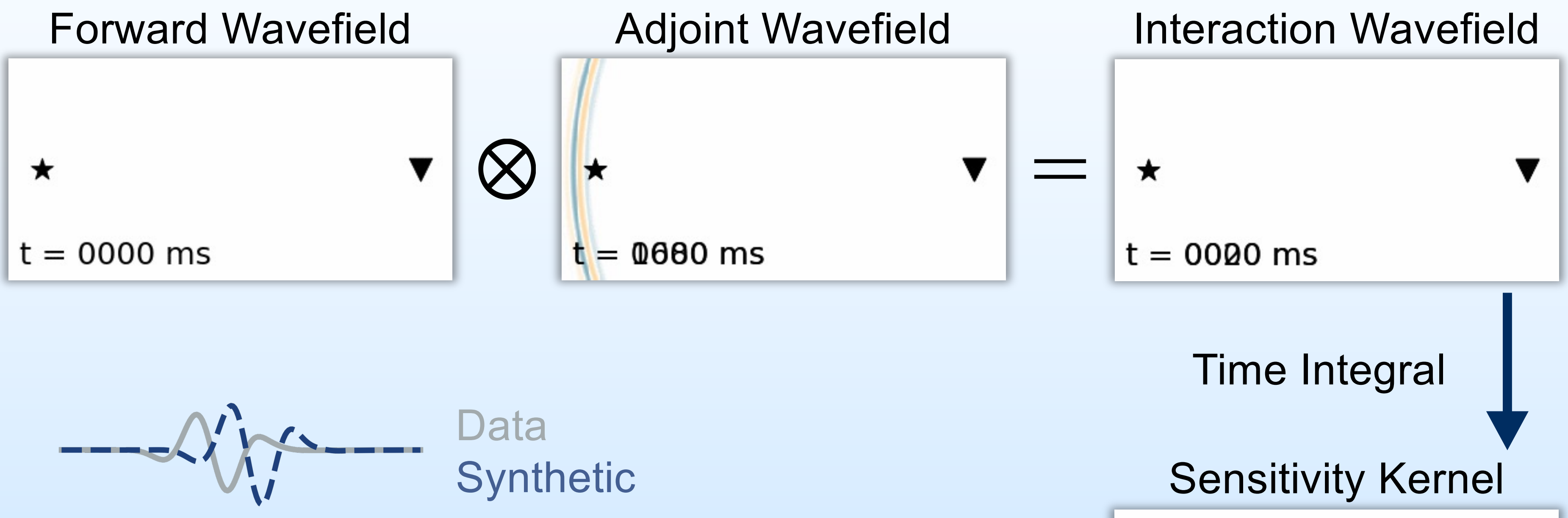
$$\mathbf{L}^*\lambda = \frac{\partial J}{\partial u},$$

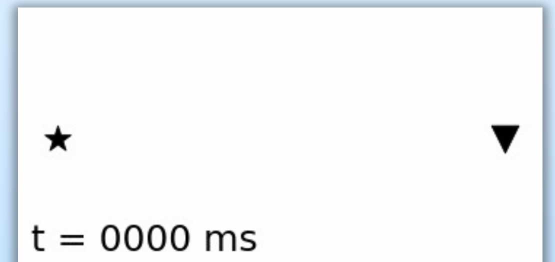
$$\mathbf{L}^* = \mathbf{L}_0 + \mathbf{L}_1 - \mathbf{L}_2$$

$$K = \frac{dJ}{dm} = -\left\langle \lambda, \frac{\partial \mathbf{L}}{\partial m}u \right\rangle,$$

Subtask 2.2: Adjoint operators for joint full waveform inversion

Interaction between forward and adjoint wavefields -> FWI sensitivity Kernel





- Vel. & Atten. -> Interact differently

Subtask 2.2: Adjoint operators for joint full waveform inversion

Algorithm

While (not converged) do

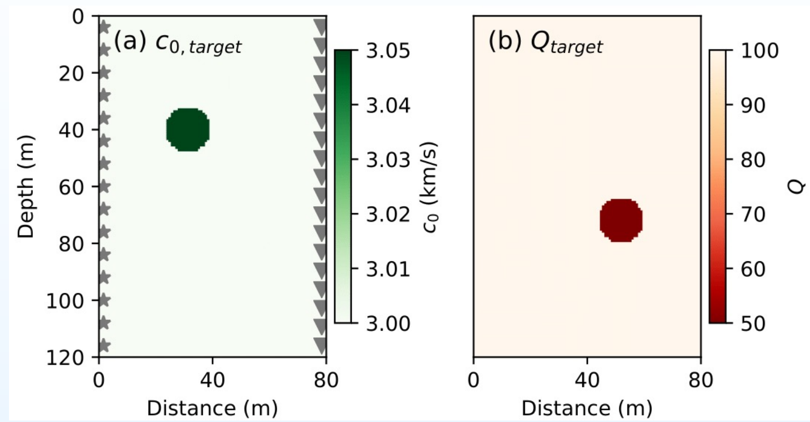
  Compute gradient g (adjoint-state method)

  Approximately solve $H\Delta m = -g$ (inner CG loop)

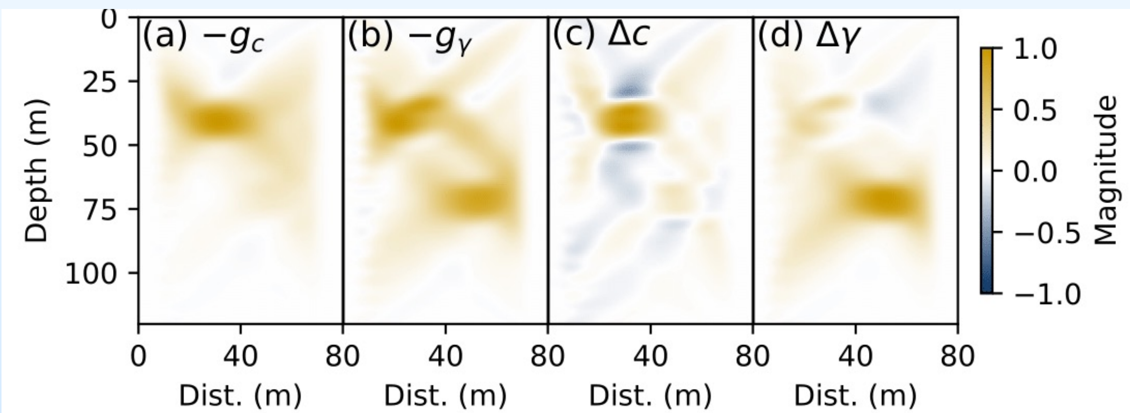
  Line search & model update

end while

Target model (velocity & Q)

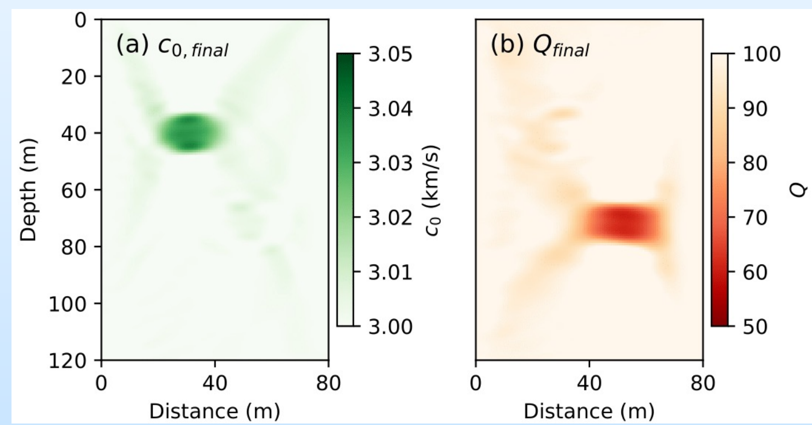


Search direction at iteration #1



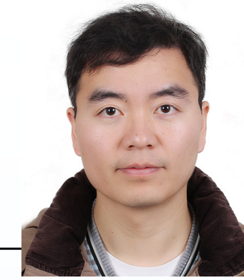
Gradient-based: (a) velocity, (b) attenuation;
Hessian-based: (c) velocity, (d) attenuation

Final model (velocity & Q)



Xing and Zhu (2021) *in prep*

Accomplishments to Date



Chao Huang
(2018-2020)

Task 3.0

- Developed a time-lapse ensemble KF full waveform inversion algorithm of seismic velocity & Q (3.1)
- Completed synthetic tests in Frio 2D models (3.2)
- Completed synthetic tests in 3D Cranfield models (3.2)

Milestone report was submitted in July 2020

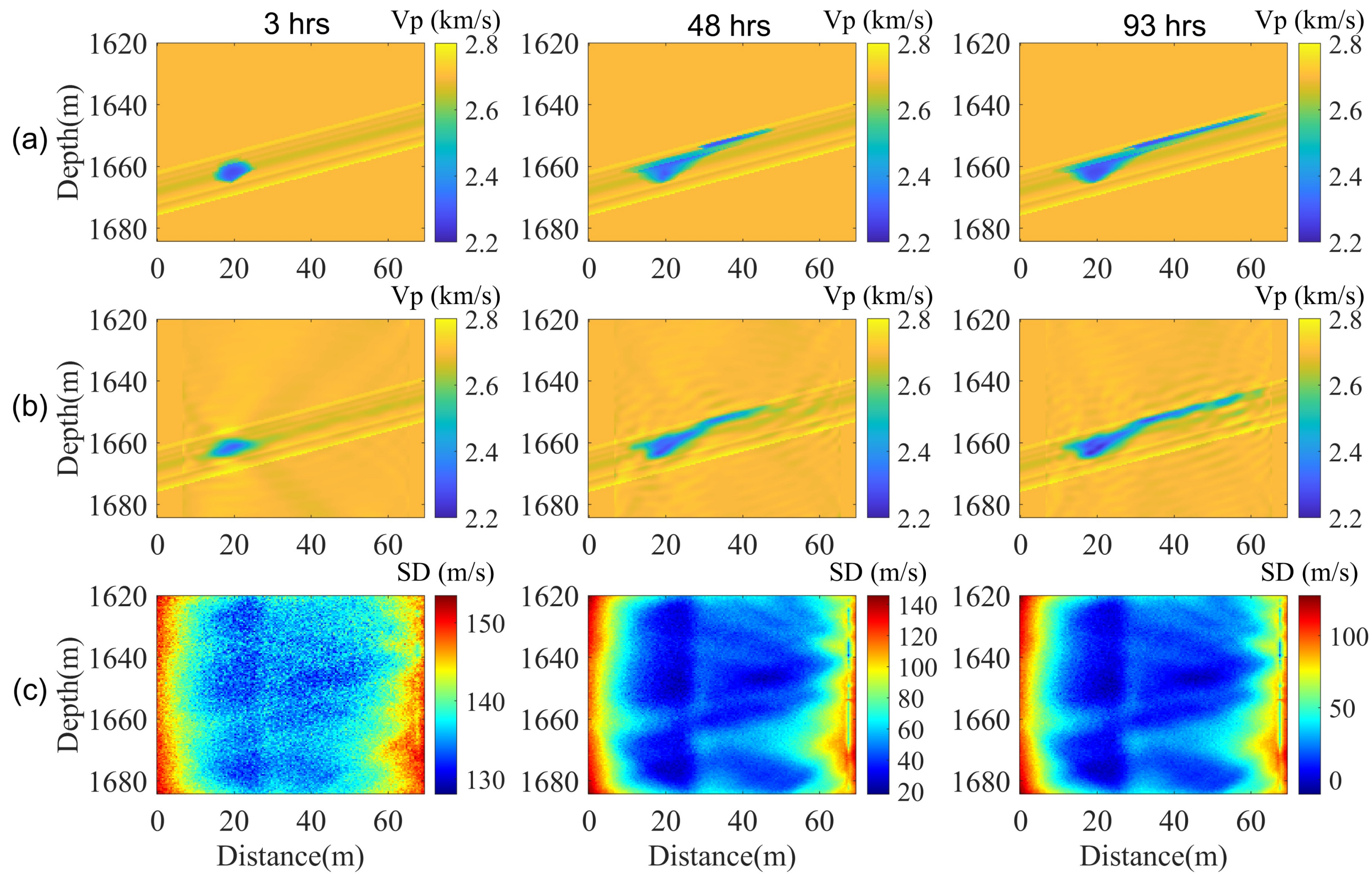
Frio-II results

Seismic P-wave velocity model

True

Inverted

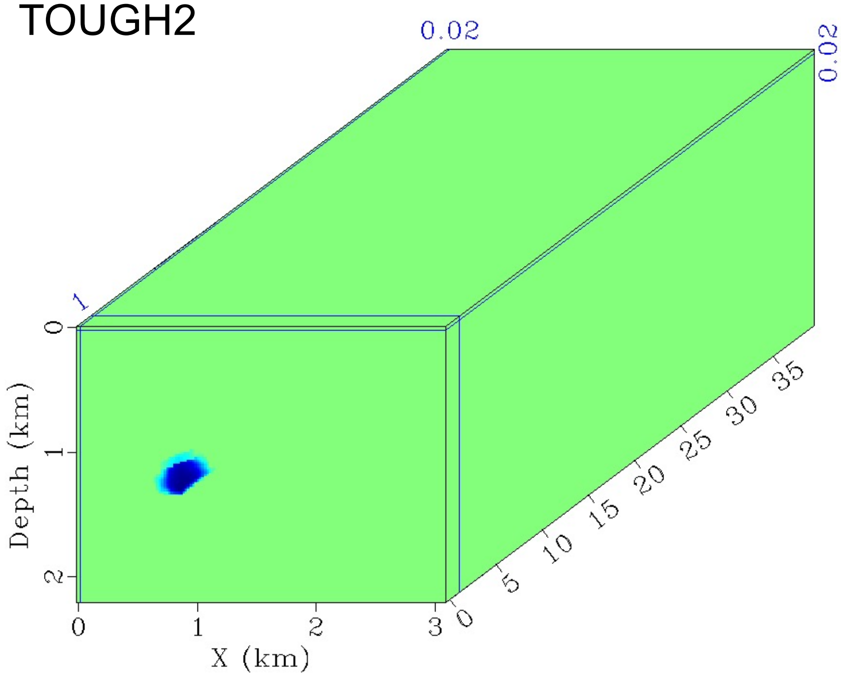
Uncertainty



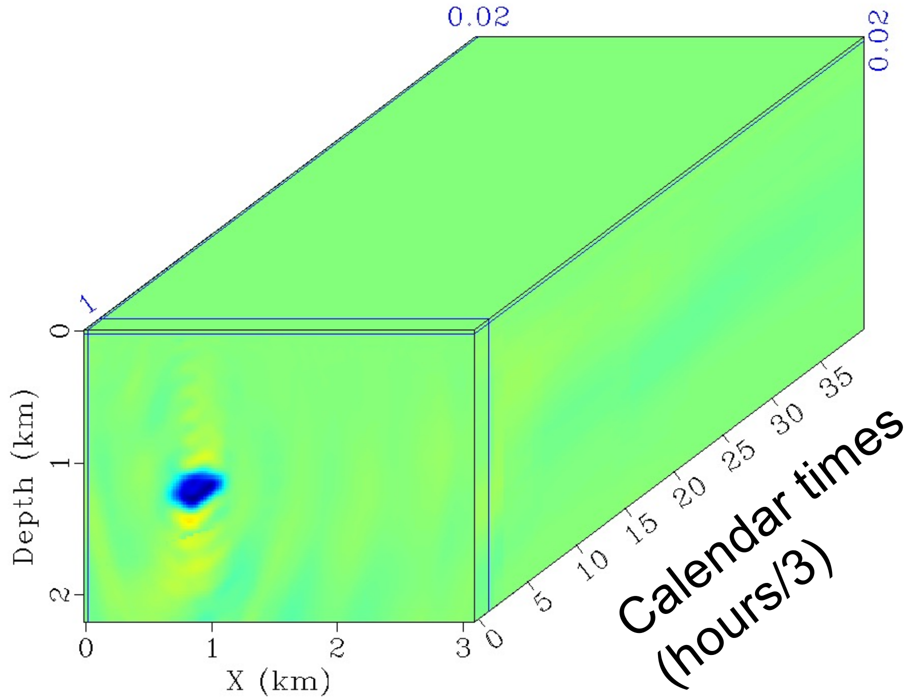
Huang and Zhu (2020) *GJI*

Frio-II 2D seismic monitoring tests

Reference timelapse Frio models from TOUGH2



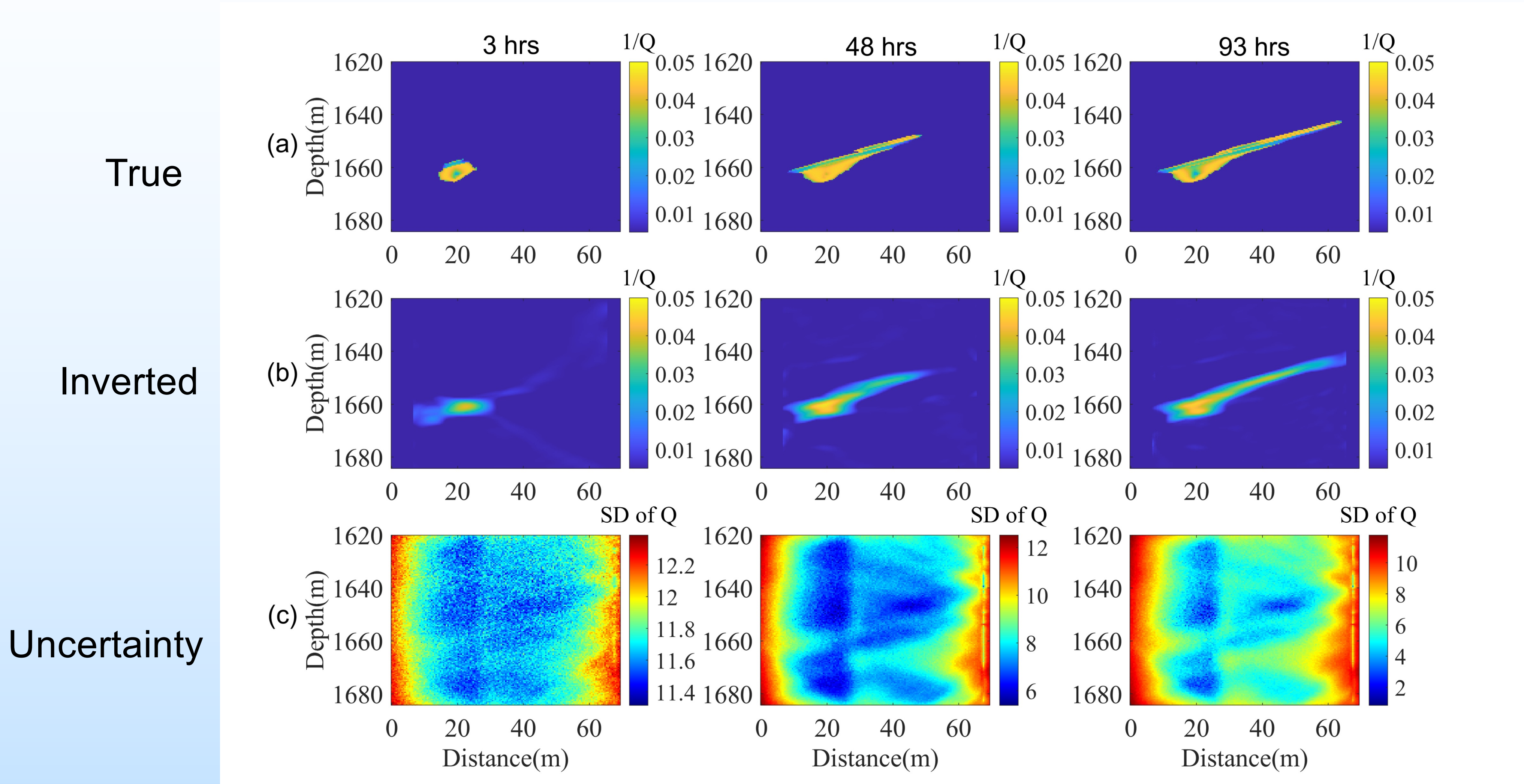
HiEFK FWI timelapse Frio models



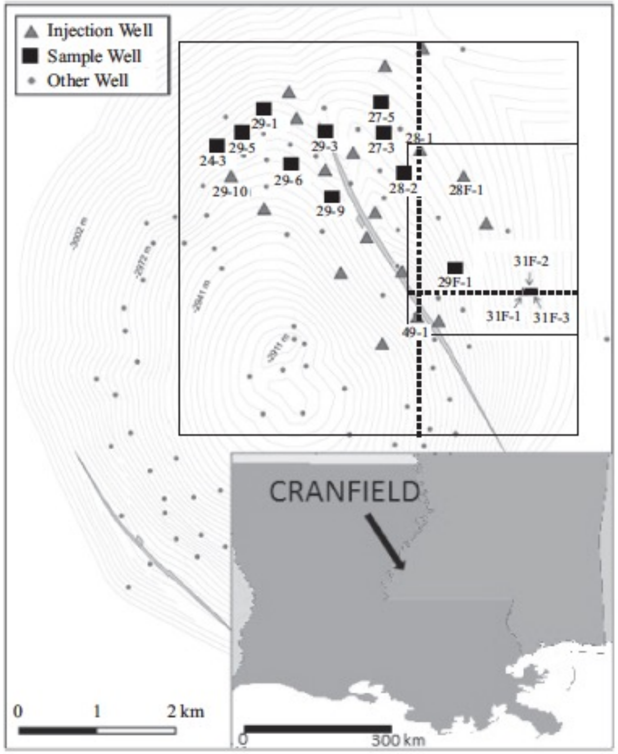
Huang and Zhu (2020) *GJI*

New Frio-II results

Seismic P-wave attenuation model

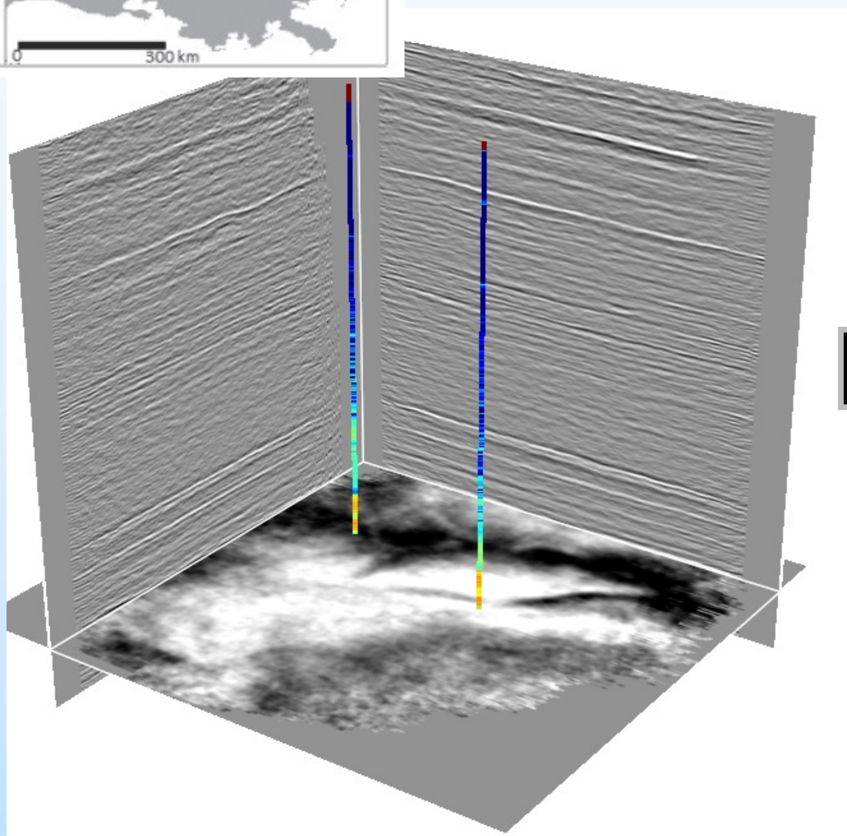


Huang and Zhu (2021) *SEG abstract*

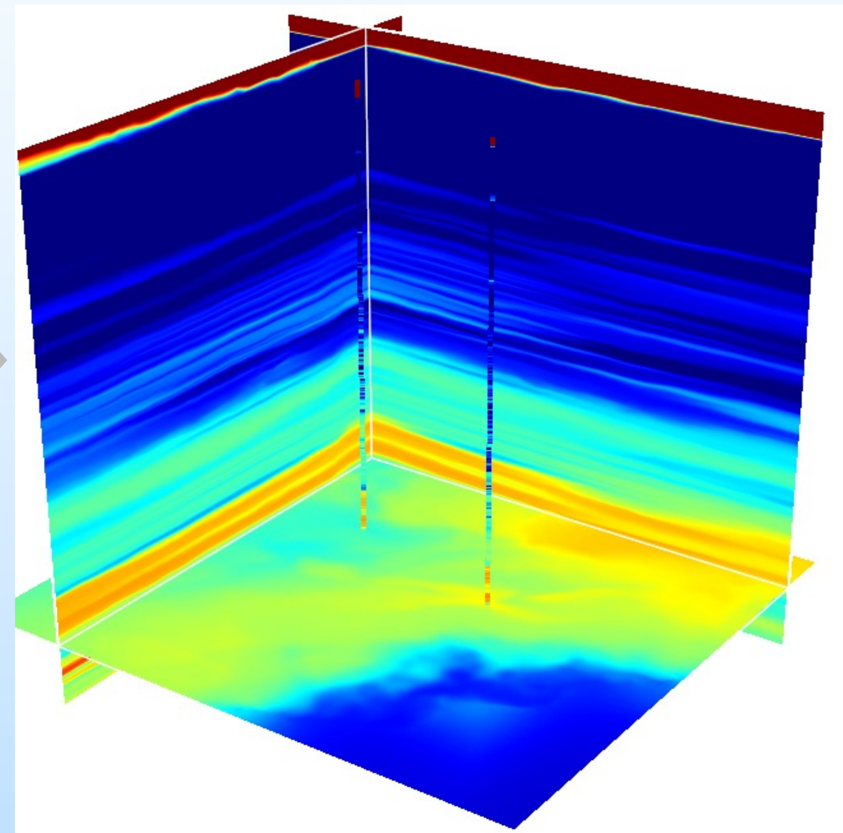


3D Cranfield validation tests

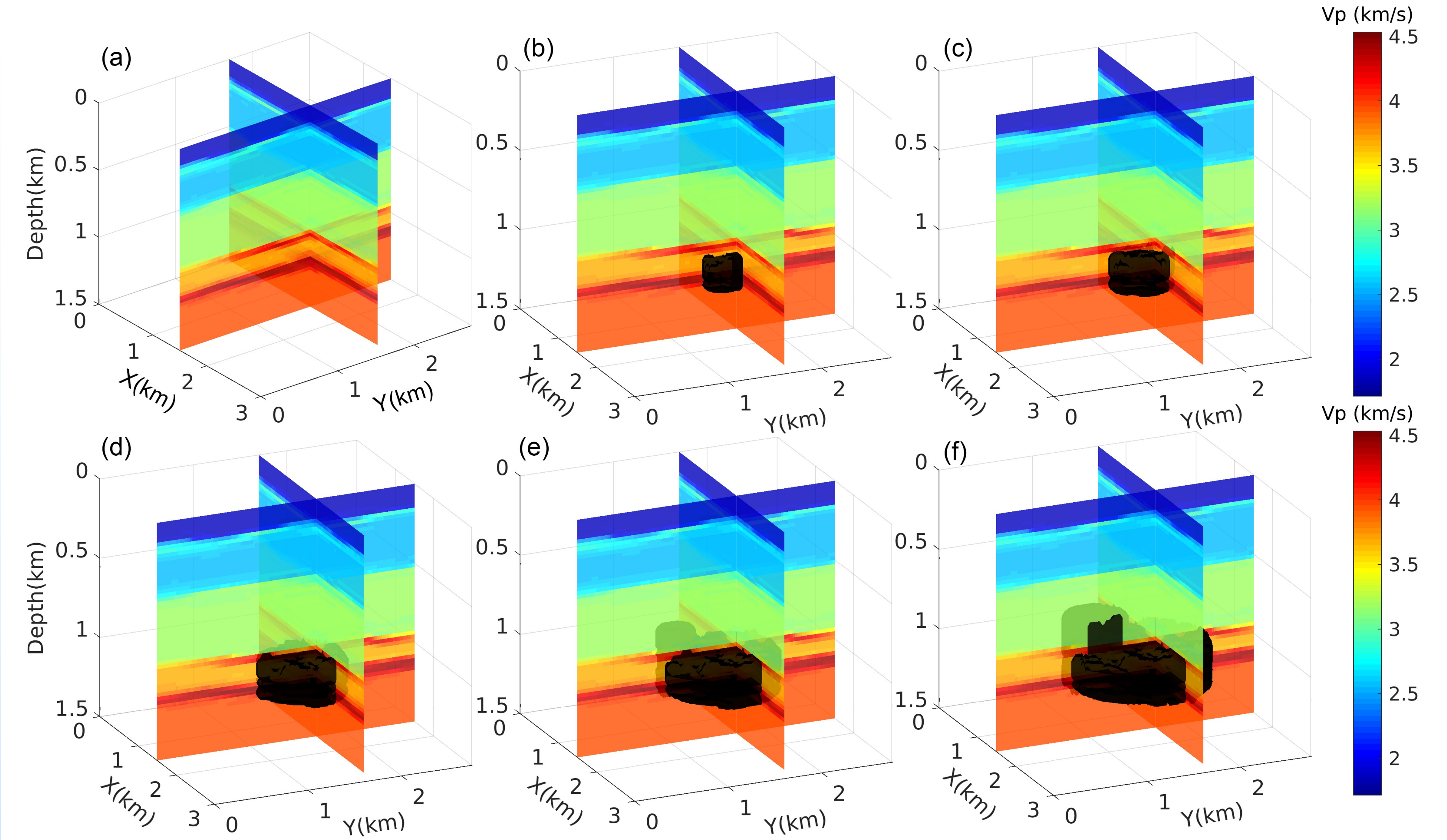
Seismic imaging section + two wells



3D seismic velocity & density profiles

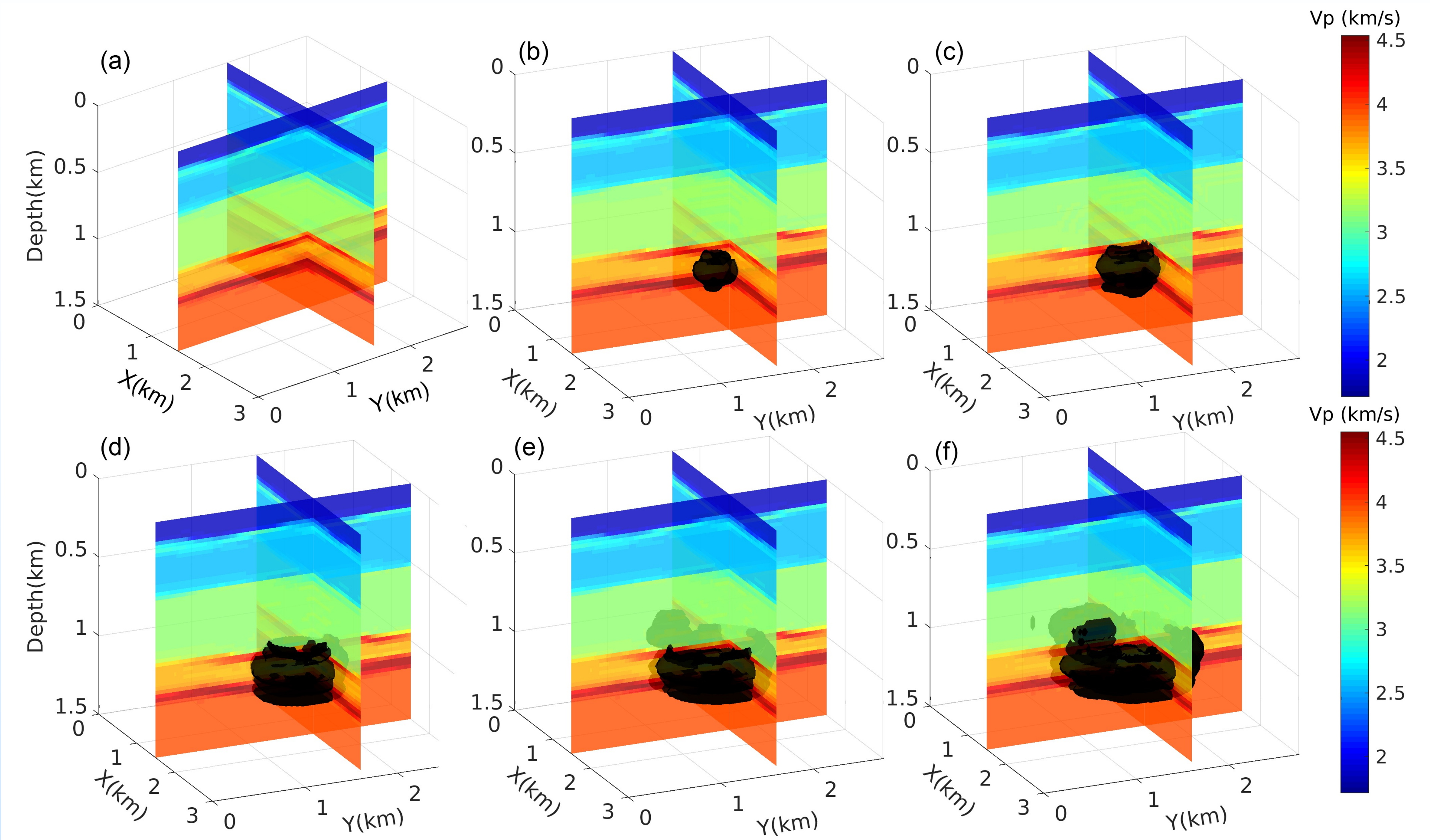


3D Cranfield validation tests



Color scale: seismic velocity
Black: CO2 plume

3D Cranfield validation tests



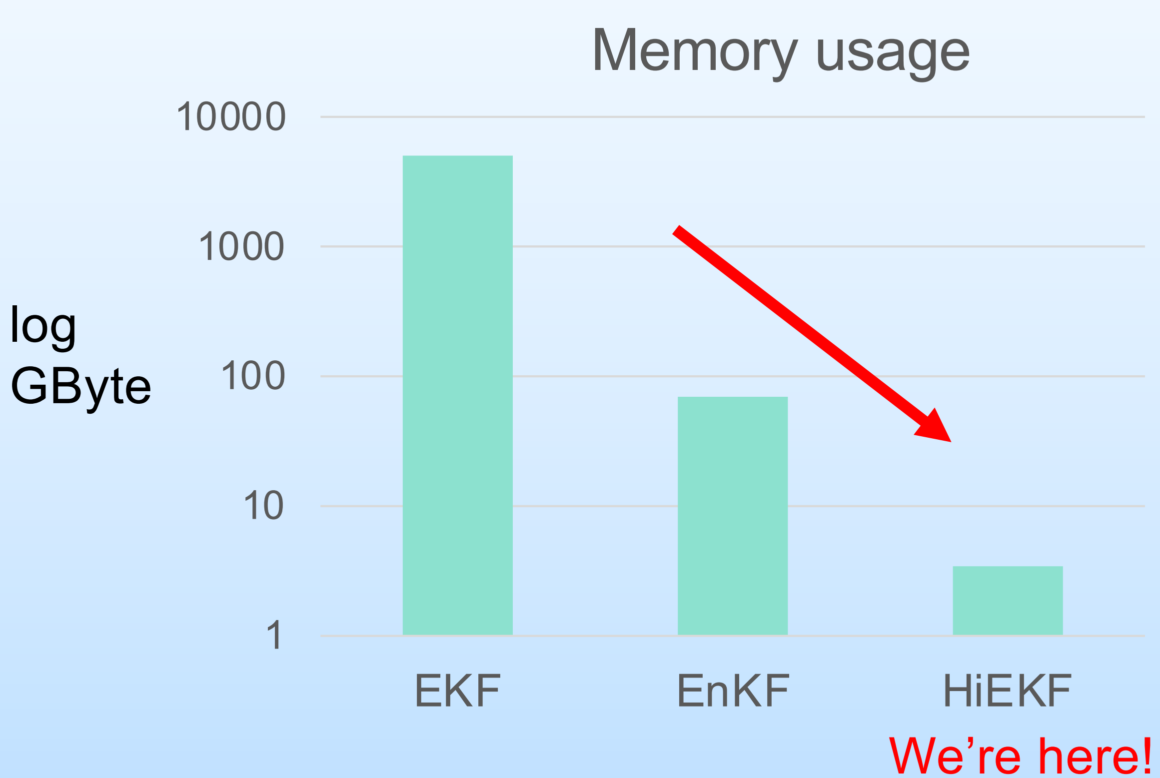
Color scale: seismic velocity

Black: CO2 plume

Huang and Zhu (2020) *GJI*

How fast the HiEKF time-lapse FWI is?

- 3D seismic FWI in Cranfield: 111x121x61. If original EKF is applied, the covariance matrix size is 819291x819291, which is approximately 5 TB, while if applying HiEKF, the maximum matrix size is 819291x528, which is 1550 times less than EKF.



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Accomplishments to Date

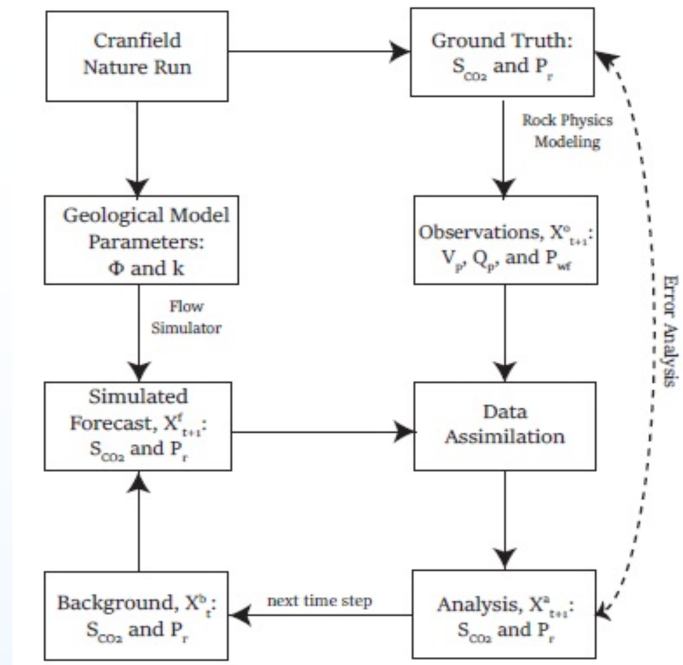
Shams Joon

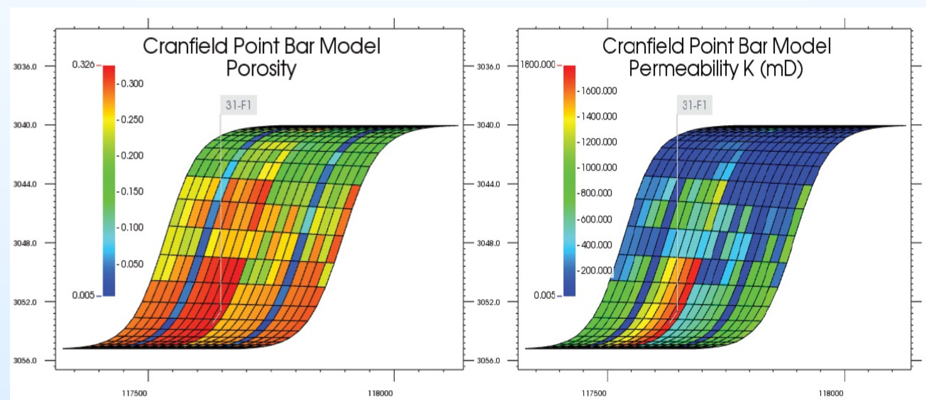
Task 4.0

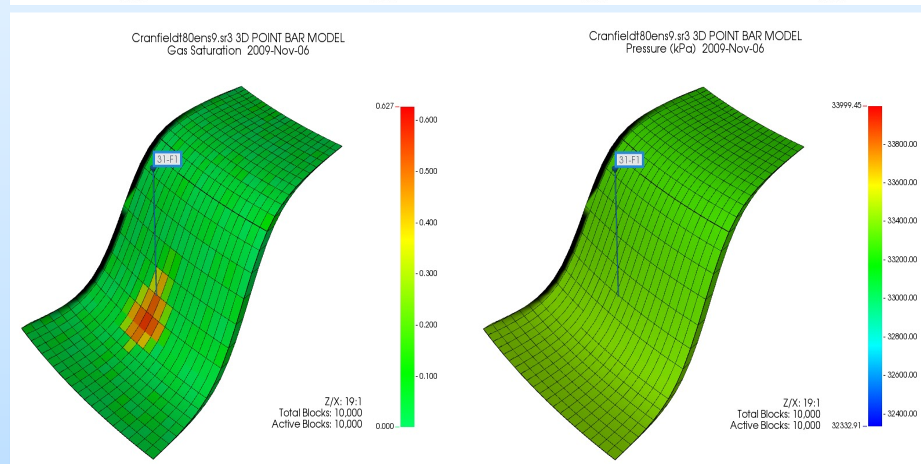
- Competed the Cranfield subsurface geologic models (4.1)
- Developed the joint inversion algorithm (4.2)
- Developed flow simulations of the Frio and Cranfield experiments. (4.3)
- EFK seismic-flow inversion (4.3)
- Direct inversion of seismic-flow using Deep Learning (4.4)

4.2 Joint seismic-pressure-petrophysics inversion in an OSSE environment

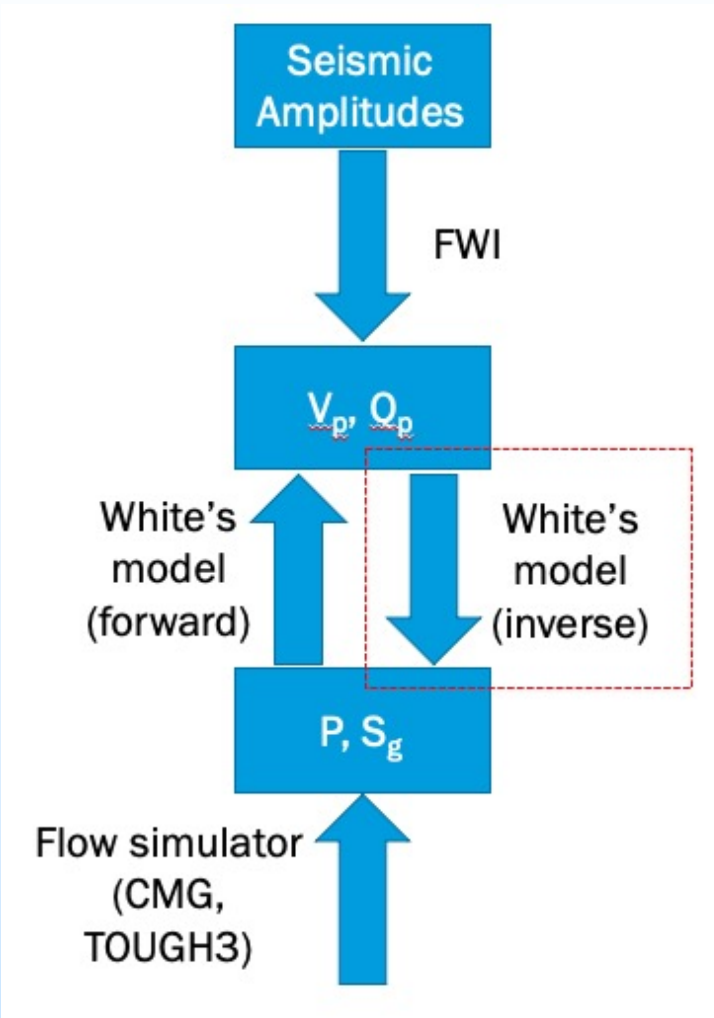
- Model Setup: An observation system simulation experiment (OSSE) is conducted using a reservoir model of the Cranfield GCS site.
- Model Simulation: CO_2 injection, plume evolution, and migration over a period of 90 years is simulated (ground truth).
- Geophysical measurements: P-wave seismic velocity (V_p), attenuation (Q_p), and pressure (P_{wf}) observations are synthesized by randomly perturbing the ground truth and applying rock physics models.
- Data assimilation: The observations are assimilated at varying time intervals: once a month for the first 2 years and once a year for subsequent years. Using ensemble-based data assimilation, EnKF and EnKS, the impact of individual observations is compared with their combined impact in the form of prediction uncertainty. **Rock physics models are incorporated in the data assimilation method to transform state variable from state space to observation space (i.e., computing seismic responses using reservoir properties along with CO_2 saturation and pressure changes)**.
- Uncertainty analysis: The prediction uncertainty is estimated by comparing the assimilated results of CO_2 saturation and reservoir pressure changes against the ground truth.







Ensemble Kalman Filter (EnKF) for inverting seismic attributes



EnKF's goal is to update state vector, which in this case contains pressure (P) and gas saturation (Sg):

$$\mathrm{X}^p = \begin{bmatrix} P_1 & & P_N \\ S_{g,1} & \cdots & S_{g,N} \end{bmatrix}$$

$$= \mathrm{X} + \mathrm{K}_{gain}(\begin{bmatrix} V_p \\ Q_p \end{bmatrix} - f(\mathrm{X}))$$

where $f(\cdot)$ is the forward model (White's model). EnKF assumes the state vector is Gaussian, so to construct the prior ensemble (X), we draw from:

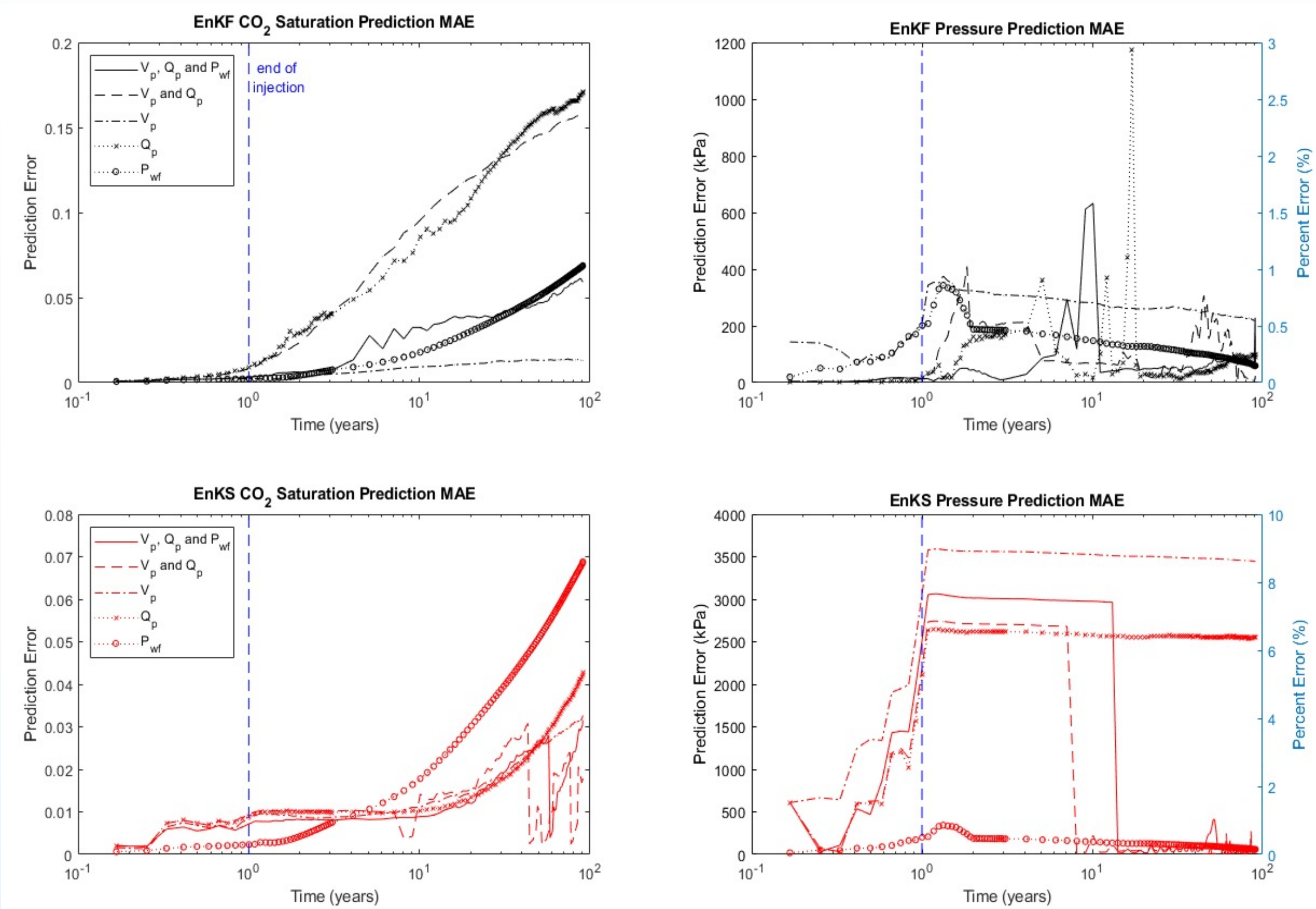
$$P \sim N(\mu_P, \sigma_P)$$

$$logit(S_g) \sim N(\mu_S, \sigma_S)$$

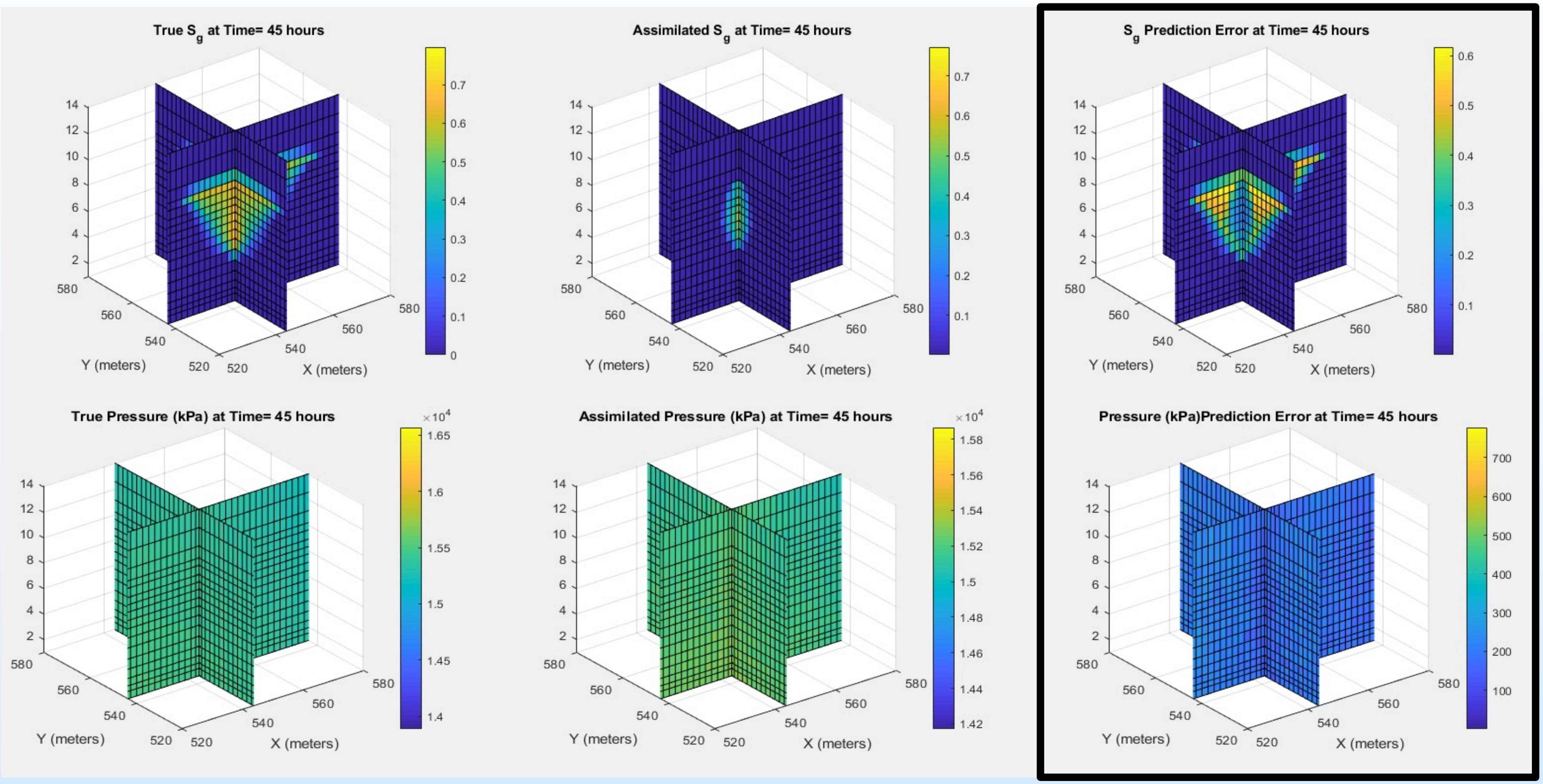
In order to honor $S_g \in [0, 1]$.

Cranfield Assimilation Results: Prediction Error

- Combining continuous measurement in the form of V_p, Q_p, and P_{wf} improves prediction estimates of CO_2 saturation (S_g) and reservoir pressure (P_r) in the simulated Cranfield GCS site.
- EnKS- V_p, Q_p,& P_{wf}: The average mean absolute error (MAE) between the deterministic ground truth and the assimilated S_g estimates is <0.03 and <3000 kPa (10%) for P_r.
- Error analysis is sensitive to the choice of assimilation algorithm.
- EnKF- Q_p only: EnKF is vulnerable to over-, under-shooting and filter divergence for highly nonlinear relationships, namely that between Q_p and S_g, as dictated by the rock physics model.



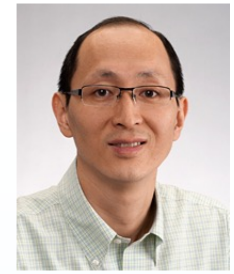
FRIO II EnKF Results (preliminary)



Joint Data Assimilation: Summary of Findings

- Combining seismic and pressure observations significantly reduces forecast error
- Including a Rock Physics Model in the data assimilation introduces additional nonlinearity, which can cause erratic behavior in forecasts
- Error analysis is sensitive to the choice of assimilation algorithm

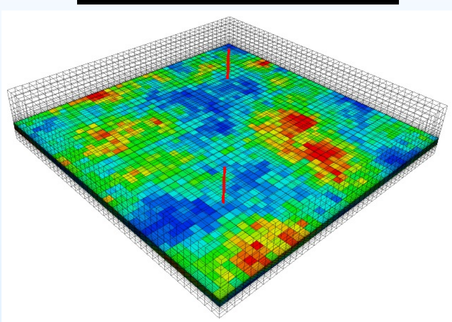
SubTask 4.4: Demonstrate workflow using deep learning (DL)



- Developed and trained DL-based surrogate models of carbon reservoir simulation models
- Developing joint inversion models by using observable reservoir responses to invert parameters

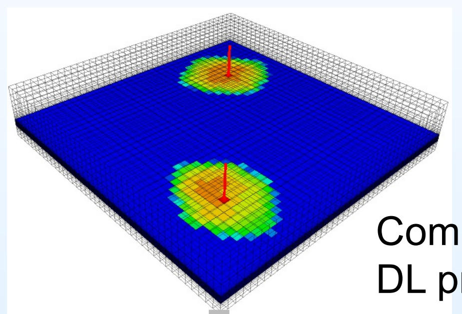
Permeability

Input



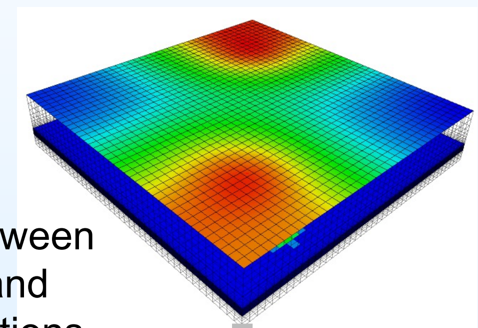
Gas saturation

Output 1

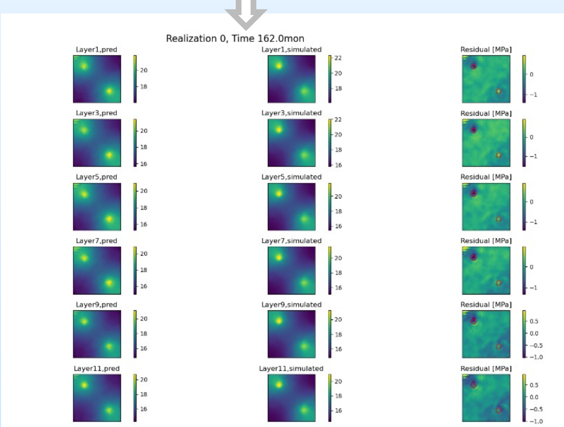


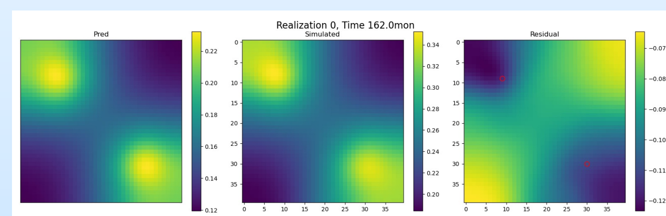
Surface displacement

Output 2



Comparison between DL predictions and reservoir simulations





SubTask 4.4:

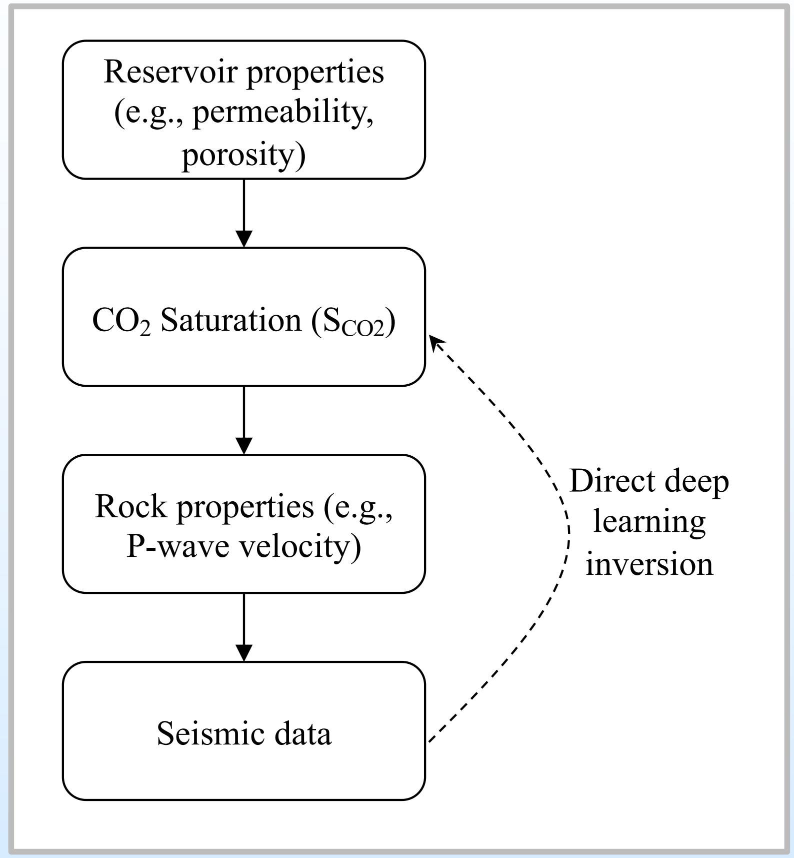
Deep learning based direct seismic to CO_2 gas saturation inversion (in progress)

Goal: To directly predict S_{CO2} from seismic data

Dataset: Using rock physics and fluid flow physics simulation, numerous seismic data and S_{CO2} are generated. The simulations will mimic field settings (e.g., Cranfield).

Method: We design a convolutional neural network (CNN) based encoder-decoder, such that the input of CNN takes in full waveform seismic data in time domain, and outputs S_{CO2} directly in spatial domain.

Workflow to simulate training samples



SubTask 4.4:

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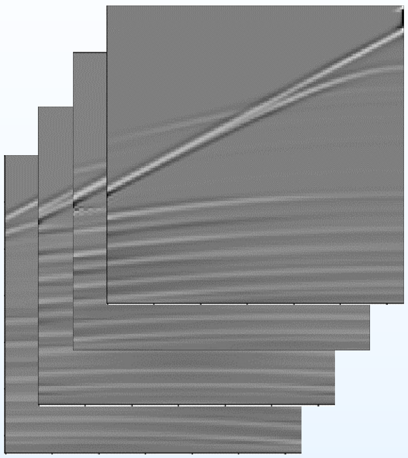
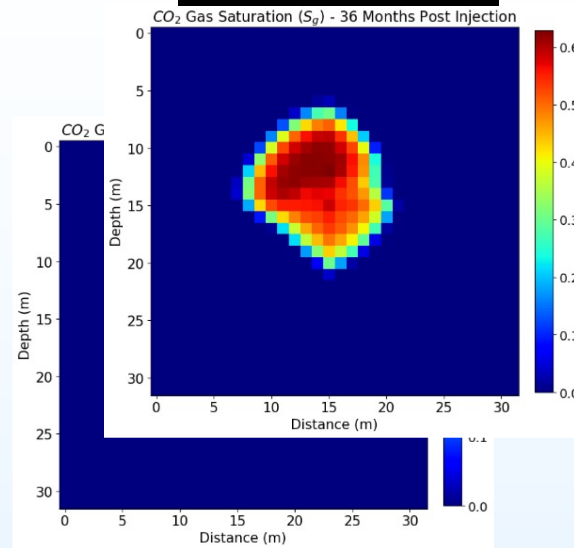
Input



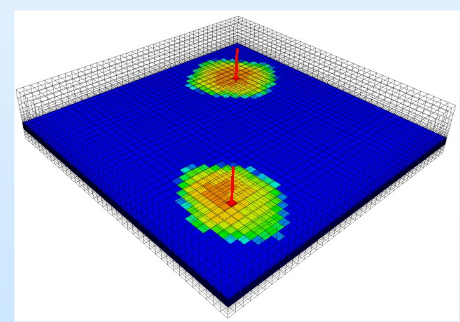
Time lapse full seismic shot gathers

CNN based encoder-decoder model

Output



CO_2 saturation maps



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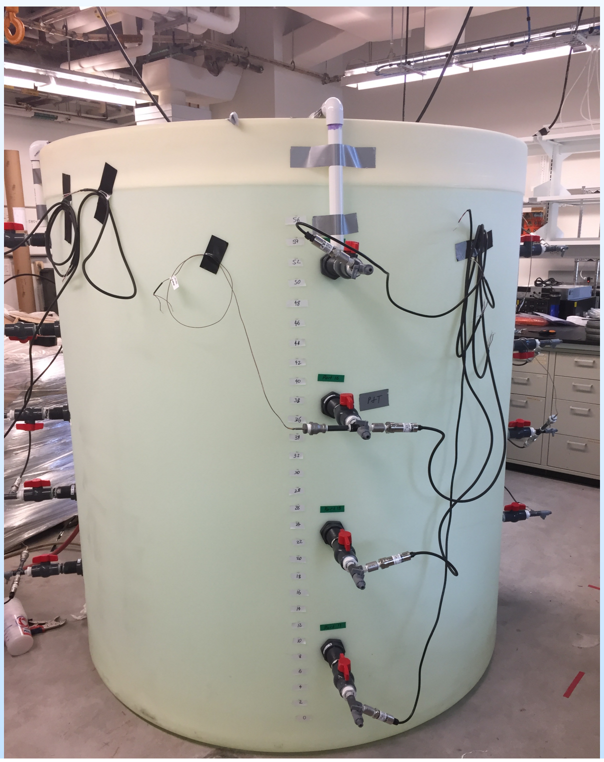
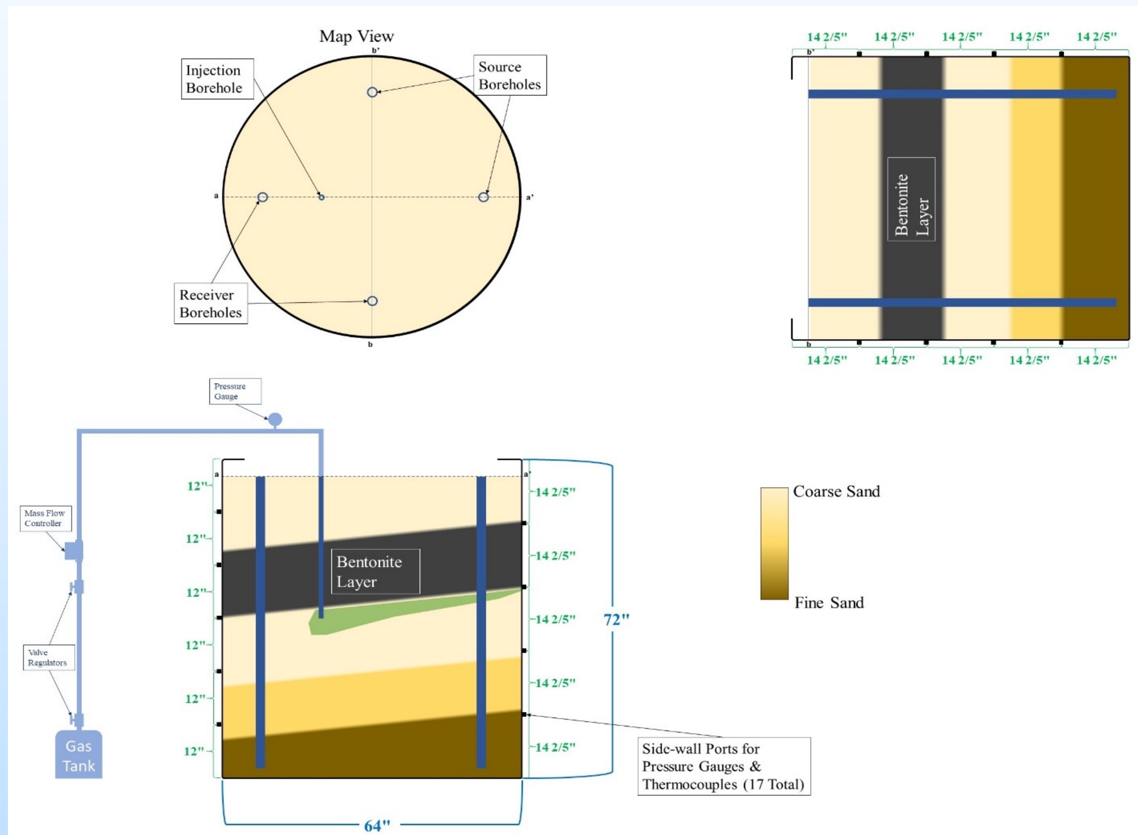
Accomplishments to Date


Tanner Shadoan

Task 5.0 (Rice U.)

- Developed a mesoscale dense CASSM dataset appropriate for the validation of the proposed inversion techniques.


Full tank with exterior sensors



Task 5:
Laboratory CASSM CO_2 Injection Study

Goal: Develop mesoscale (~2-3 m) testbed for experimental acquisition of GCS-relevant CASSM datasets in a controlled environment.

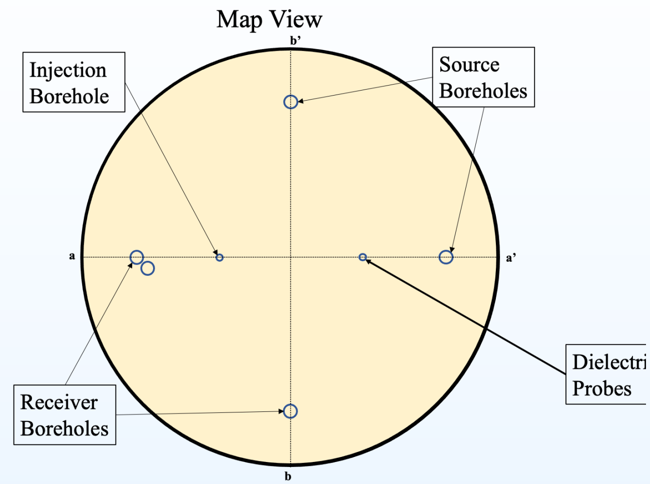
Motivation: Provide test datasets for inversion methodologies developed in other portions of the project with appropriate physics, instrumentation limits, and supporting datasets.

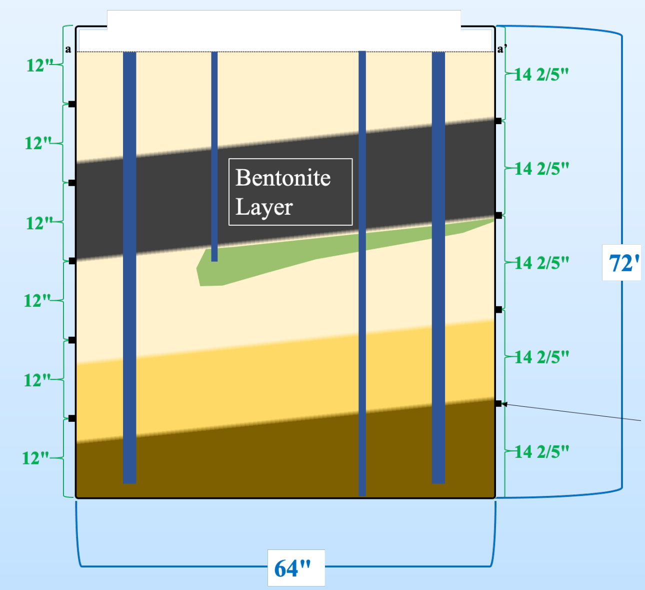
Challenge: Complicated laboratory construction effort in a period where laboratory work has encountered operational barriers (e.g. COVID).

Subtask 5.1: Experimental design and fabrication:

Subtask 5.2: Experimental acquisition:

Subtask 5.3: Data processing and analysis:





Meso-Scale Tank Experiment Design

General operational goals:

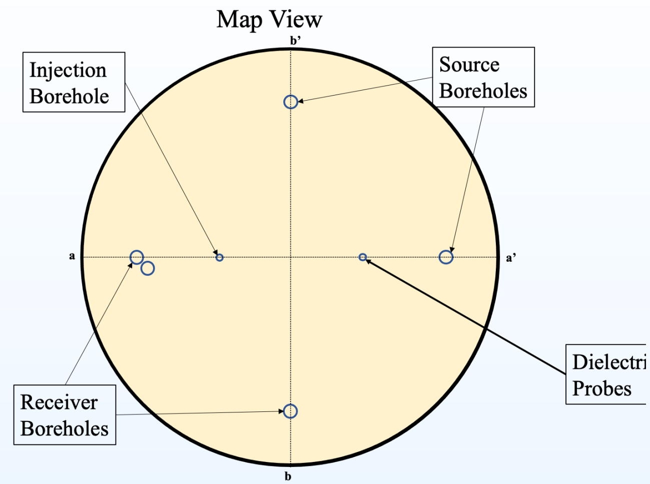
Injection: Replicate up-dip $scCO_2$ migration to understand utility of CASSM in real-time mapping applications (use dipping formations to allow gravity induced flow).

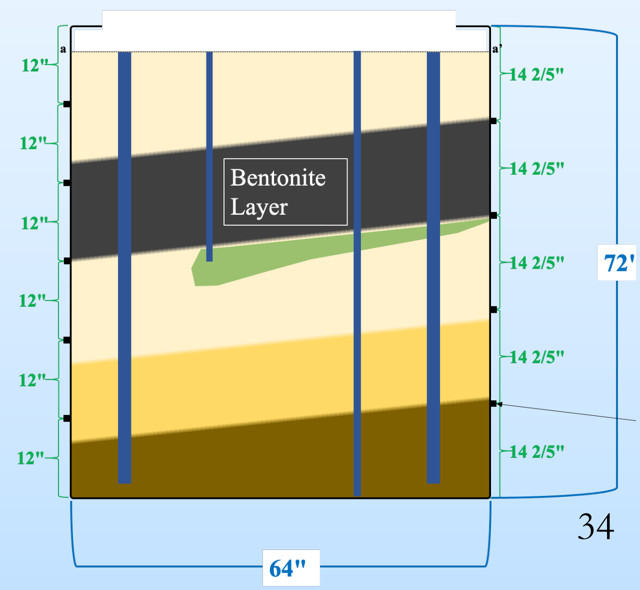
Dissolution: Design de-gassed water injection system to allow CASSM monitoring of seismic signature of CO2 dissolution.

Geometry: Four wells for CASSM/secondary sensor acquisition. One well for gas injection.

Boundary conditions & monitoring: Side ports for P/T measurements and boundary induced flow. 4 on each quadrant except for source side (5). Use arrays of side ports to control/measure lateral pressure gradient.

Ground Truth: Two 1-m dielectric probes (12 points) for monitoring CO_2 saturation (ground truth).



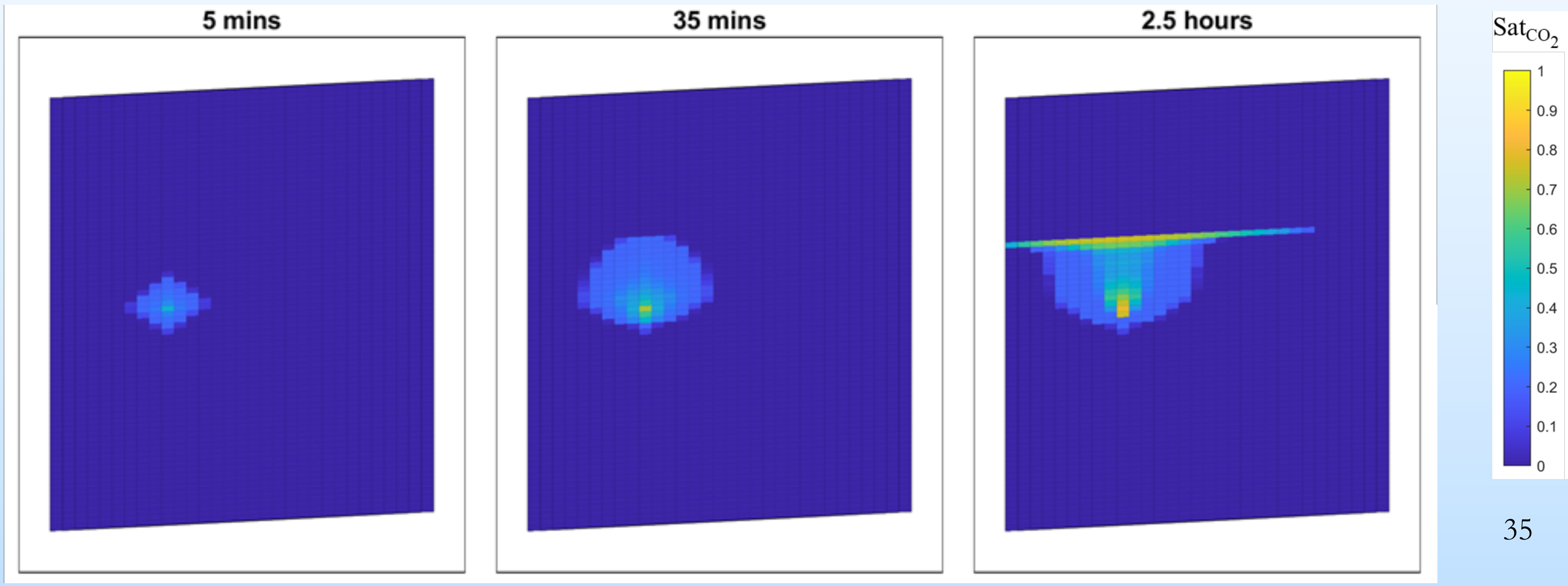


Pre-modeling Meso-Scale Injection Experiments

Injection Simulation: Conducted 3D simulation of a CO_2 injection inside a meso-scale reservoir using a two-phase reservoir simulation software (MRST).

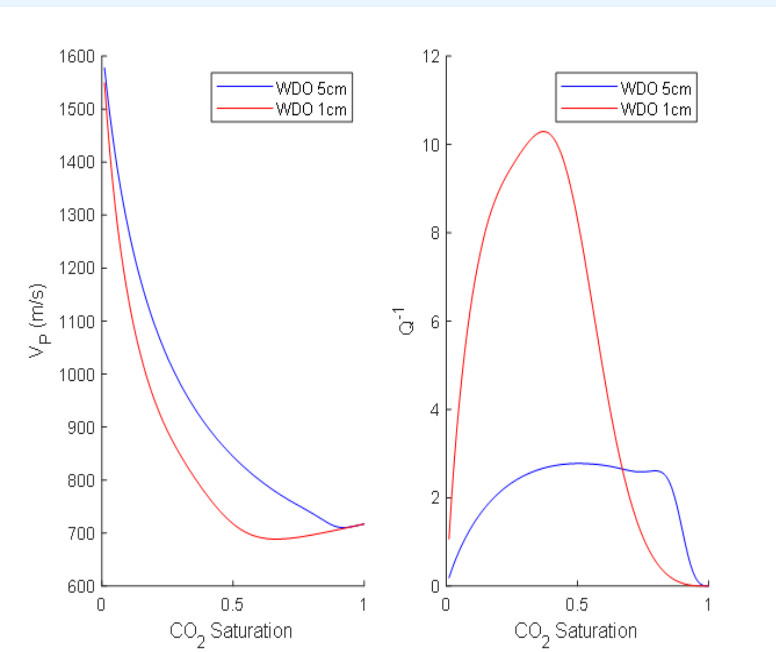
True Geometry: Physical model used for simulation is the designed meso-scale experiment currently being fabricated, which includes a reservoir and cap-rock inside a 1000-gallon tank. Permeabilities based on sands selected (next sections).

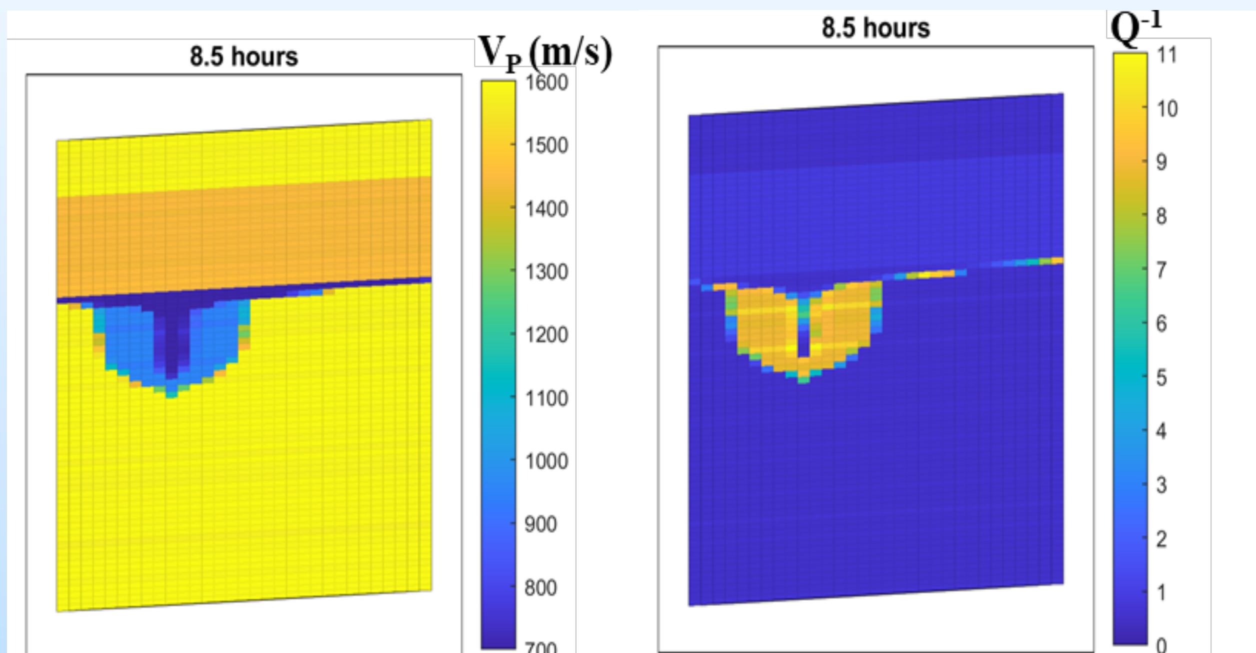
Observations: At rates/pressures considered, experiment will run to completion in less than a day. Highest saturations are directly above injection well and along seal boundary.



Pre-Modeling of Seismic Response

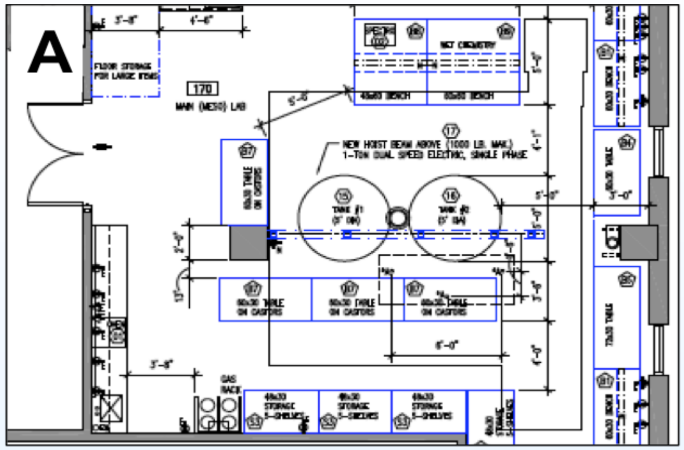
- **Forward Modeling:** Elastic property models (V_P and Q^{-1}) were computed using White and Dutta-Ode's patch saturation model from flow simulation results.
- **Results:** The models show that different CO_2 saturations yield unambiguous elastic properties when combining Vp & Qp; important for determining CO_2 saturations during the experiment. Vp & Qp perturbations are sufficient for easy measurement with CASSM system.
- **Take-Away:** With good results from the forward model, we are confident in the mesoscale model testbed design.

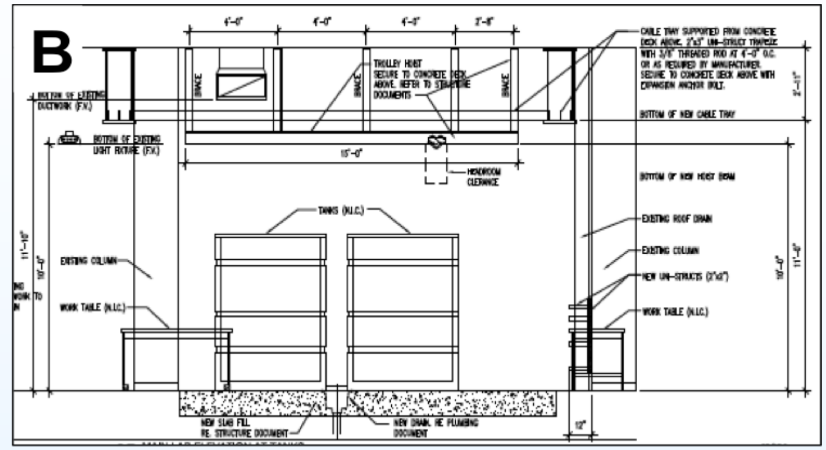




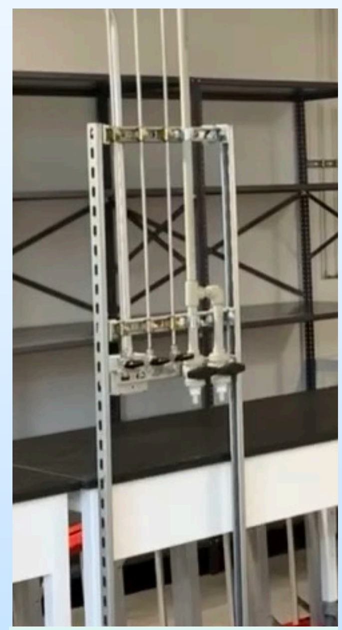
Meso-Scale Experiment: Infrastructure

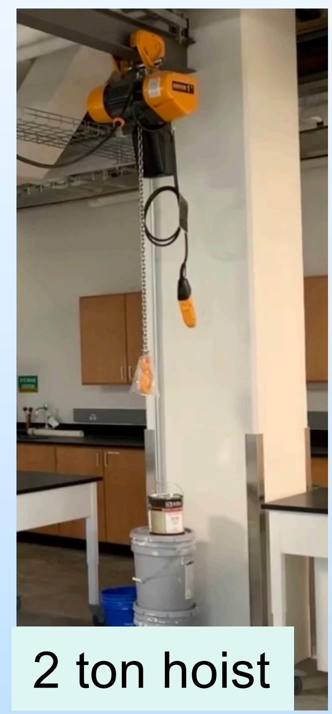
- Large (6+ ft sand tank) challenging to site.
- Opportunity to conduct lab remodel around tank (Fall 2019 – Spring 2020).
- Space included high ceiling, 24” slab floor on grade for large loads, 2 ton ceiling hoist for moving heavy objects into tanks.
- Pole-mounted utilities (power, water, gas, data transfer) and frame added to service tanks.






Finished lab


Utilities drop


2 ton hoist

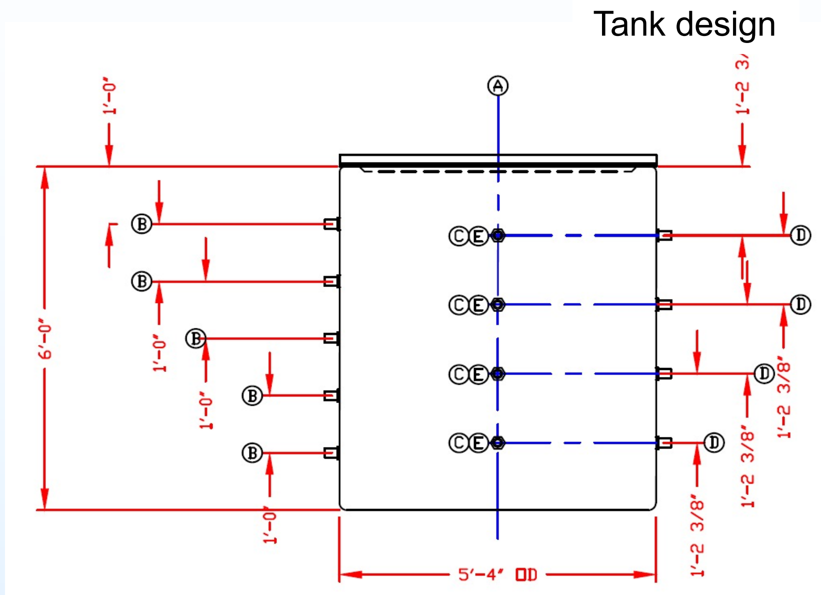
Meso-Scale Experiment: Development 1

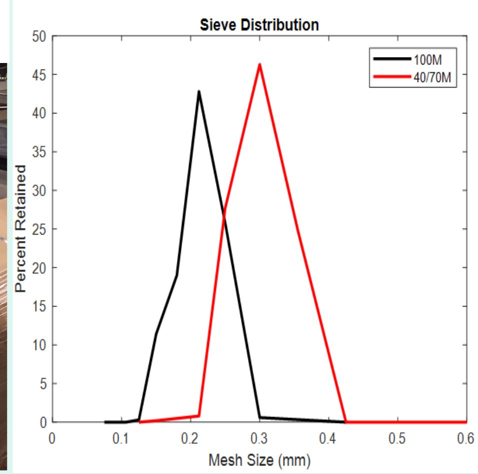
Broad comment: many procurement tasks were constrained by COVID-19 in 2020/21

Tank: Designed and procured special-purpose tank for sand containment with port system (Poly-Processing)

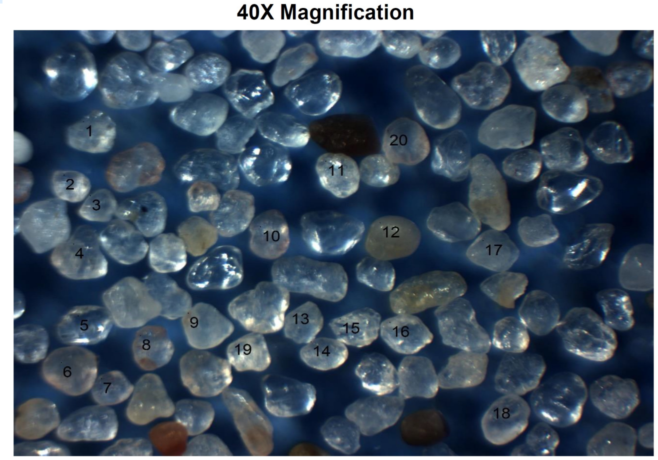
Tank Size: 963 gallons, 5.4' OD, 6' high (delivered Sep. 2020).

Packing Media: Obtained 12,000 lbs of washed sieved sand (100, and 40/70 mesh) for tank packing (delivered April 2021).





40X Magnification



Meso-Scale Experiment: Development 2

CASSM System: In concert with LBNL, developed lab-scale CASSM electronics stack.

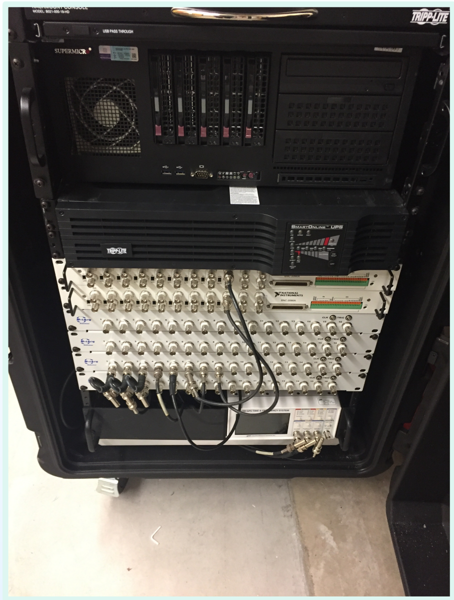
Sensors: 40 pre-amplified hydrophones (x-well), 10 monitor sensors (single well) [HTI-96].

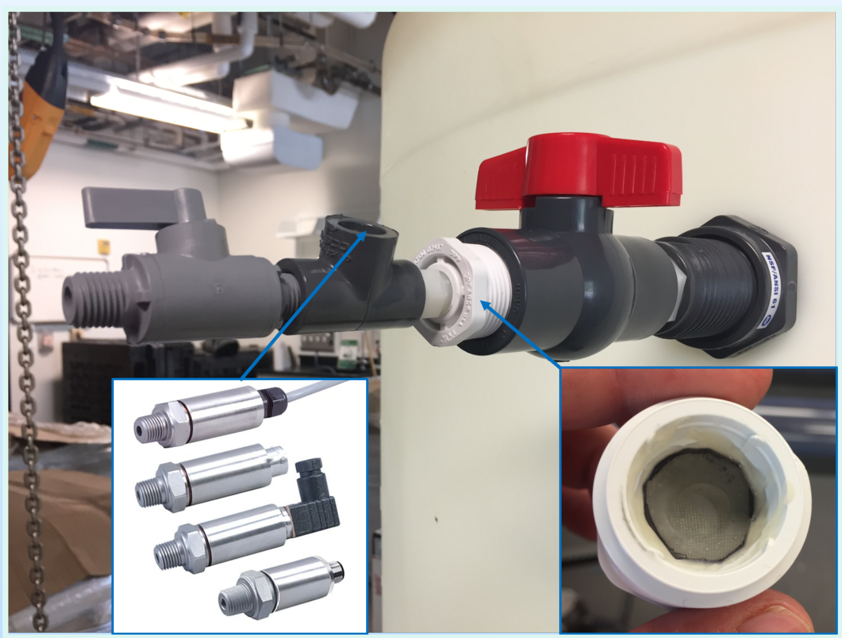
Sources: 22 4” piezo sources (tested).

Recording: Custom 1 MB, 18 bit, 48 channel A/D system (D-TAQ).

Timing: Full system (A/D, D/A) slaved to rubidium clock to reduce long-term drift (SRS).

Side Ports: Pressure transducers & thermocouples to track boundry conditions.



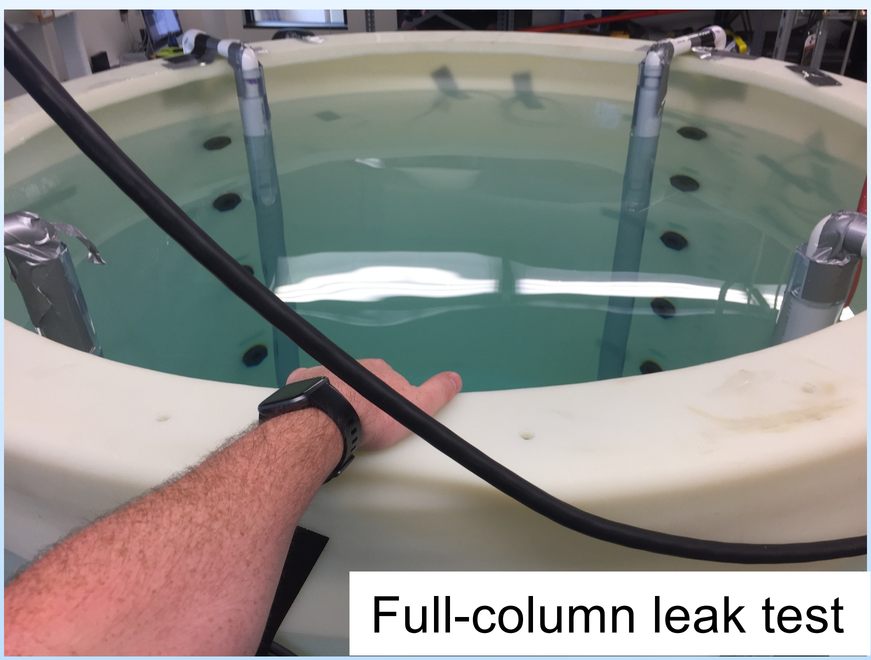


Meso-Scale Experiment: Development 3

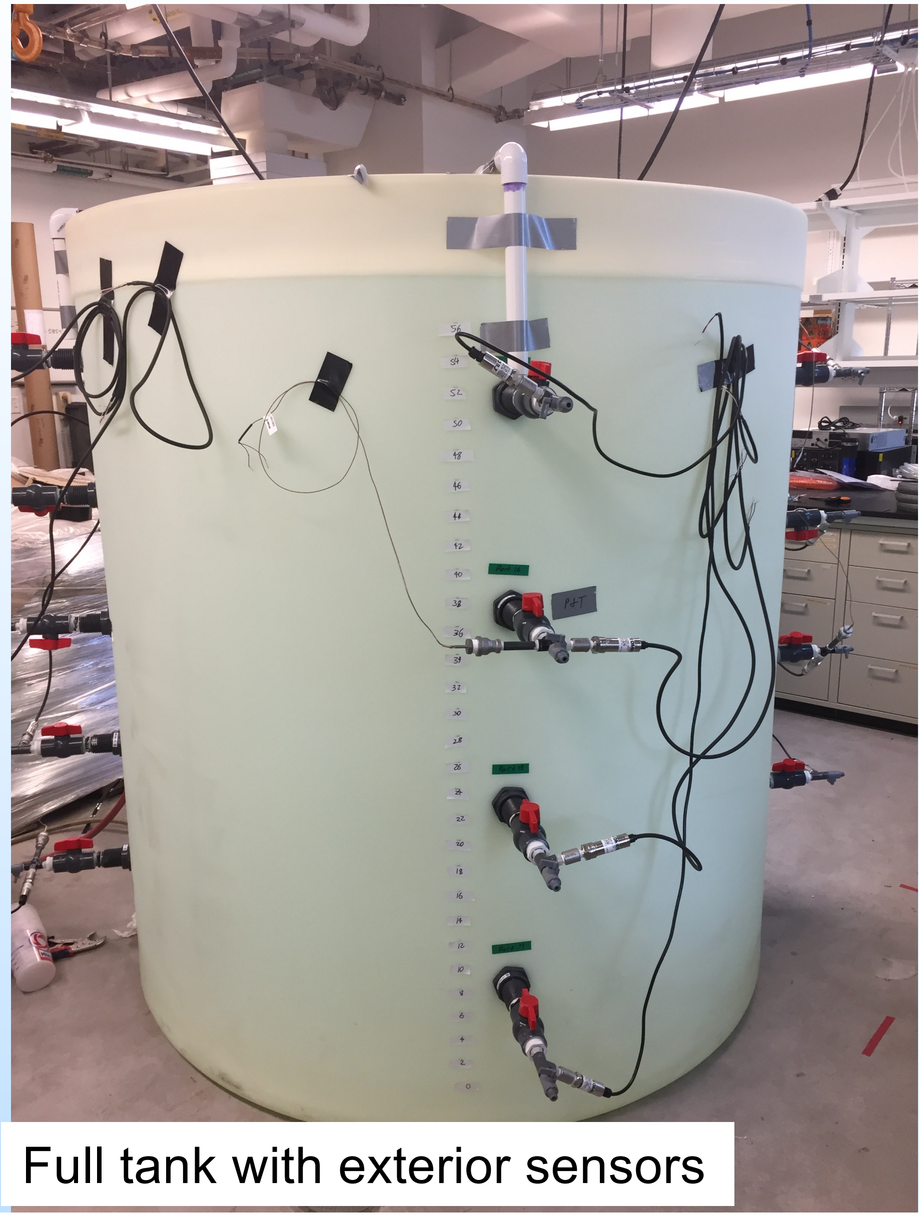
Current Work:

- Testing/integration side-wall port thermocouples and pressure transducers
- Finishing final leak tests.

Aug. 2021:	Pack tank with media
Sep-Oct: 2021:	Initial CASSM tests/baseline
Winter 2021/2022:	Gas injection experiments (1st set)
Spring 2022:	Long-term dissolution tests



Full-column leak test



Full tank with exterior sensors

Project Summary

Task	Milestone Title	Planned Completion	Actual Completion	Verification method	Comments
1.0	Project management plan	FY18 Q1	02/27/2018	Submit updated PMP	Completed
1.1	Project kick-off meeting	01/22/2018	01/23/2018	Presentation	Completed
1.2	Update DMP & TMP	FY18 Q2	04/26/2018	Submit updated TMP	Completed
2.1	Complete theoretical development and preliminary results	FY19 Q3	~~03/31/2020~~	Milestone report on evaluation of modeling and inversion algorithms	Completed
3	Complete development of time-lapse full waveform inversion	FY20 Q1	~~07/27/2020~~	Algorithms successfully demonstrated for synthetic data and submit milestone report	95% complete
4.1	Complete Multiscale reservoir modeling of plume migration	FY20 Q1	~~04/28/2020~~	Milestone report on Frio and Cranfield flow models	Completed
4.3	*Complete Bayesian Inversion*	FY21 Q3		Algorithms successfully demonstrated for Frio data and submit milestone report	In progress
5.1	*Complete the design and fabrication of the CASSM Experimental facility*	FY21 Q3		The laboratory equipment is ready and perform experiments	In progress
5.2	*Complete* mesoscale CASSM studies	FY22 Q1		Report on preliminary experimental results	
6	Complete lab and field data tests	FY22 Q1		Final report is produced and main findings	

Synergy Opportunities

- develop methodologies for fast seismic full waveform inversion of continuous active source seismic monitoring, (CASSM) datasets; ---- DAS data (DE-FE0032058)

- develop deep-learning based full waveform inversion of seismic models and pressure data for providing and updating CO_2 saturation models;

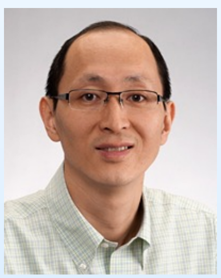
Thank you for your attention!

Thank you all!

Leading task 4

Task 4.1

Leading ALL tasks



Task 4.2/4.4

Leading task 5

PhD student: <u>Guangchi Xing</u>
Task 2

Postdoc: <u>Chao Huang/Xuejian Liu</u>
Task 3, 6, 7

PhD student: <u>Ismeal Dawuda</u>
Task 4.1

PhD students: <u>Shams Joon/Zi Xian Leong</u>
Task 4.2, 4.3, 4.4

PhD student: <u>Tanner Shadoan (Rice U.)</u>
Task 5

Benefit to the Program

- This project is closely related to Program's goal of **developing and validating methodologies and technologies to measure and account for 99 percent of injected CO_2 in the injection zones**.

- The proposed methodology will enable us to delineate the CO_2 plume boundaries with great confidence, addressing FOA goals including "…***detect stored CO_2 and assess the CO_2 plume boundaries over time within the target reservoir***…"

Benefit to the Program

- The integrated inversion results from the Bayesian approach can give the estimate realizations of CO_2 saturation models but also can quantify the limits of detection and thresholds of uncertainty, directly addresses FOA requesting "…***quantify the limits of detection and thresholds of uncertainty**… **methods should take into account the qualities of fluids (i.e., CO_2 saturation, composition, etc.)***".

- "Real-time" ability to delineate CO_2 plume boundaries and quantifying CO_2 saturation using seismic CASSM and pressure data should allow DOE's investment in future monitoring systems that eliminate the expensive and personnel-intensive effort of independent inversions.

Gantt Chart

Task	Description	Budget Period 1								Budget Period 2							
		Year 1				Year 2				Year 3				Year 4			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Update project management plan	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	**Joint FWI for Vp and Qp**																
	2.1 Derivation of viscoacoustic equation	■	■	■													
	2.2 Theoretical development			■	■	■	■										
	2.3 Validation tests					■	■ *										
3	***Time-lapse FWI with data assimilation***																
	3.1 Data assimilation					■	■	■	■								
	3.2 Validation tests						■	■	■ *								
4	**Bayesian inversion technique**																
	4.1 Reservoir modeling	■	■	■	■	■	■	■	■								
	4.2 Pressure inversion						■	■	■	■							
	4.3 Bayesian inversion framework									■	■	■	■	■ *			
5	**Lab experiments**																
	5.1 Experimental design and fabrication						■	■	■	■							
	5.2 Experimental acquisition									■	■	■	■				
	5.3 Data processing and analysis												■	■			
6	**Demonstration**																
	6.1 Laboratory data													■	■	■	
	6.2 Field data														■	■	■
7	**Synthesis of results**						■	■	■	■	■	■	■	■	■	■	■

Publications

Published:

Sun A. Y., (2018). Discovering state-parameter mappings in subsurface models using generative adversarial networks. *Geophysical Research Letters*, 45, 11,137– 11,146.

Zhu T., Ajo-Franklin J., Daley T.M., and Marone C., (2019) Dynamics of geologic CO2 storage and plume motion revealed by seismic coda waves, *Proceedings of the National Academy of Sciences of the United States of America*, 116 (7) 2464-2469

Xing G. and Zhu T., (2019) Modeling frequency-independent Q viscoacoustic wave propagation in heterogeneous media, *Journal of Geophysical Research: Solid Earth*, 124(11), 11568-11584

Huang C., and Zhu T., (2020) Towards real-time monitoring: data assimilated time-lapse full waveform inversion for seismic velocity and uncertainty estimation, Geophys. J. Int, 223 (2), 811-824

Xing G., and Zhu T., (2021) *A viscoelastic model for seismic attenuation using fractal mechanical network*, Geophys. J. Int,

Submitted:

Xing G. and Zhu T., (2021) Anelastic Fréchet kernels based on a fractional viscoacoustic wave equation, submitted to Geophysics

Harpreet Kaur, Alexander Sun, Zhi Zhong, and Sergey Fomel, (202*) Time-lapse seismic data inversion for estimating reservoir parameters using deep learning, submitted to Interpretation.

Presentations

2019:

Xing G. and Zhu T., (2019), Frechet kernels based on a fractional viscoacoustic wave equation, SEG Annual meeting 2019

Huang C., and Zhu T., (2019), Time-lapse full waveform inversion plus extended Kalman filter for high-resolution seismic models and uncertainty estimation, SEG Annual meeting 2019

Joon S. and Morgan E., (2019), Real-time monitoring of CO2 plume during GCS with integrated continuous active-source seismic and pressure monitoring data, AGU fall meeting 2019

Xing G. and Zhu T., (2019), Finite-frequency Fréchet Kernels for Adjoint Tomography of Frequency-independent Q, AGU fall meeting 2019

2020:

Huang C., and Zhu T., (2020), SEG Annual meeting 2020

Xing G. and Zhu T., (2020), SEG Annual meeting 2020

Xing G. and Zhu T., (2020), AGU Annual meeting 2020