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

Project Number: FE0031544

01/24/2018 – 01/23/2022

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U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

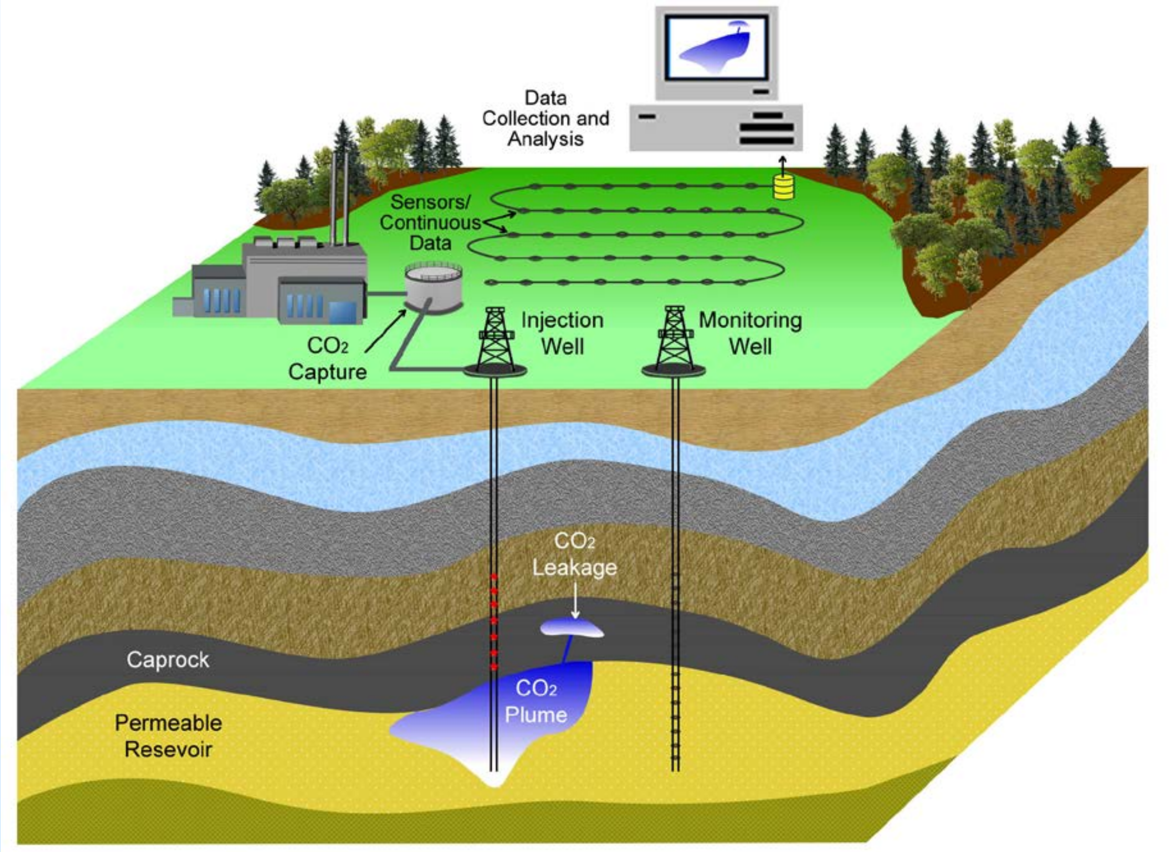
August 26-30, 2019

Presentation Outline

- Background
  - Challenges
  - Proposed Solutions
- Project Overview
- Technical Status
- Accomplishments to date
- Synergy Opportunities
- Project Summary

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)

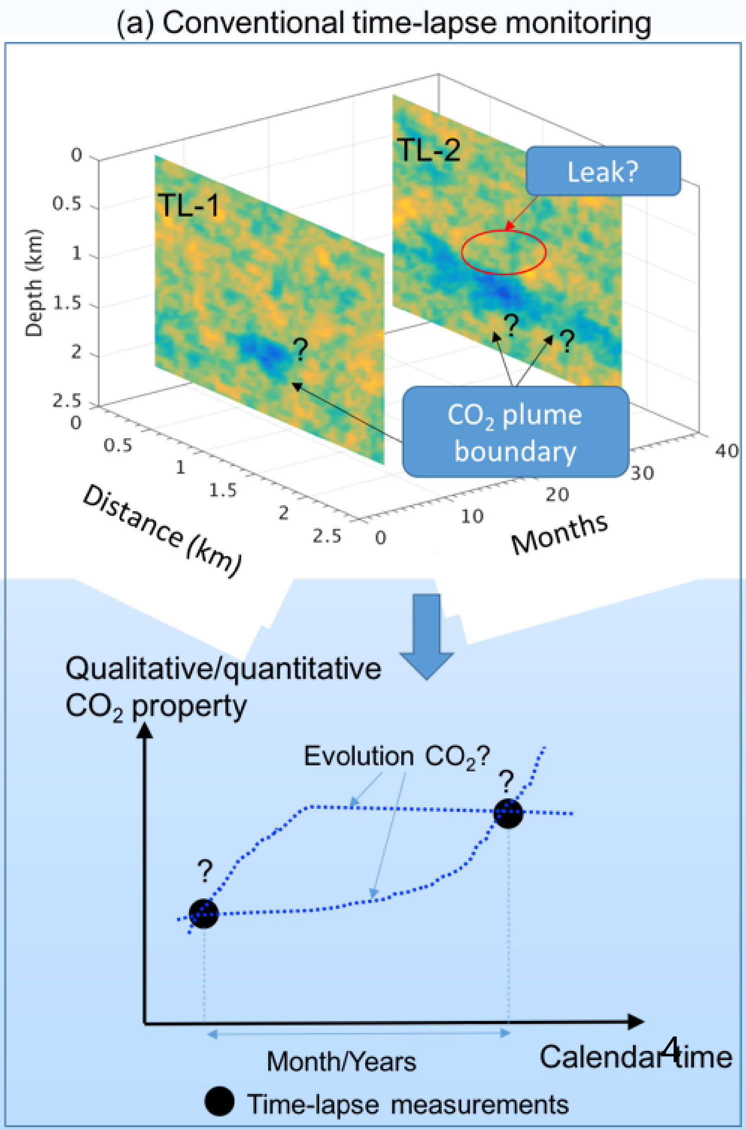


Major Challenges

- Sparse time-lapse data
  e.g. Cranfield 4Dseismic
  Baseline: 2007
  Repeat: 2010

- Lack of estimated physical properties of CO_2 plume

- Lack of a quantitative estimation of plume uncertainty

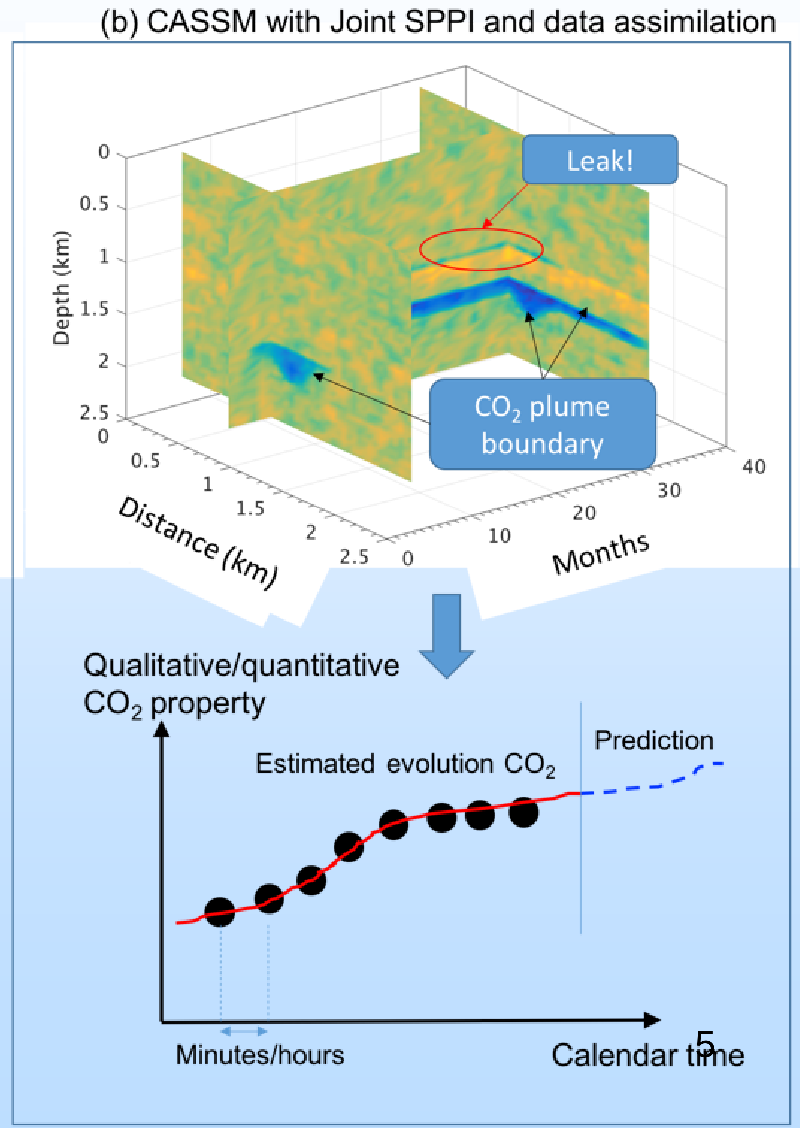


Proposed solutions

- Sparse time-lapse data

(Nearly) Continuously monitoring

- ❖ temporal (Daley et al., 2007)
- ❖ spatial resolution



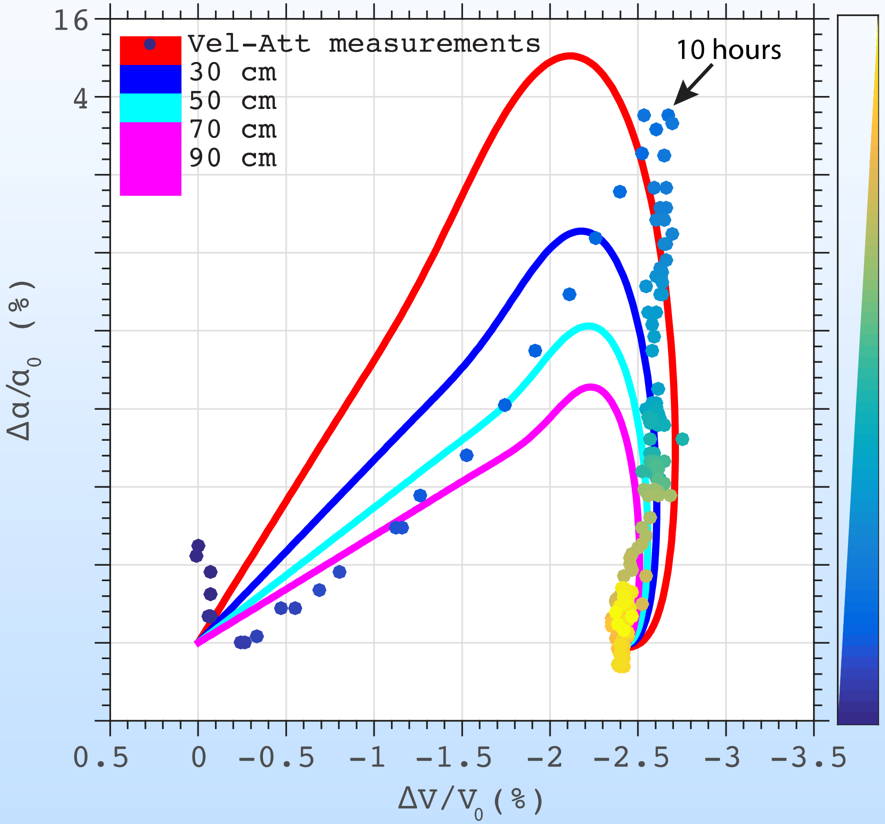
Proposed solutions

- Sparse time-lapse data

Continuous monitoring

- Lack of estimated physical properties of CO_2 plume

Time-lapse full waveform inversion of Vel. & attenuation (1/Q) with data assimilation



Zhu et al., JGR, 2017

Proposed solutions

- Sparse time-lapse data

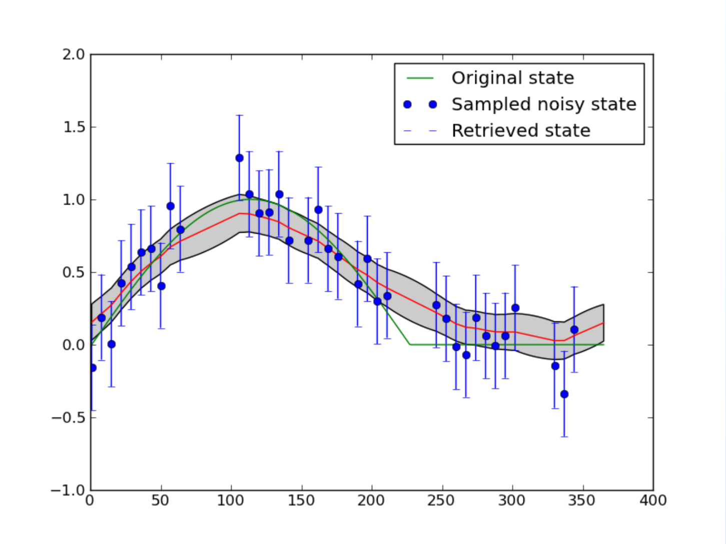
Continuous monitoring

- Lack of estimated physical properties of CO_2 plume

Time-lapse full waveform inversion of Vel. & Q with data assimilation

- Lack of a quantitative estimation of plume uncertainty, lack of integration of seismic-flow

Bayesian inversion framework, data assimilation



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)

Technical status

- develop methodologies for fast seismic full waveform inversion of CASSM datasets for simultaneously estimating velocity and attenuation, and with data assimilation; (Tasks 2 & 3)
  - subtasks 2.1, 2.2, 2.3
  - task 3.1
- develop joint Bayesian petrophysical inversion of seismic models and pressure data for providing and updating CO_2 saturation models; (Task 4)
  - subtasks 4.1, 4.2
- demonstrate the methods using multiple datasets including (surface and borehole) synthetic, laboratory, and field CASSM datasets. (Tasks 5 & 6)

Task 2: Joint seismic inversion

- Find a suitable wave equation (2.1)
  - model wave propagation with attenuation
  - Facilitate inverse wave propagation
- Joint full waveform inversion (2.2)
  - Adjoint operators with attenuation
- Validation tests (2.3)
  - Frio synthetic tests and comparison with field data

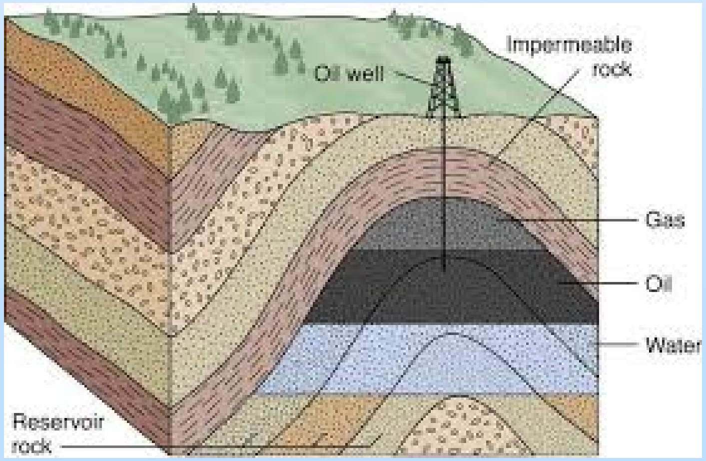
To find a better efficient solver (subtask 2.1)

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

Dispersion **Loss**

Zhu and Harris (2014) *Geophysics*

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



Gas: low Q(x,y,z)

Dry rock: high Q(x,y,z)

To find a better efficient solver (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, in revision*

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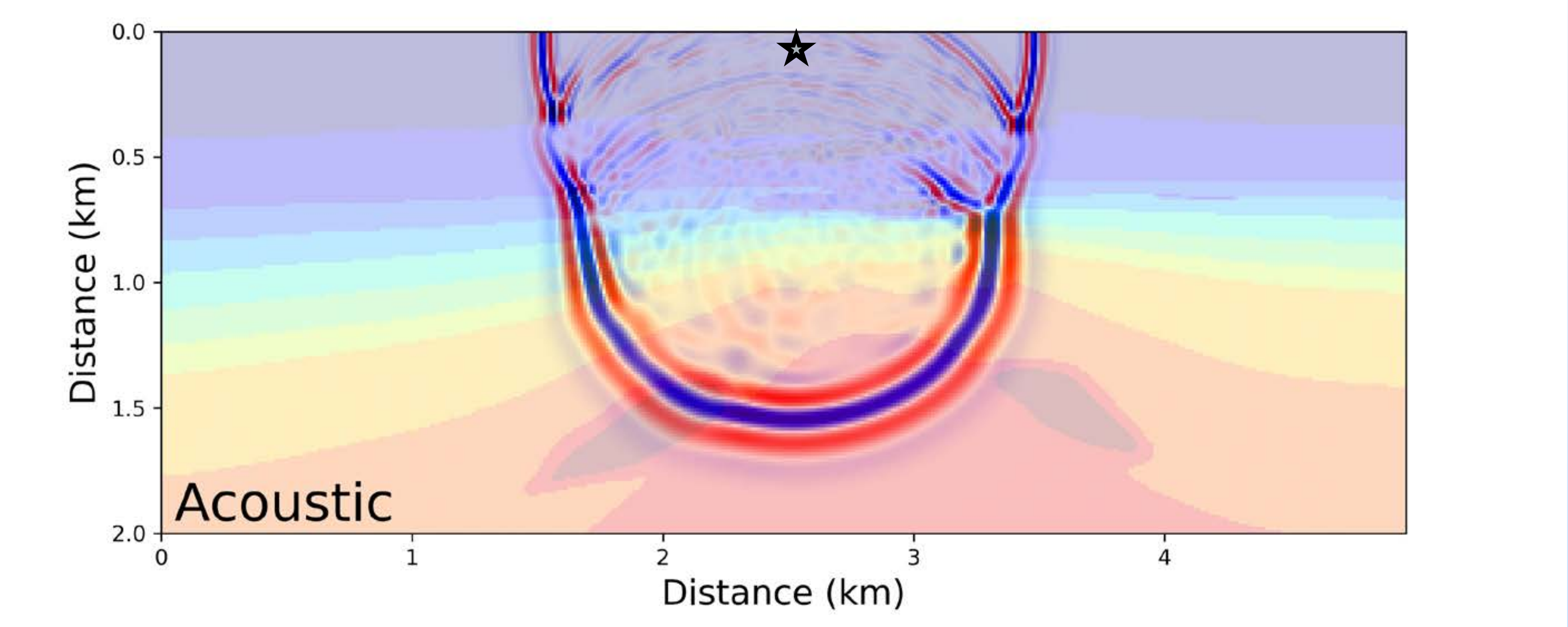
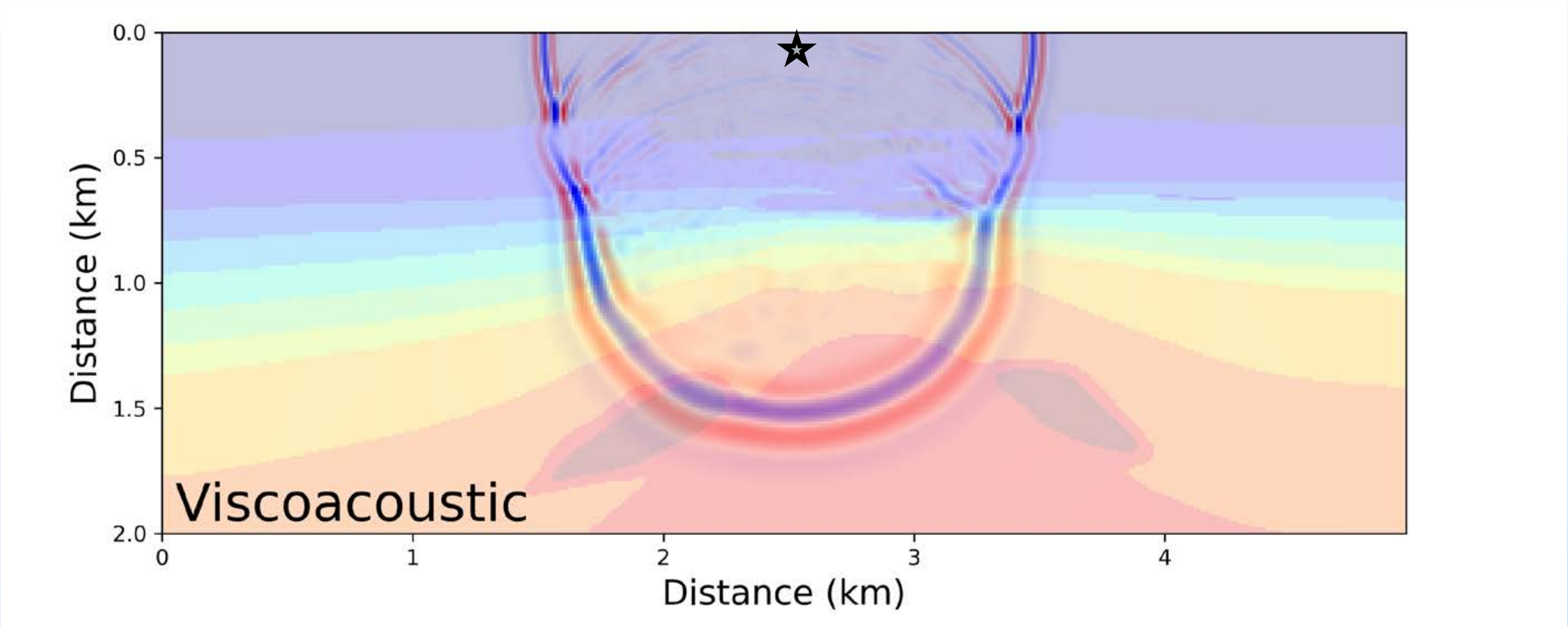
Wavefield snapshot



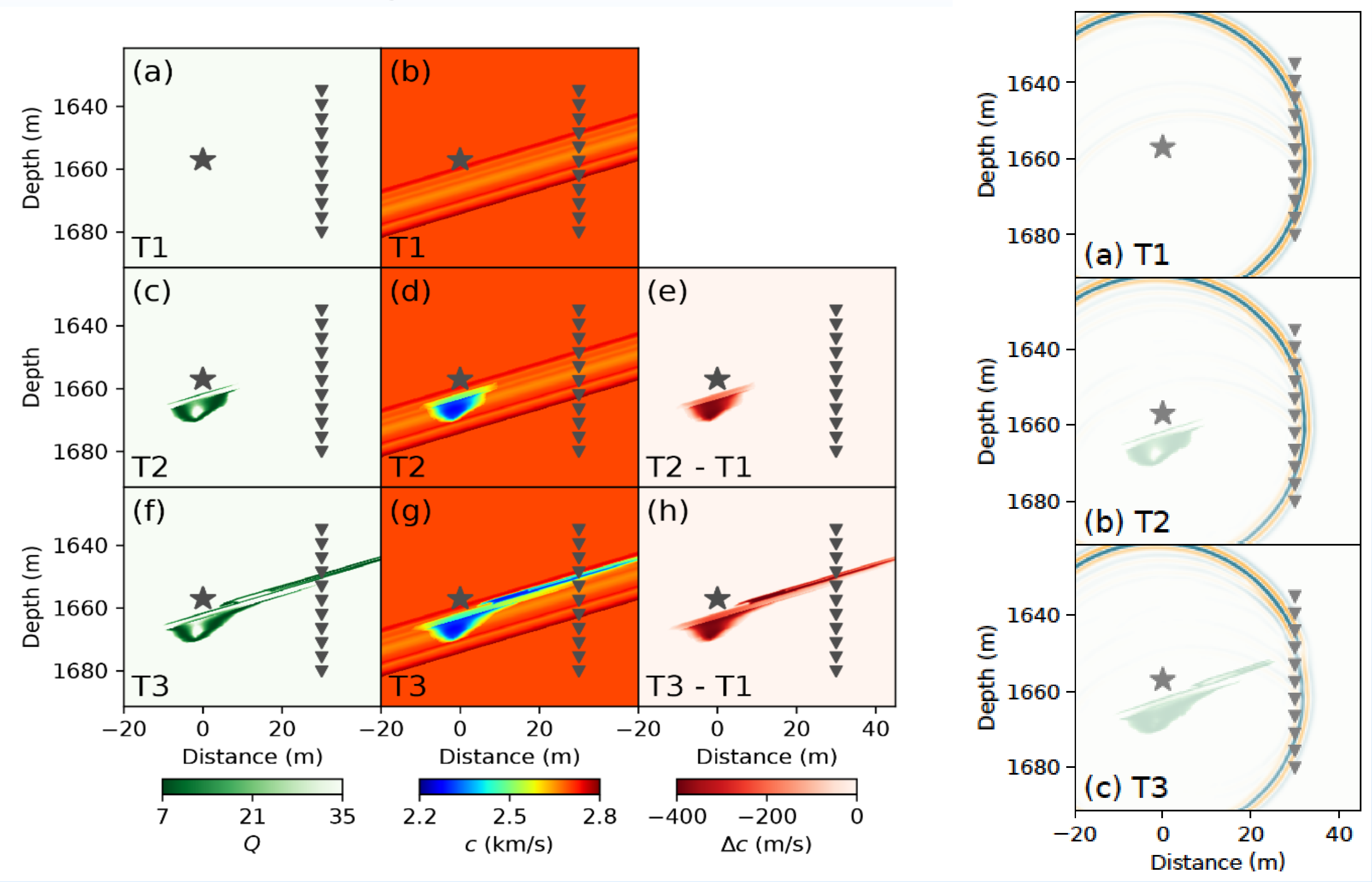
Xing and Zhu (2019) *JGR-Solid Earth, in revision*

Wavefield snapshot



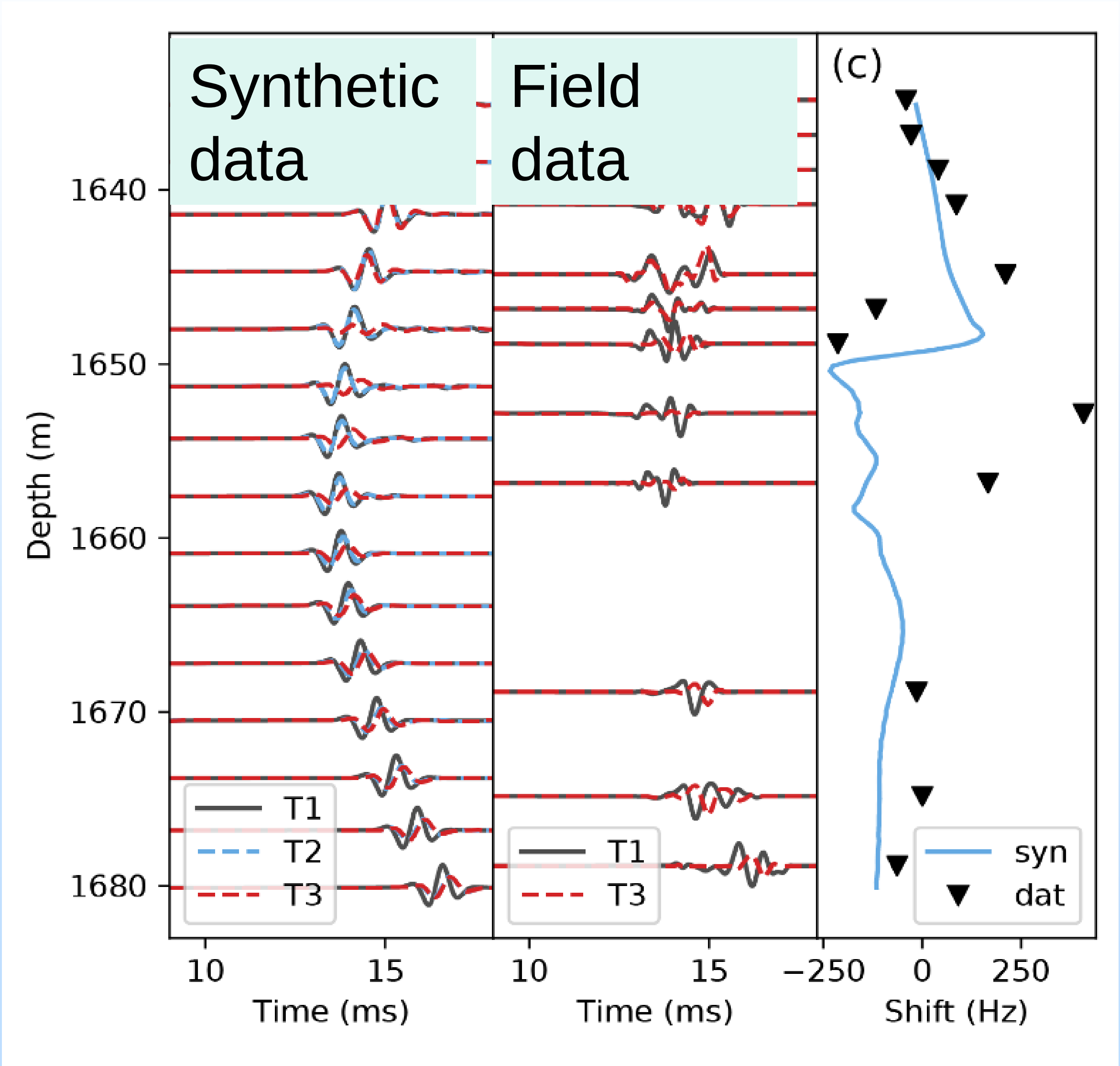
Xing and Zhu (2019) *JGR-Solid Earth, in revision*

Subtask 2.3: Frio CO2 site – modeling and field data calibration



Xing and Zhu (2019) *JGR-Solid Earth, in revision*

Subtask 2.3: Validation with Frio II field data



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

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

Amplitude loss

Adjoint modeling

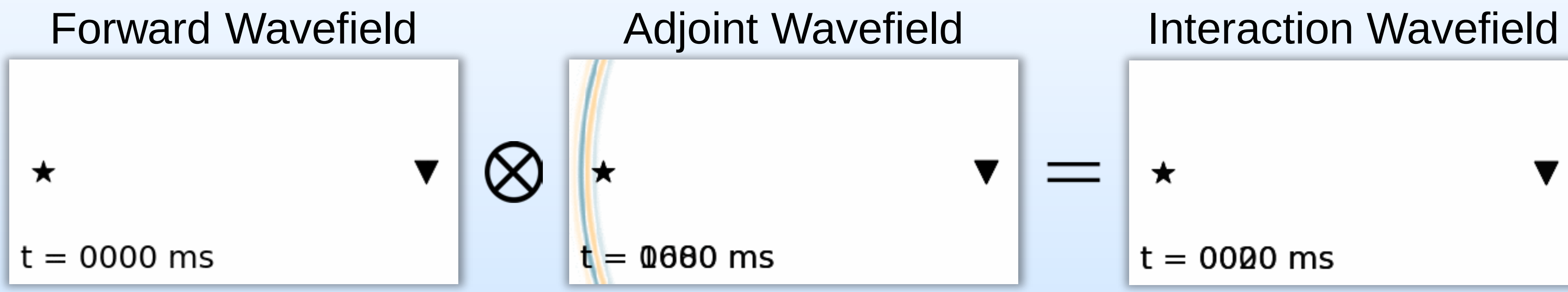
$$\mathbf{L}^*\lambda = \frac{\partial J}{\partial u},$$

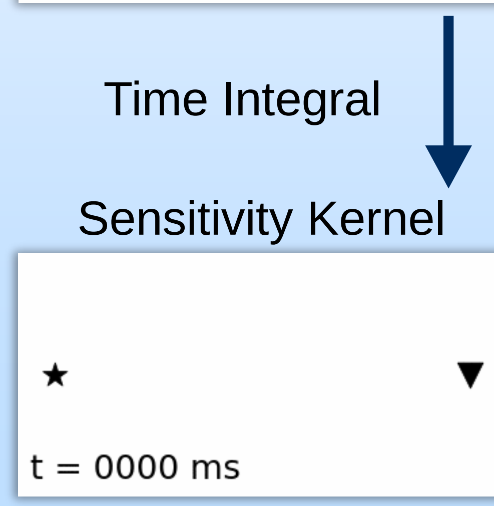
$$\mathbf{L}^* = \mathbf{L}_0 + \mathbf{L}_1 - \mathbf{L}_2$$

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

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: numerical example

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

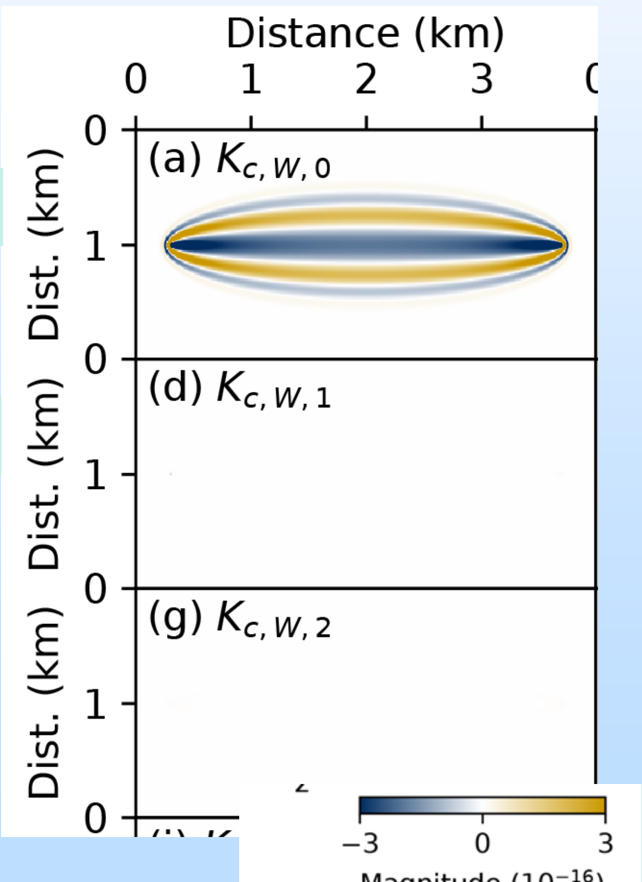
$$\mathbf{L_2} = (\pi\gamma\frac{1}{c}(-\nabla^2)^{\frac{1}{2}} - \pi\gamma^2\frac{1}{\omega_0}\nabla^2)\frac{\partial}{\partial t}$$ Amplitude loss

Velocity Fréchet kernels

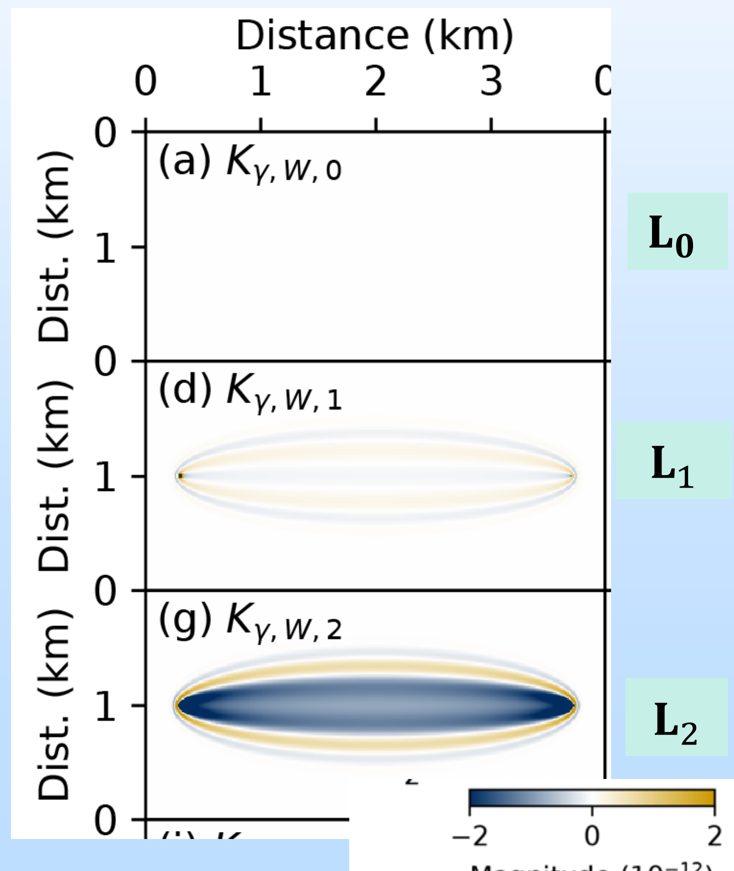
$\mathbf{L_0}$

$\mathbf{L_1}$

$\mathbf{L_2}$



Attenuation Fréchet kernels



$\mathbf{L_0}$

$\mathbf{L_1}$

$\mathbf{L_2}$

Task 3

- *3.1: Time-lapse joint FWI with data assimilation*
  - Seismic velocity
- *3.2: Validation of time-lapse FWI with simulated Frio II and Cranfield monitoring data*

FWI-HiEKF

- Predict:

$$\hat{\boldsymbol{v}}_{k+1}^{-} = \hat{\boldsymbol{v}}_{k} + \delta \boldsymbol{v}_{k} \quad (1)$$

$$\boldsymbol{C}_{\boldsymbol{k+1}}^{-} = \boldsymbol{C}_{\boldsymbol{k}} + \boldsymbol{A}_{k} \quad (2)$$

- Update:

$$\boldsymbol{K}_{k+1} = \boldsymbol{C}_{\boldsymbol{k+1}}^{-}\left(\boldsymbol{H}_{k+1}\boldsymbol{C}_{k+1}^{-}{}^{\boldsymbol{T}} + \boldsymbol{R}_{k+1}\right)^{-} \quad (3)$$

$$\hat{\boldsymbol{v}}_{k+1} = \hat{\boldsymbol{v}}_{k+1}^{-} + \boldsymbol{K}_{k+1}(\boldsymbol{d}_{k} - G(\hat{\boldsymbol{v}}_{k+1}^{-})S(\omega)\delta(\boldsymbol{x} - \boldsymbol{x}_{r})) \quad (4)$$

$$\boldsymbol{C}_{k+1} = (I - \boldsymbol{K}_{k+1}\boldsymbol{H}_{k+1})\boldsymbol{C}_{\boldsymbol{k+1}}^{-} \quad (5)$$

The diagonal of covariance matrix P (variance) in Eq.5 can be calculated using

$$\delta_{k+1}^{2} = \delta_{k}^{2} - \sum_{j=1}^{n}(K_{k+1})_{ij}\,(C_{k+1}^{-})_{ij} \quad (6)$$

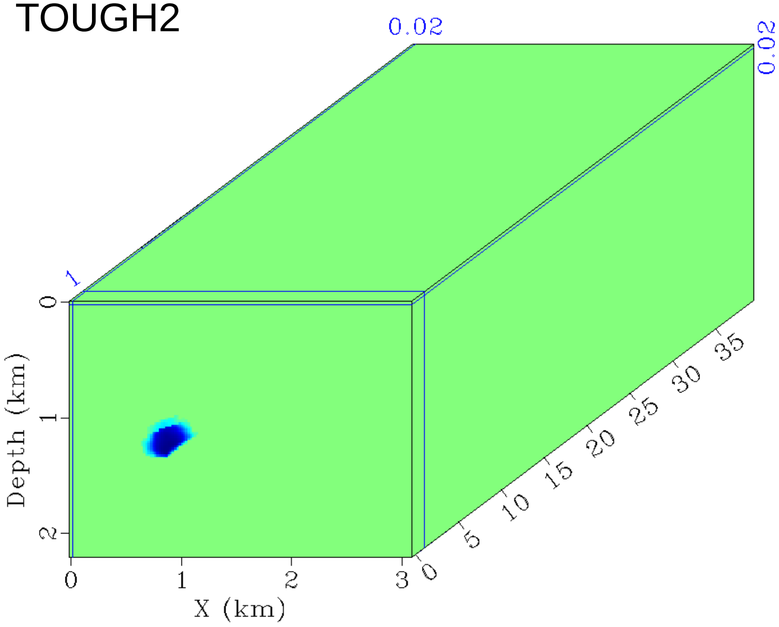
Define cross-covariance C and A:

$$\boldsymbol{C}_{\boldsymbol{k+1}}^{-} = \boldsymbol{P}_{k+1}^{-}\boldsymbol{H}_{k+1}^{\boldsymbol{T}} \text{ and } \boldsymbol{C}_{\boldsymbol{k+1}} = \boldsymbol{P}_{\boldsymbol{k+1}}\boldsymbol{H}_{k+1}^{\boldsymbol{T}} \quad (7)$$

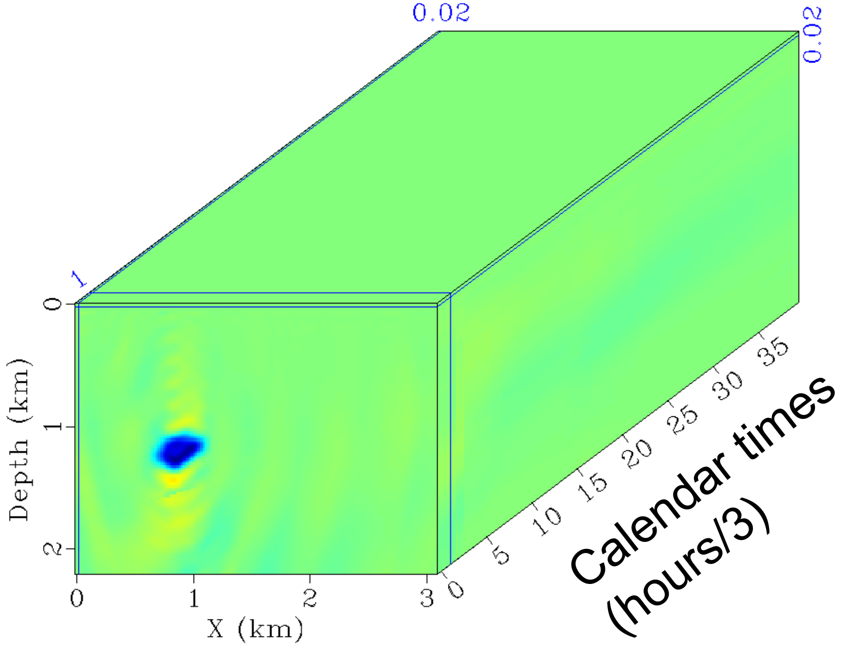
$$\boldsymbol{A}_{\boldsymbol{k+1}} = \boldsymbol{Q}_{\boldsymbol{k+1}}\boldsymbol{H}_{k+1}^{\boldsymbol{T}} \quad (8)$$

Frio validation 2D seismic tests

Reference timelapse Frio models from TOUGH2

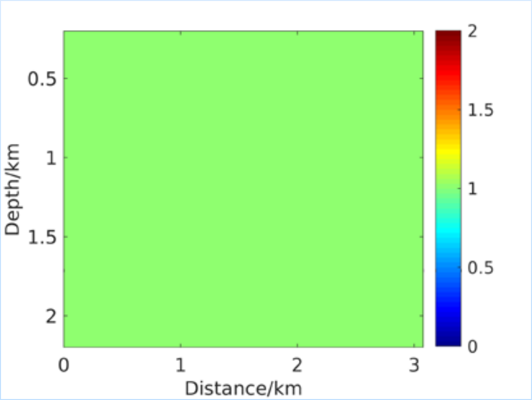


HiEFK FWI timelapse Frio models

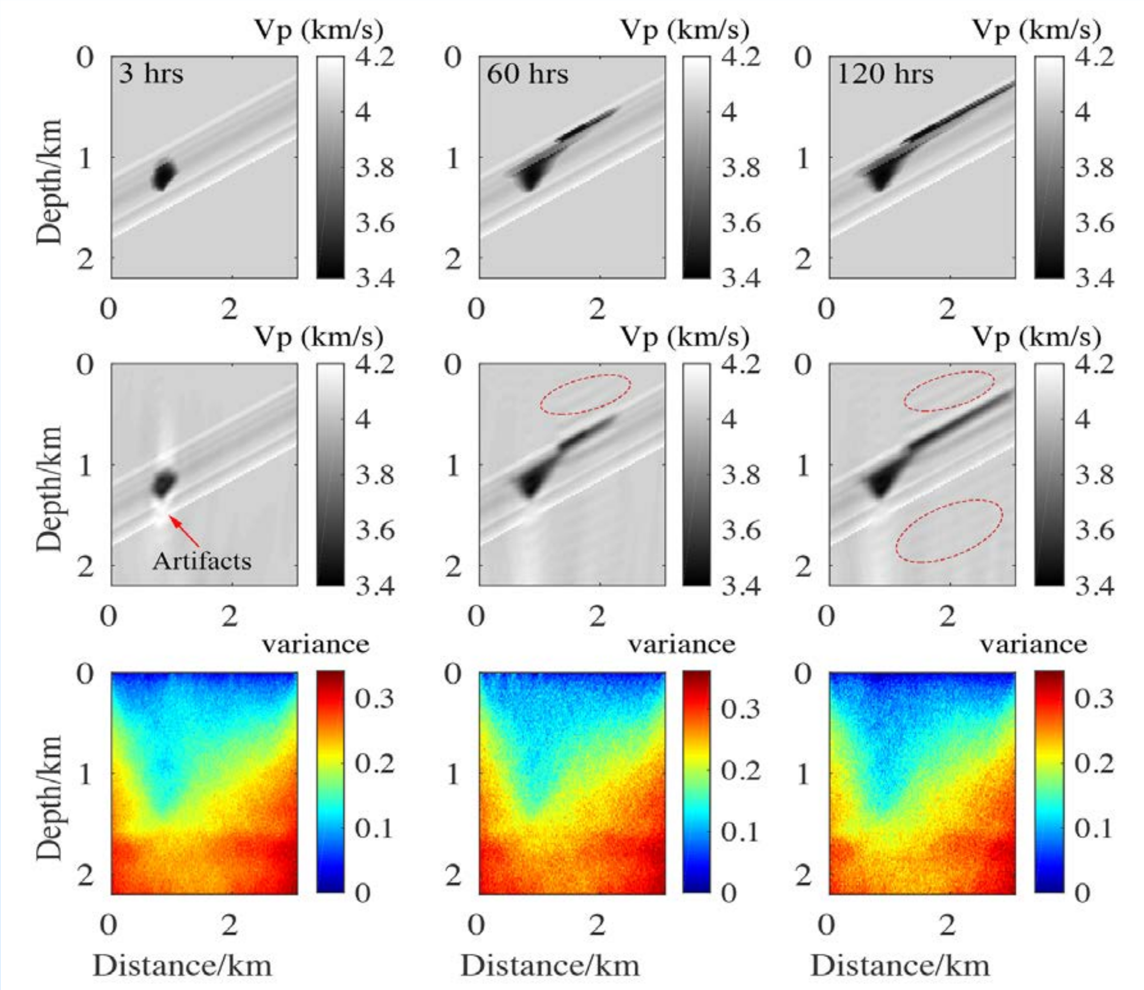


Huang and Zhu (2019) *presentation in coming SEG 2019*

Frio validation 2D seismic tests – uncertainty

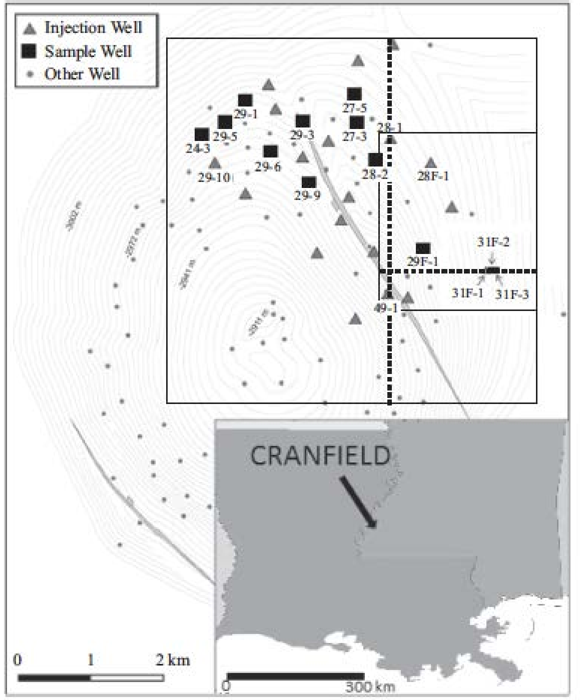


Priori deviation



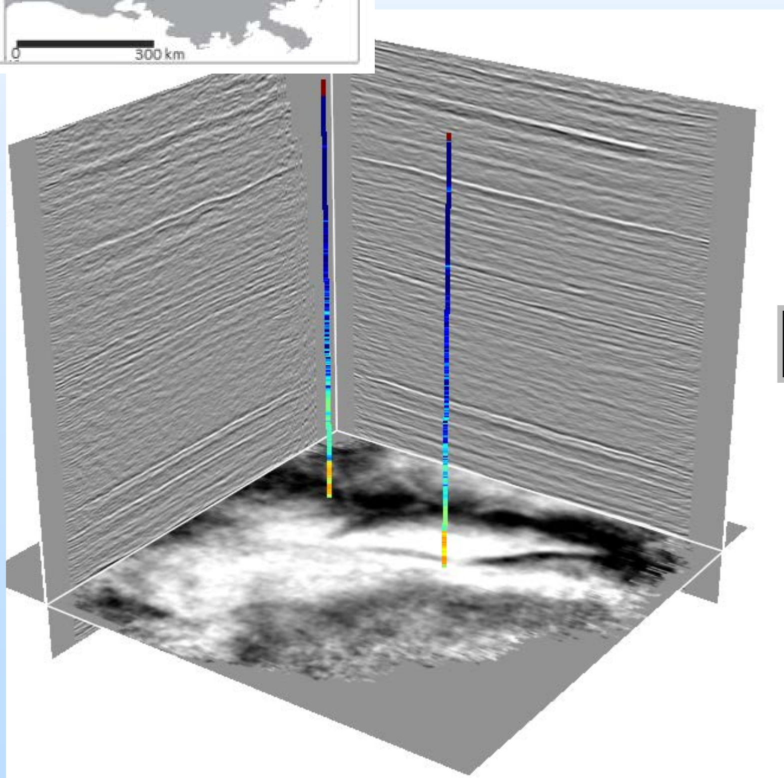
Posterior deviation

Huang and Zhu (2019) *presentation in coming SEG 2019*

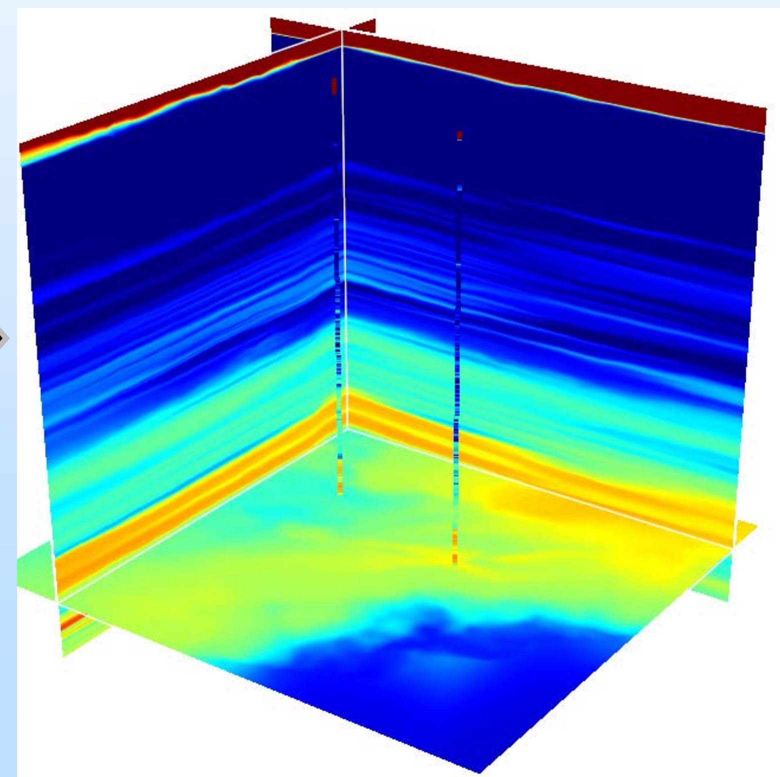


3D Cranfield validation tests

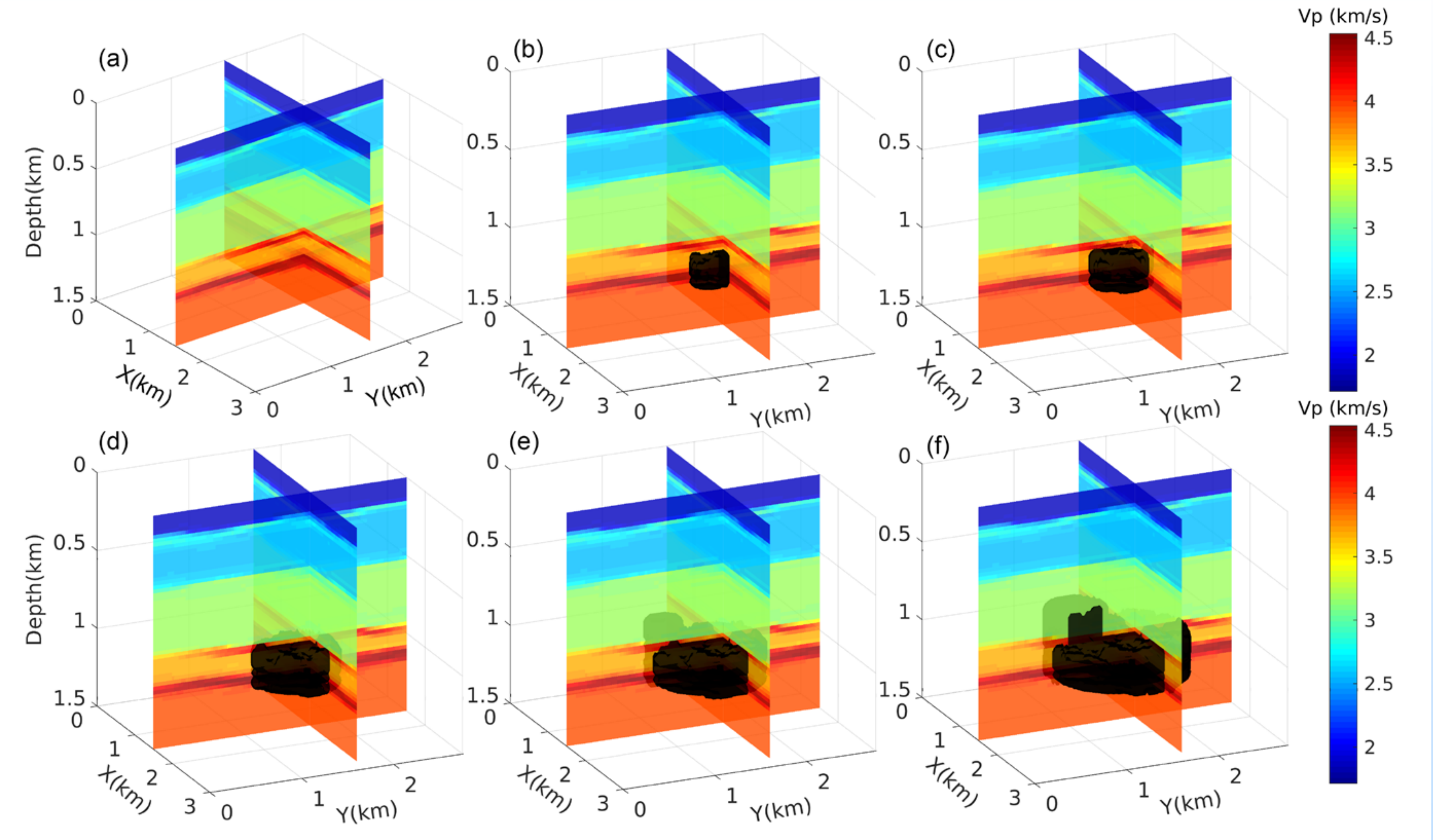
Seismic imaging section + two wells



3D seismic velocity & density profiles

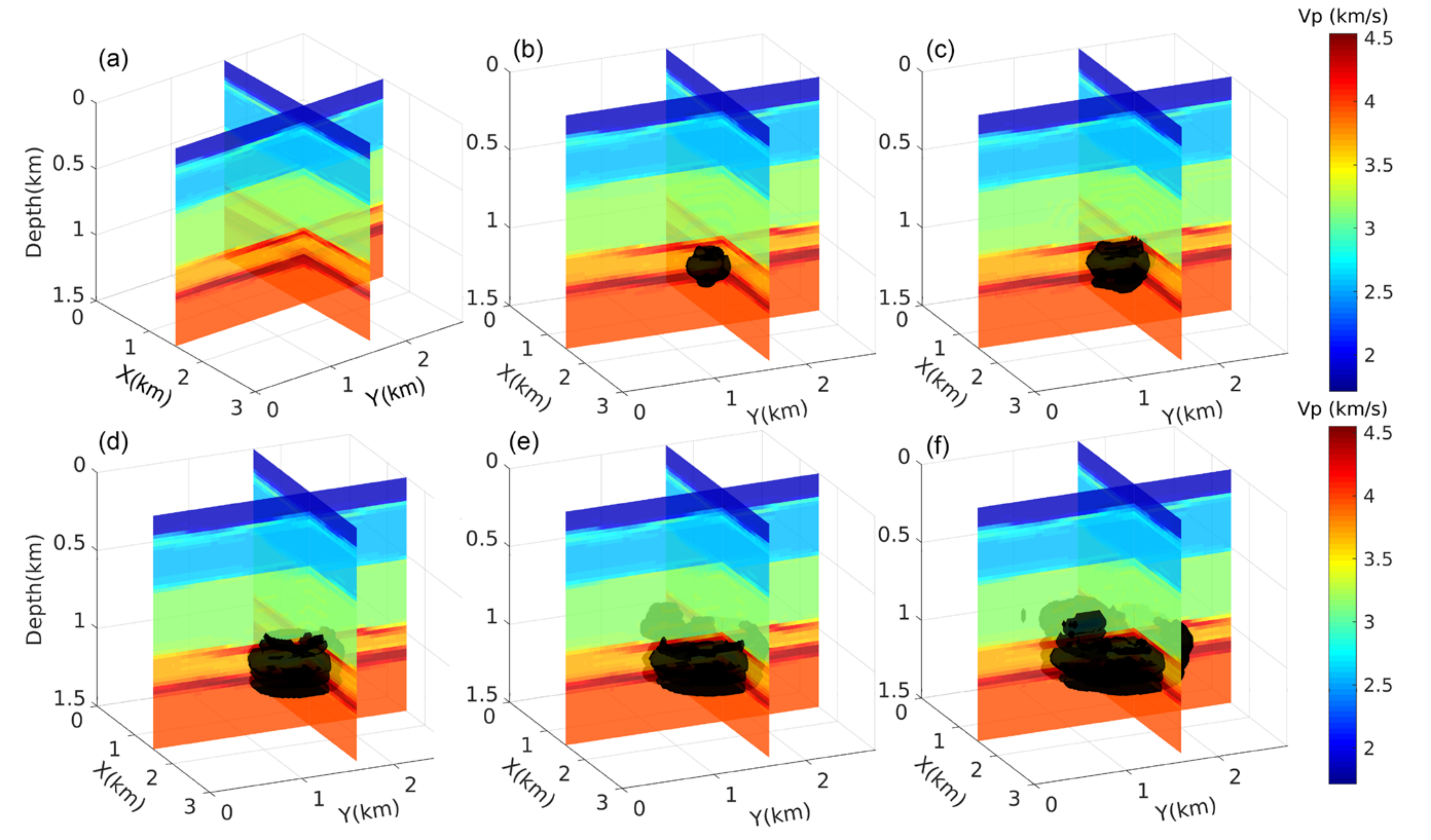


3D Cranfield validation tests



Color scale: seismic velocity
Black: CO2 plume

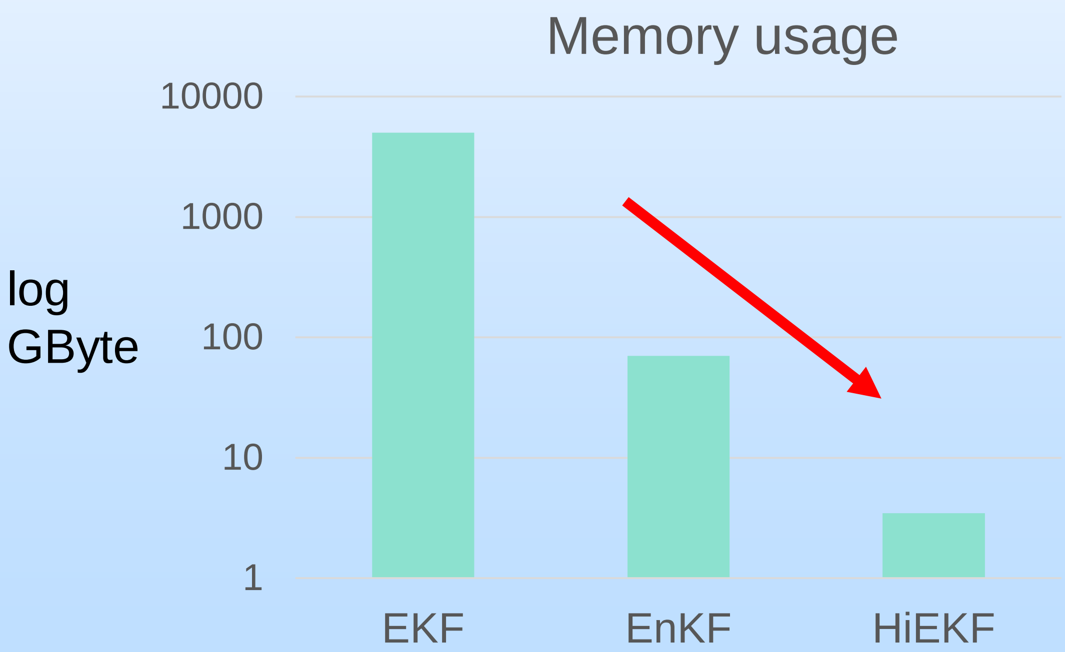
3D Cranfield validation tests



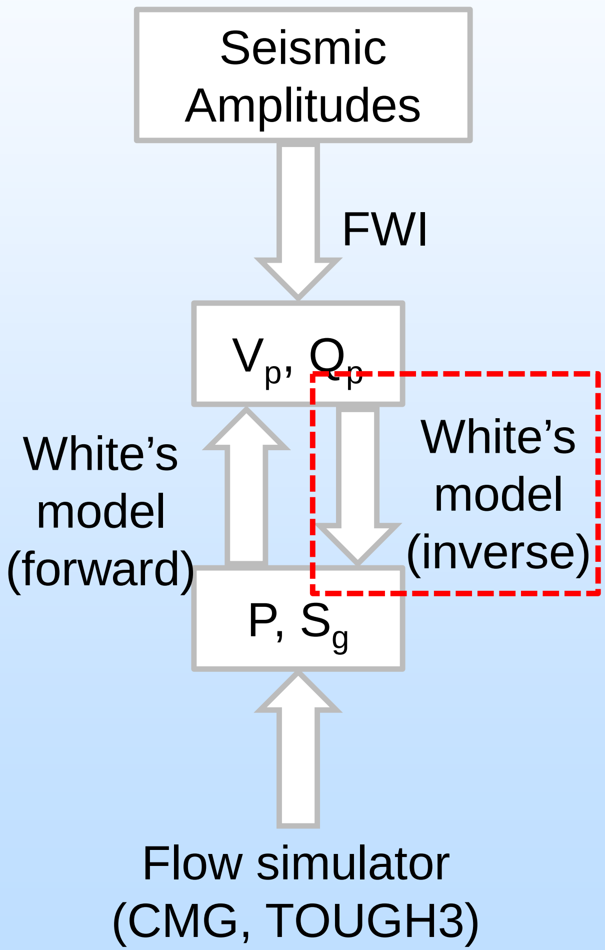
Color scale: seismic velocity
Black: CO2 plume

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.



Task 4: 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):

$$\mathrm{X}^p = \begin{bmatrix} P_1 & \cdots & P_N \\ S_{g,1} & \cdots & S_{g,N} \end{bmatrix} = \mathrm{X} + \mathrm{K}_{gain}\left(\begin{bmatrix} V_p \\ Q_p \end{bmatrix} - f(\mathrm{X})\right)$$

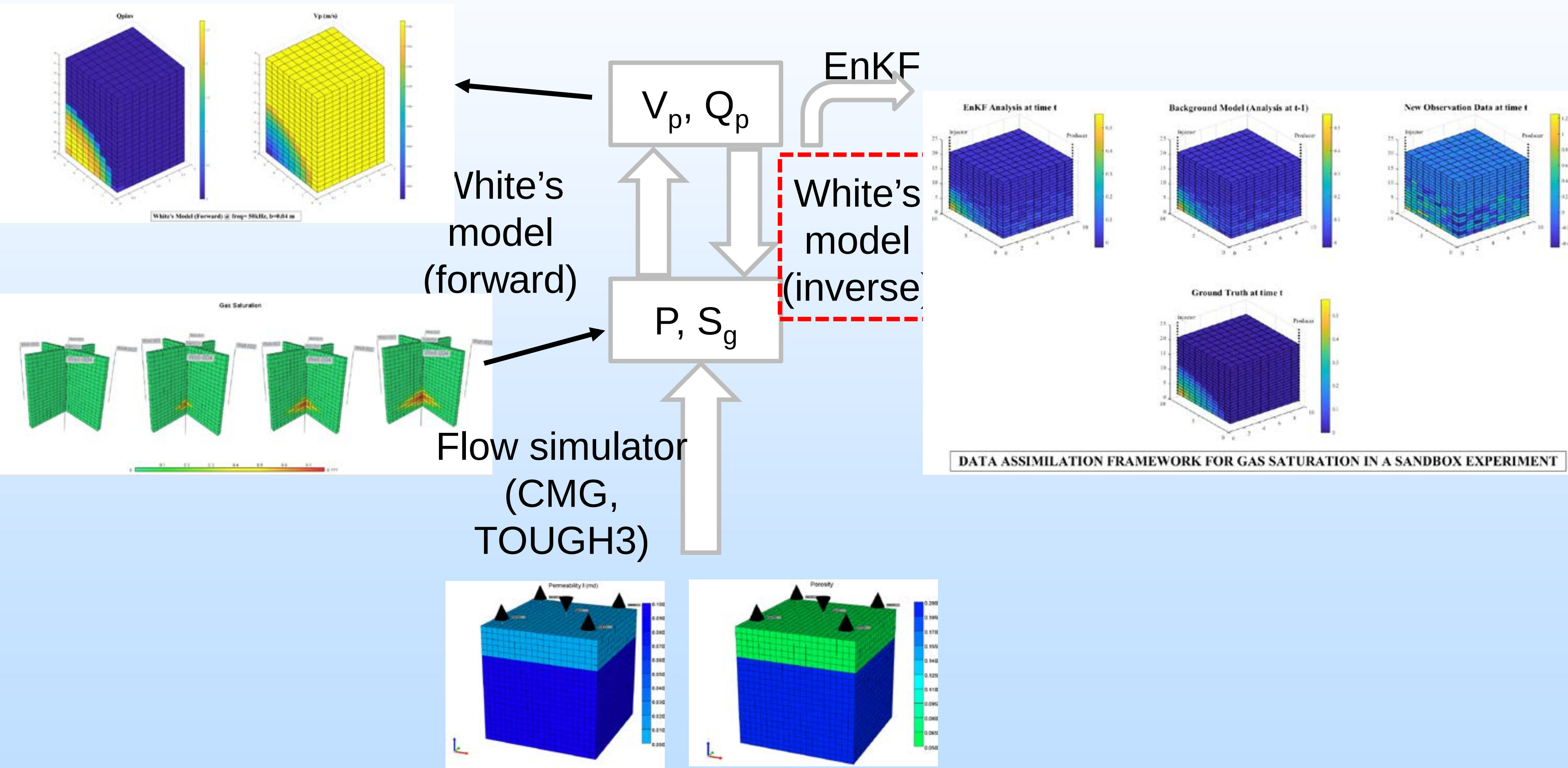
where $f(\cdot)$ is the forward model (White's model). EnKF assumes the state vector is Gaussian, so to construct the prior ensemble (X), we draw from:

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

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

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

Task 4 & 5: Preliminary Results: Synthetic Test on the sandbox experiment in LBL Case



A simple, hypothetical “sandbox” experiment

By Joon and Morgan 2019 Penn State

Accomplishments to Date

Task 2.0

- Development of a simple formulation of time-domain viscoacoustic wave equation (2.1)
- Building the numerical scheme and numerical code of solving the new wave equation (2.1)
- Derivation of adjoint operators for further developing the algorithm of full waveform inversion (2.2)
- Validation tests in Frio (2.3)

Accomplishments to Date

Task 3.0

- Development of a time-lapse ensemble KF full waveform inversion algorithm of seismic velocity (3.1)
- Synthetic tests in Frio 2D models (3.2)
- Synthetic tests in Cranfield models (3.2)

Task 4.0

- Updates the Cranfield subsurface geologic models (4.1)
- Flow simulations of the Sandbox experiments jointly effort by Penn State and LBL. (4.3)
- EFK seismic-flow inversion (4.3)

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Synergy Opportunities

- develop methodologies for fast seismic full waveform inversion of continuous active source seismic monitoring, (CASSM) datasets; ---- DAS data (collab. with DAS projects)

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

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Project Summary

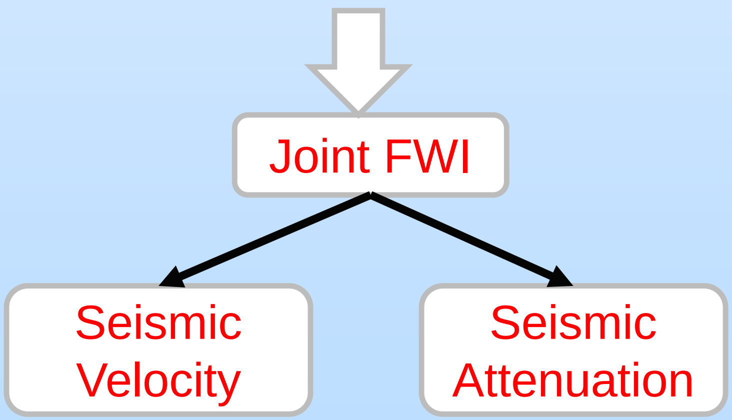
- **Key findings:**
- Build our seismic modeling with attenuation code (Task 2.1)
- Adjoint operators for build up the joint FWI (Task 2.2)
- Validation tests in Frio (Task 2.3)

- Time-lapse FWI with EnFK (Task 3.1)
- Validation tests in Frio and Cranfield models (Task 3.2)

- Updates the Cranfield subsurface geologic models (Task 4.1)
- Flow simulations in the Sandbox lab experiments and tests on the EnFK seismic-flow inversion (Task 4.3)

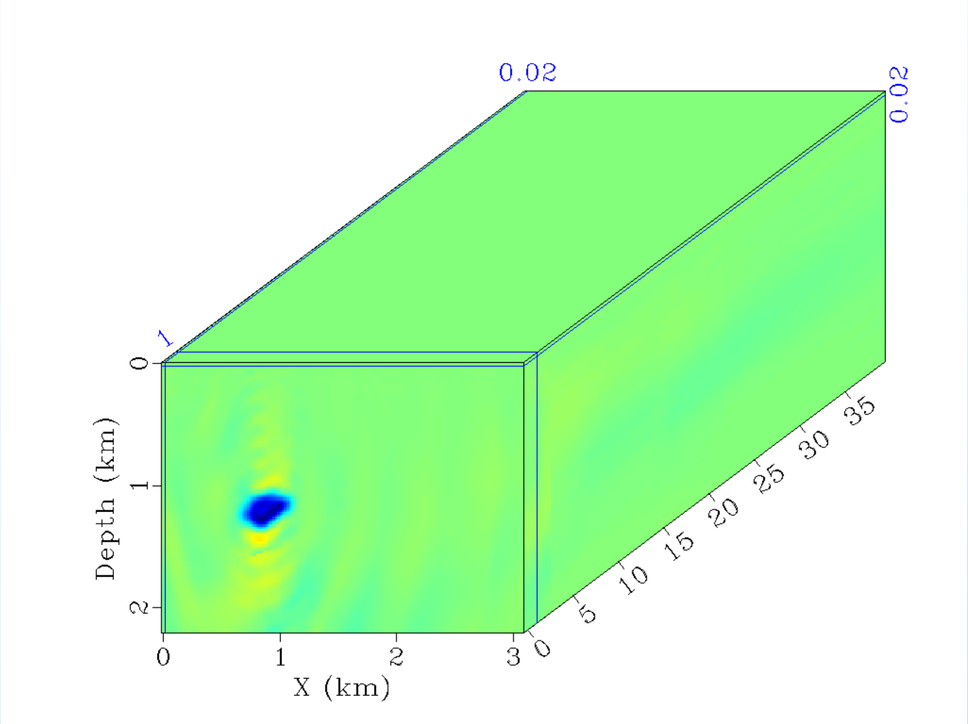
Next Step

- *Subtask 2.2 – Theoretical development of joint full waveform inversion (FWI):*



Next Step

- *Task 3 – Time-lapse of joint full waveform inversion (FWI):*

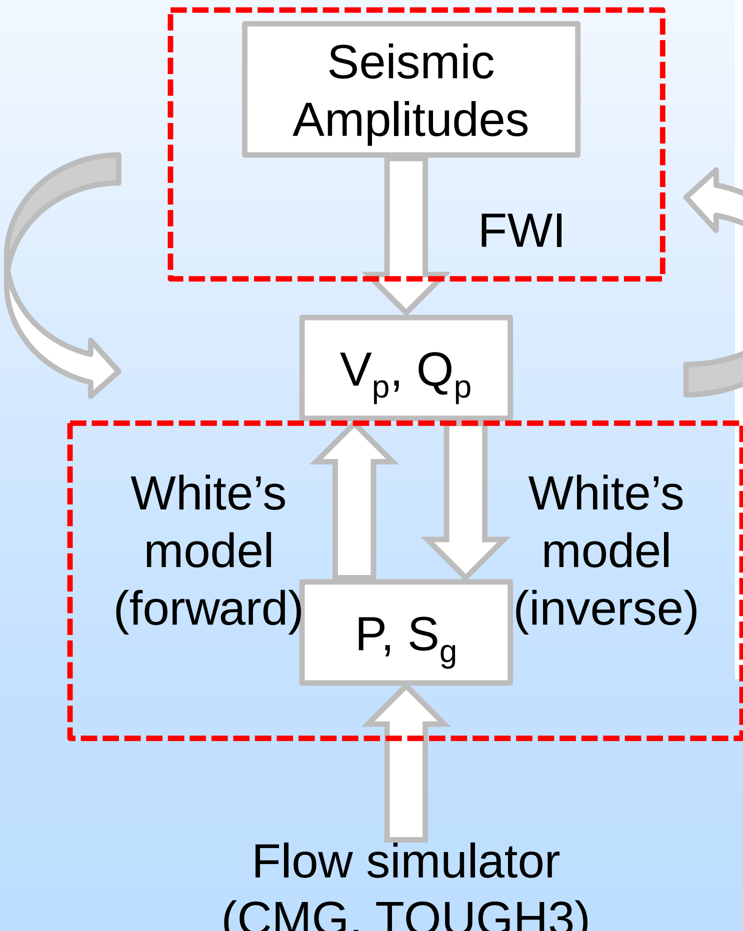


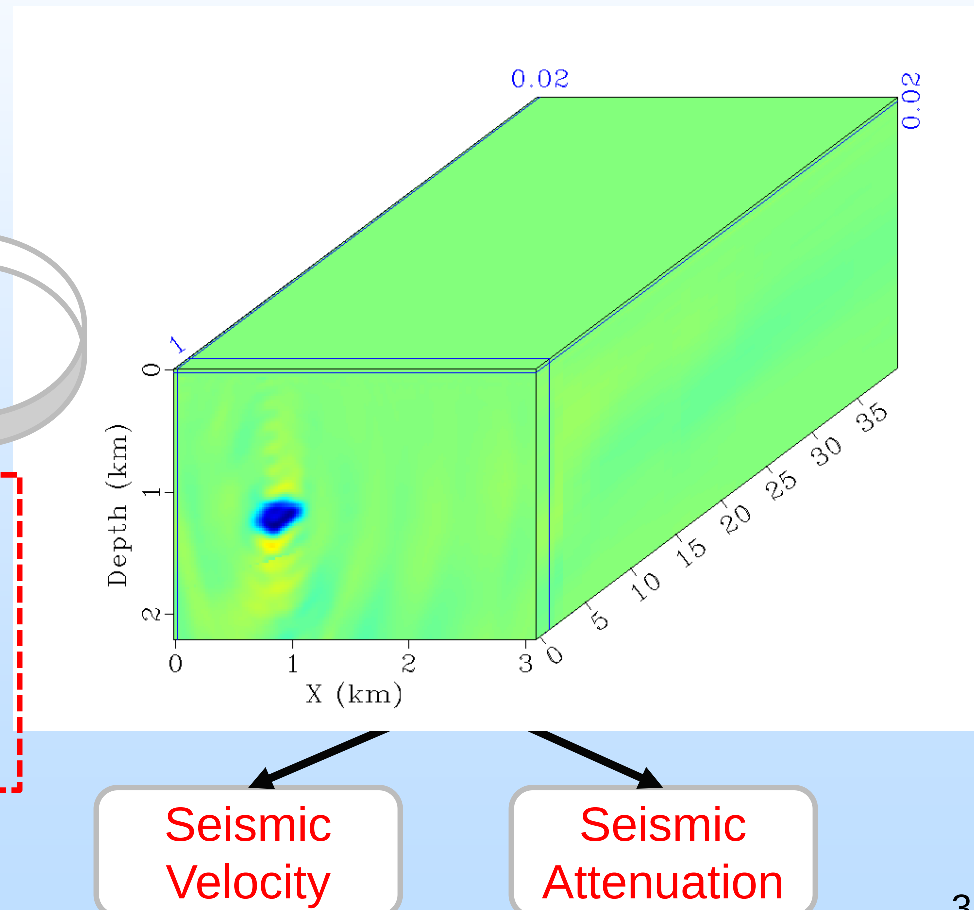
Seismic Velocity

Seismic Attenuation

Next Step

- *Task 4 – Integration of seismic-petrophysics inversion:*





Next Step

- *Task 5 – Lab setup and experiments (J. Ajo-Franklin, Rice U.):*

- Thank you for your attention!

Appendix

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.)**".

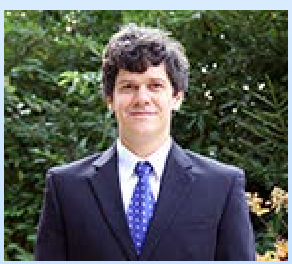
- "Real-time" ability to delineate CO_2 plume boundaries and quantifying CO_2 saturation using seismic CASSM and pressure data should allow DOE's investment in future monitoring systems that eliminate the expensive and personnel-intensive effort of independent inversions.

Organization Chart

Task 4.1 — Srinivasan (co-PI)

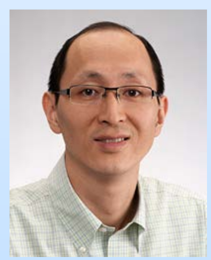
Zhu (PI) — All Tasks; Tasks 2 & 3, &6

- Morgan (co-PI)
- Ajo-Franklin (co-PI)
- Sun (co-PI)
- Daley
- Postdoc & graduate student(s)



Leading task 4

Leading task 5



Task 4.2

Help on Frio and CASSM systems

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**																

Bibliography

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