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

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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

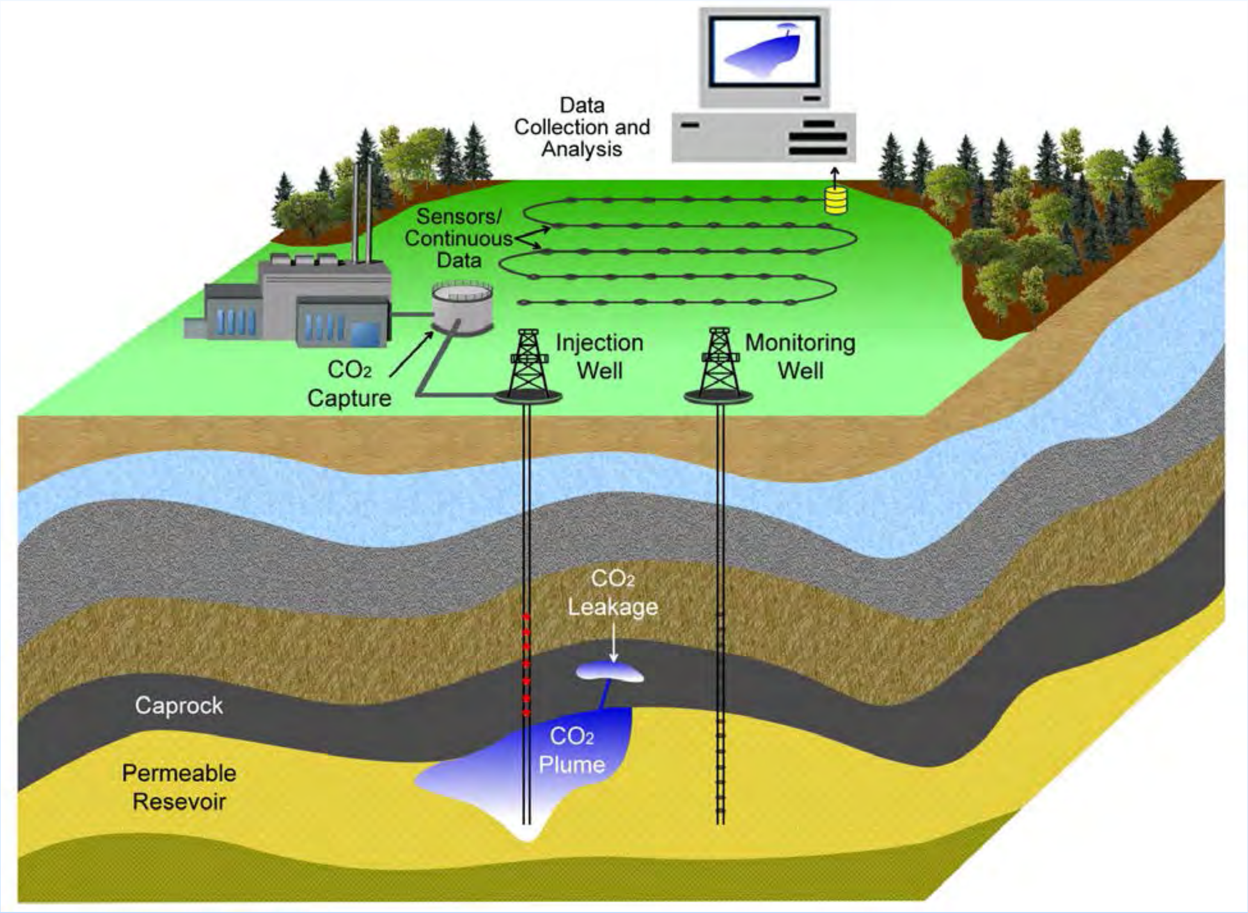
August 13-16, 2018

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%?

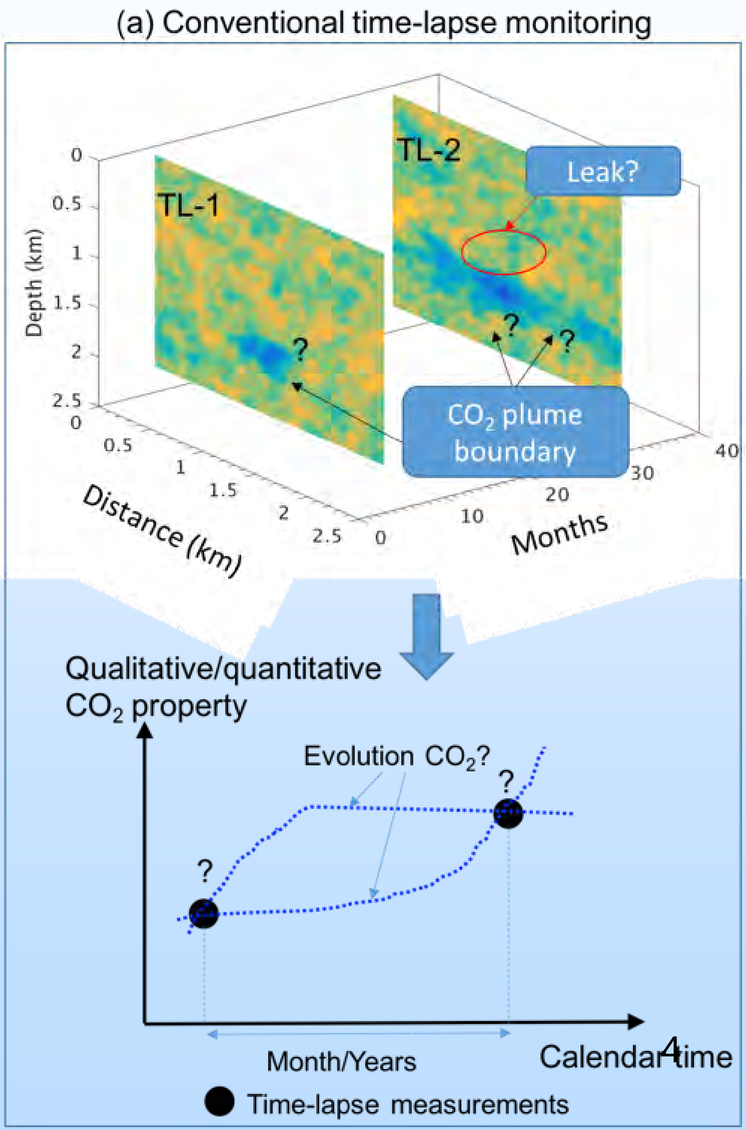


Major Challenges

- 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

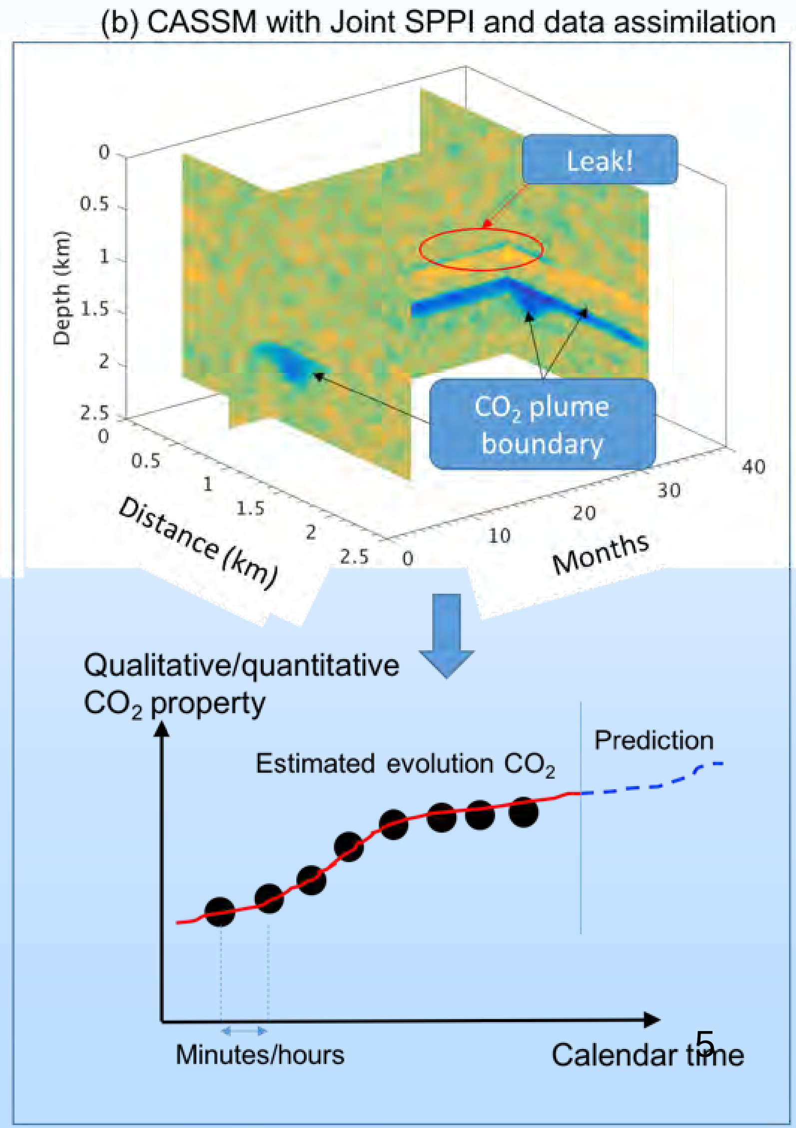


Proposed solutions

- Sparse time-lapse data

(Nearly) Continuously monitoring

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



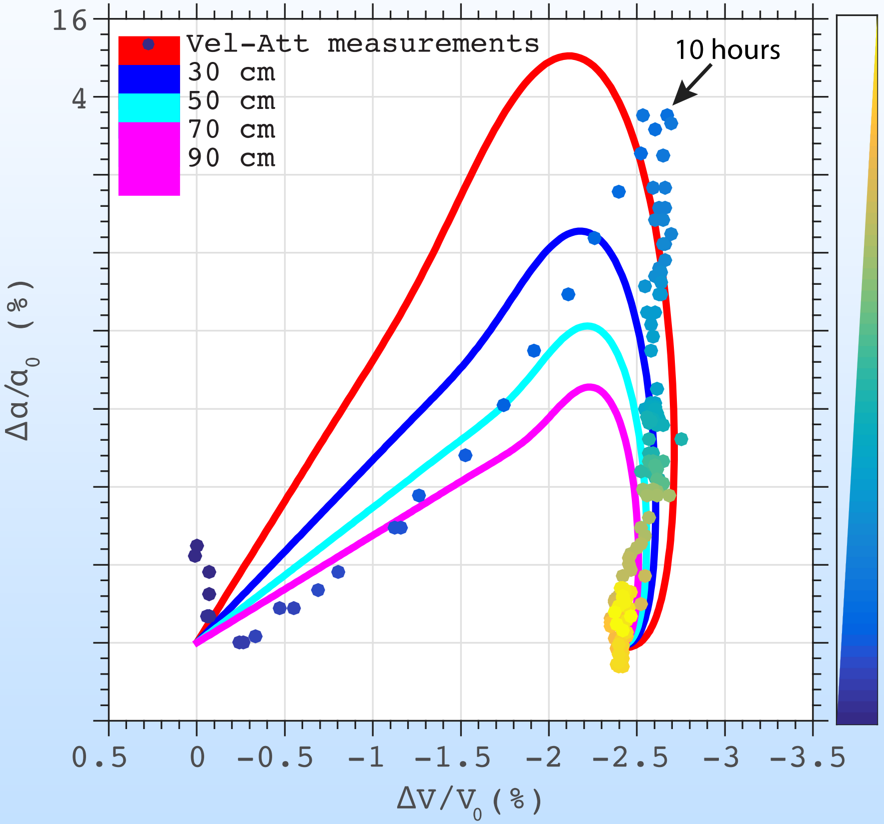
Proposed solutions

- Sparse time-lapse data

Continuous monitoring

- Lack of estimated physical properties of CO_2 plume

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



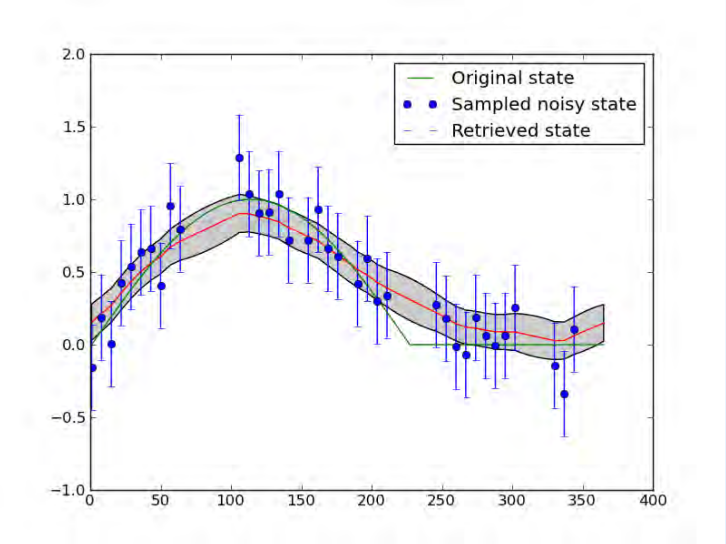
Zhu et al., JGR, 2017

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
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; (Tasks 4)

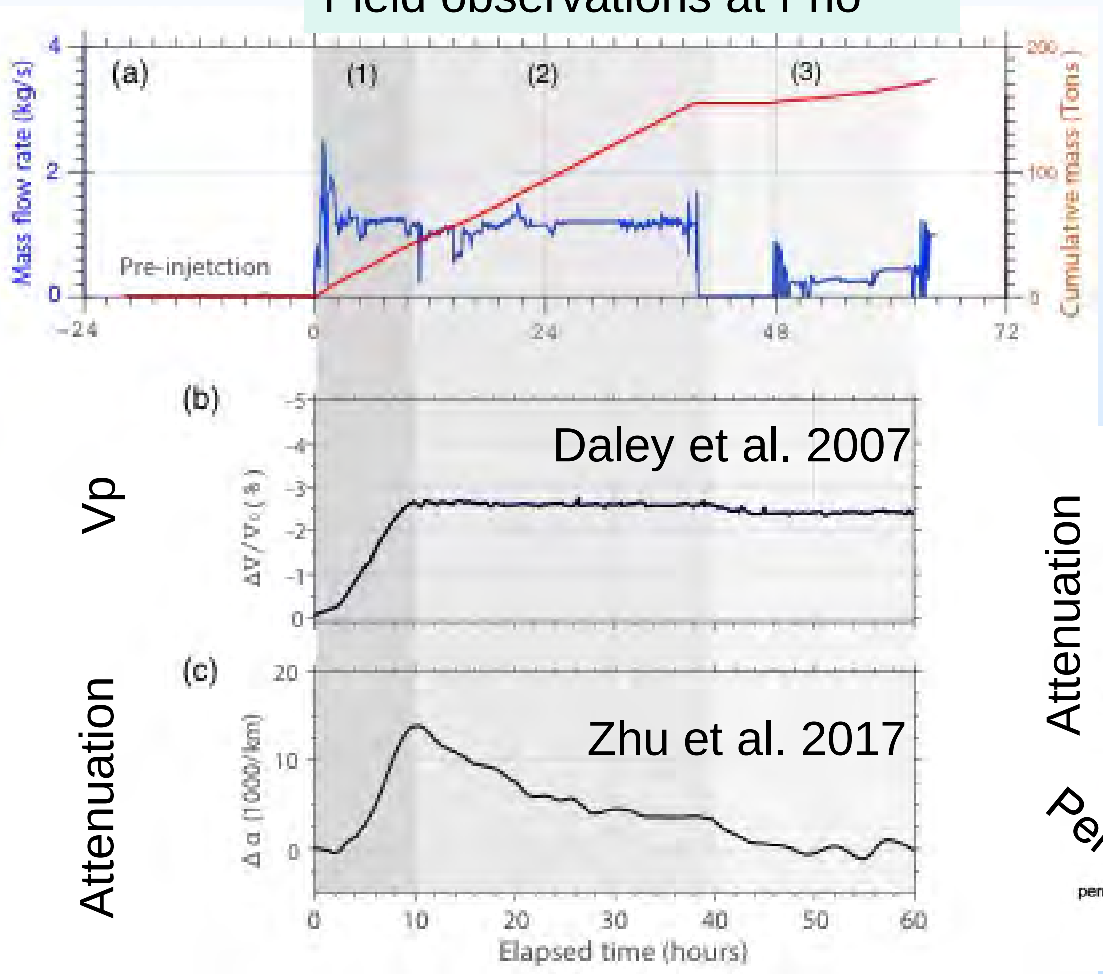
- demonstrate the methods using multiple datasets including (surface and borehole) synthetic, laboratory, and field CASSM datasets. (Tasks 5 & 6)

Technical status

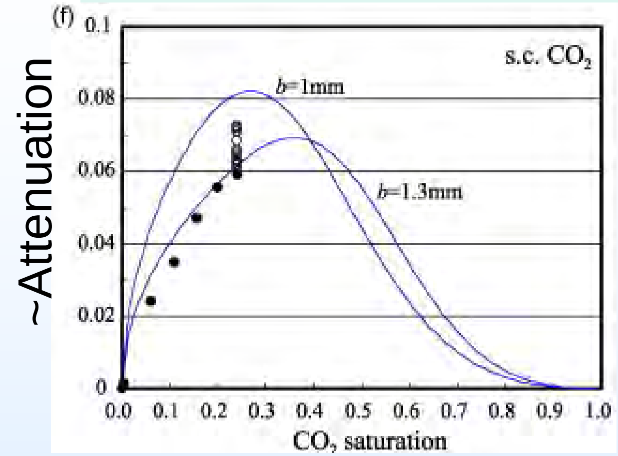
- develop methodologies for fast seismic full waveform inversion of CASSM datasets for simultaneously estimating velocity and attenuation, and with data assimilation; (Tasks 2 & 3)
  - Tasks 2.1
- develop joint Bayesian petrophysical inversion of seismic models and pressure data for providing and updating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

Why attenuation?

Field observations at Frio

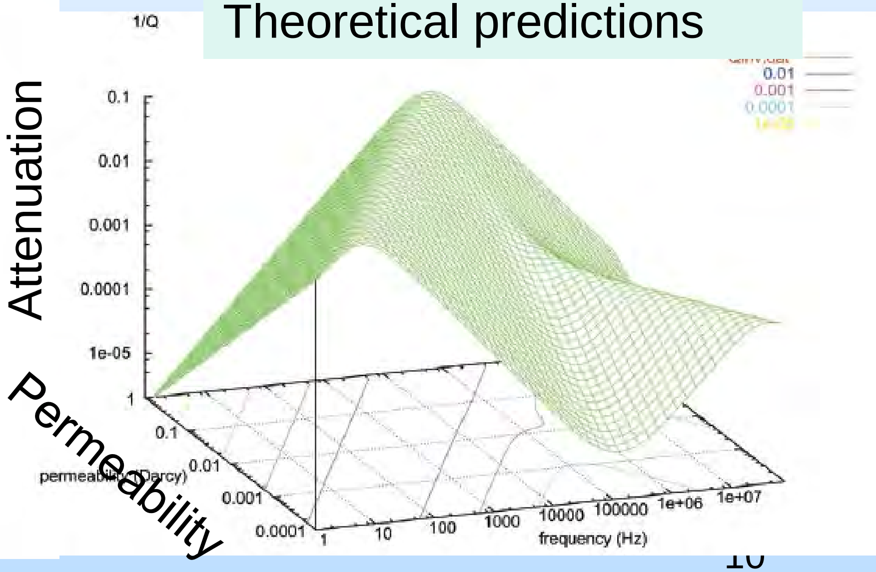


Ultrasonic observations



Lei and Xue 2009

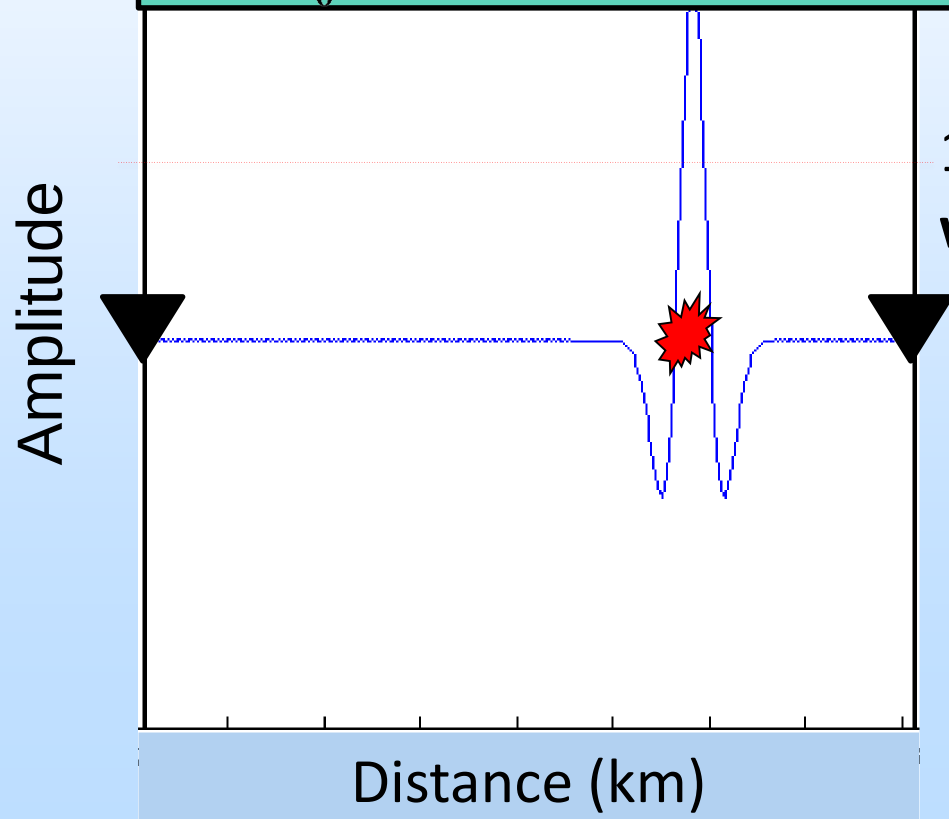
Theoretical predictions



Pride et al. 2003

Basis of current full waveform inversion technique

$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p$$

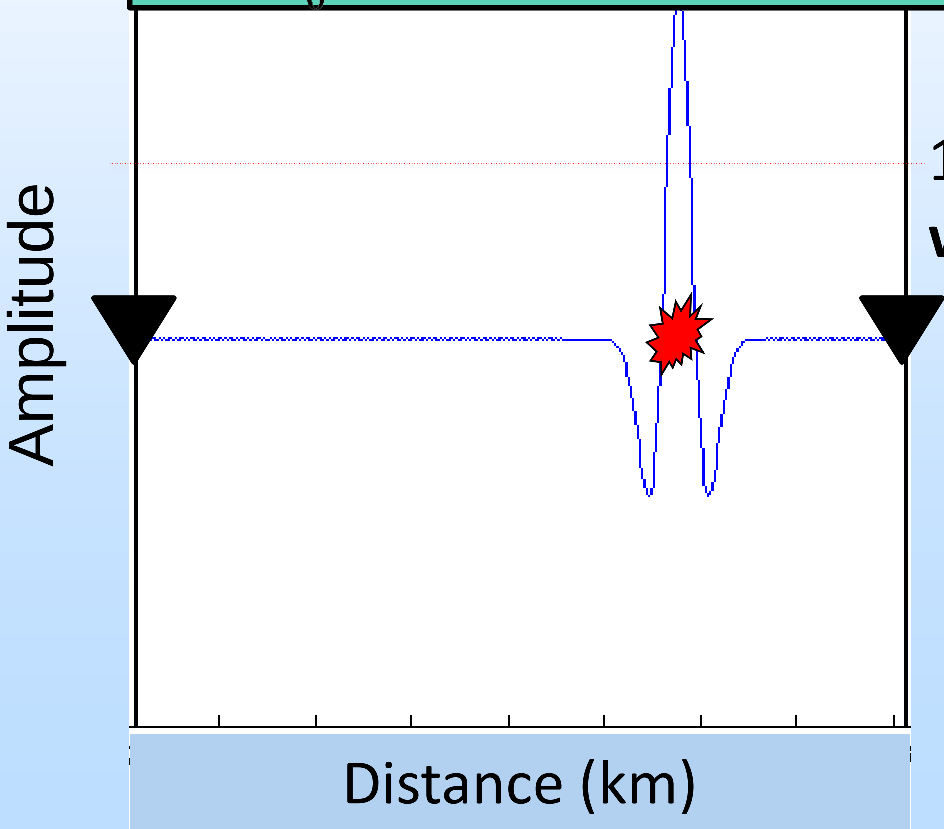


1D wave propagation **without** attenuation

▼ receiver

But, reality……

$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p + attenuation$$



1D wave propagation **with** attenuation

receiver

Task 2

- Find a suitable wave equation
  - model wave propagation with attenuation
  - Facilitate inverse wave propagation

Seismic attenuation modeling by a viscoacoustic wave equation

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

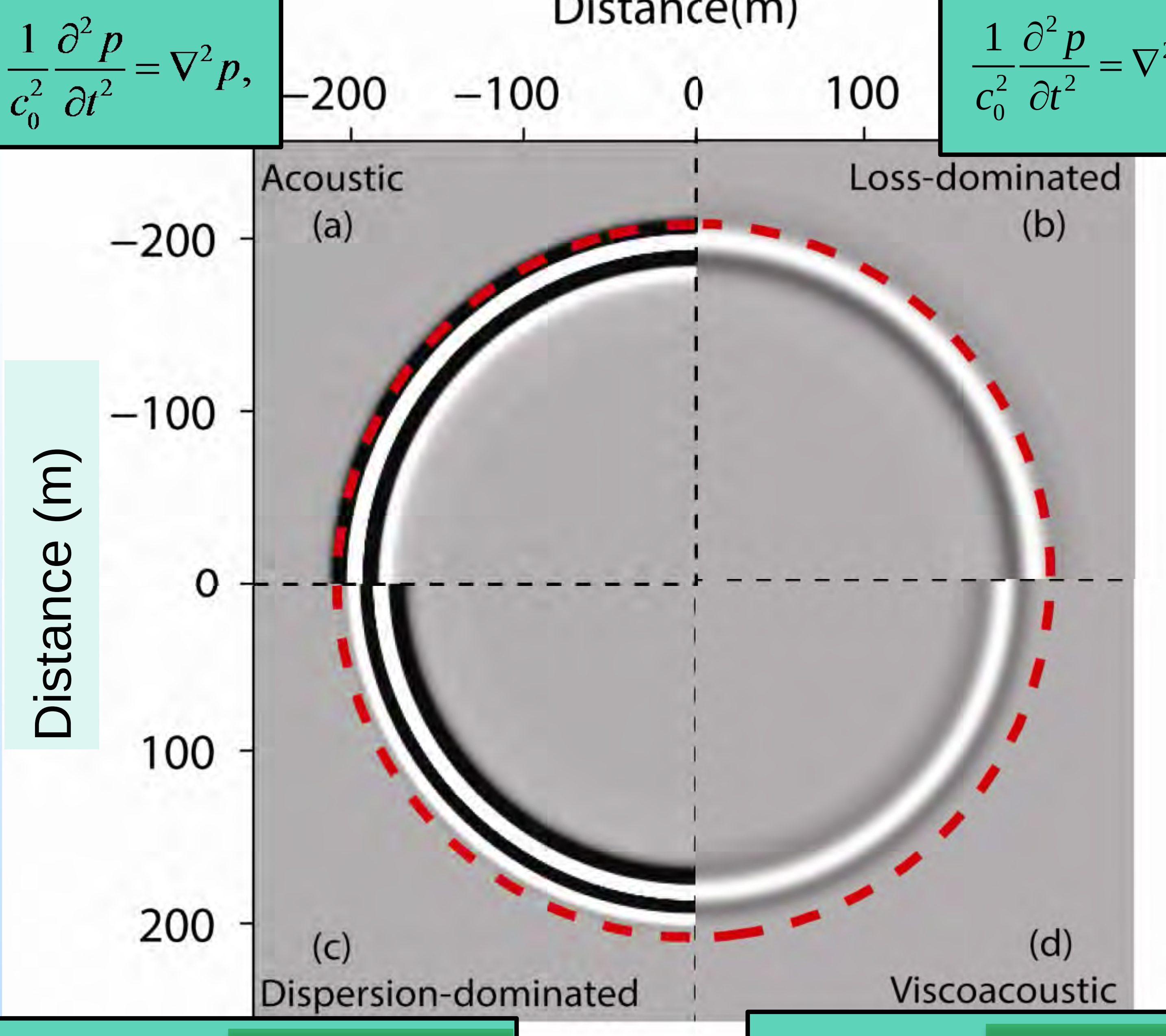
Dispersion **Loss**

Attenuation

Zhu and Harris (2014) *Geophysics*

$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p,$$

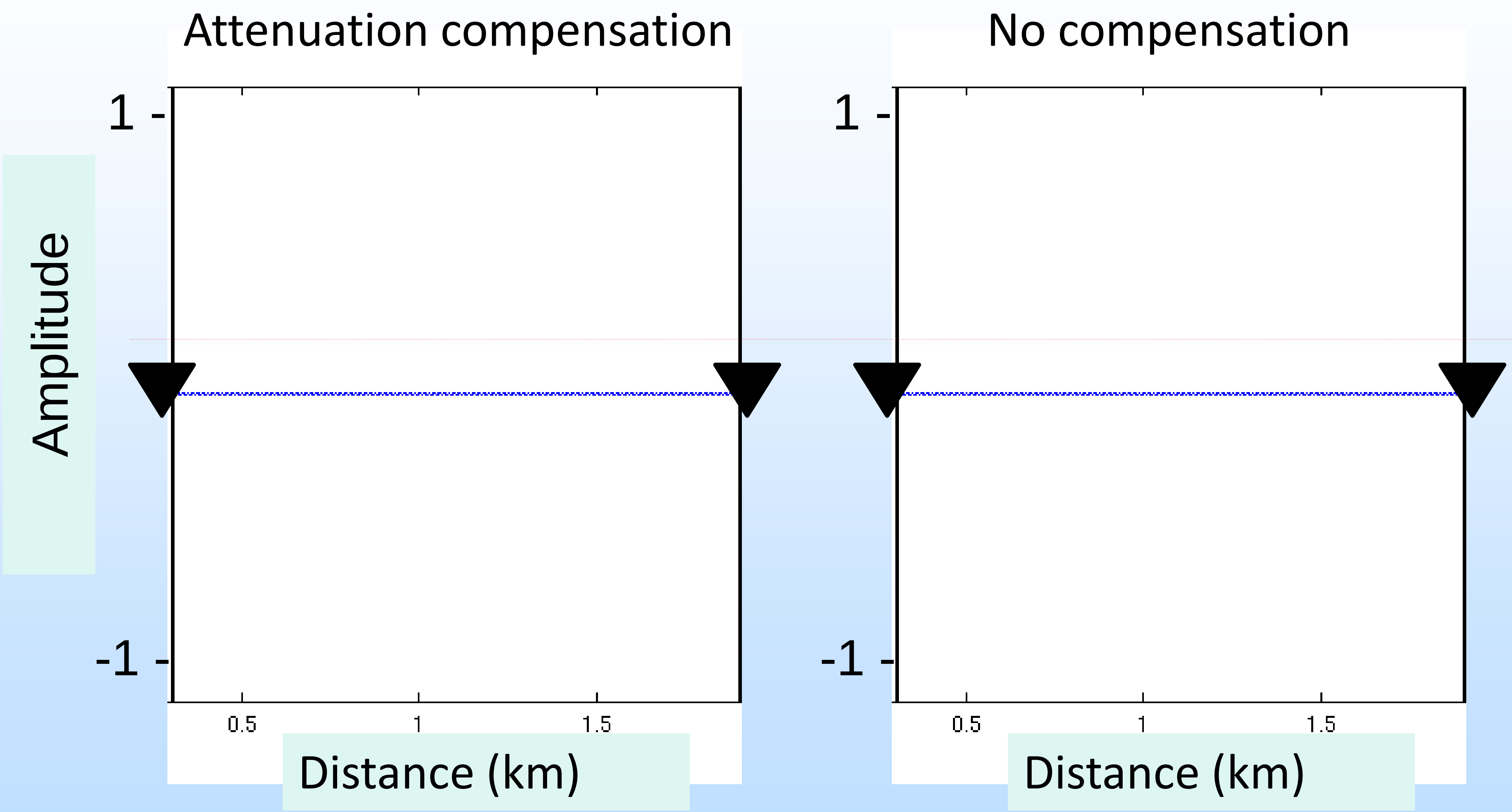
$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p + \tau\frac{d}{dt}\left(-\nabla^2\right)^{\gamma+1/2} p$$



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

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

1D inversion example



Zhu (2014) *GJI*

To find a better efficient solver (subtask 2.1)

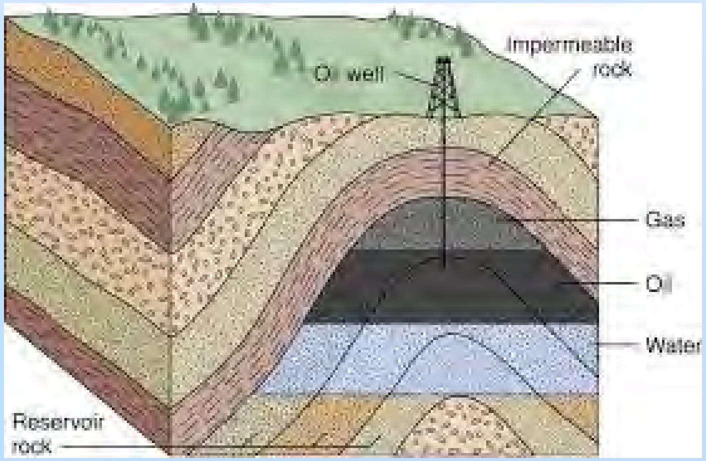
$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p + \left[\eta\left(-\nabla^2\right)^{\gamma+1} - \nabla^2\right]p + \tau\frac{\partial}{\partial t}\left(-\nabla^2\right)^{\gamma+1/2} p$$

Dispersion — $\left[\eta\left(-\nabla^2\right)^{\gamma+1} - \nabla^2\right]$

Loss — $\tau\frac{\partial}{\partial t}\left(-\nabla^2\right)^{\gamma+1/2}$

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)

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

Zhu and Harris (2014) *Geophysics*

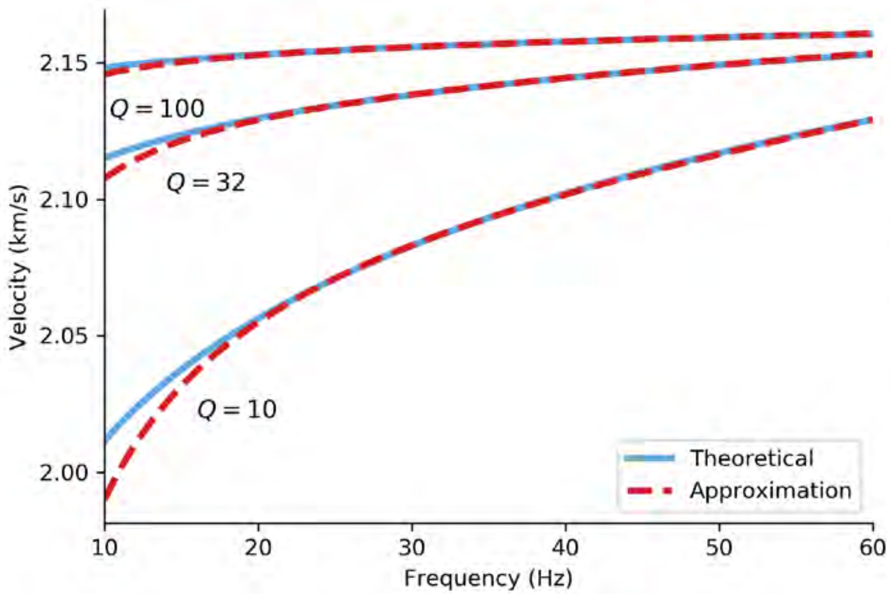
Difficulty!!! because of spatial variable $\gamma(x, y, z)$

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

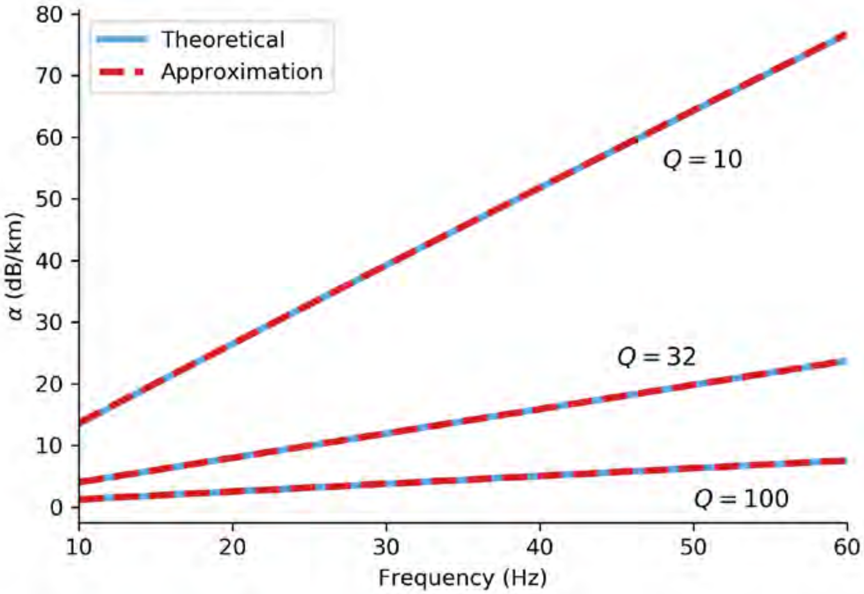
Xing and Zhu (2018) *SEG abstract*

Accuracy tests

Phase Velocity

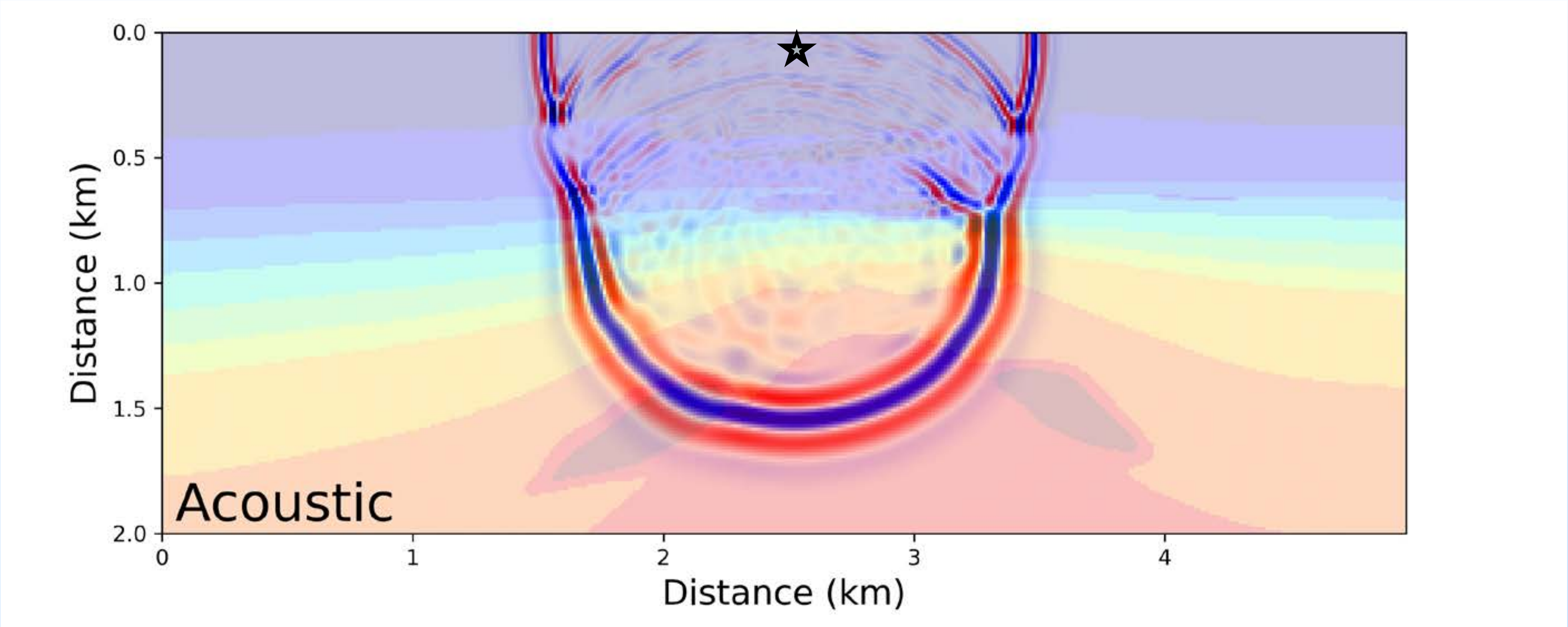


Loss Coefficient



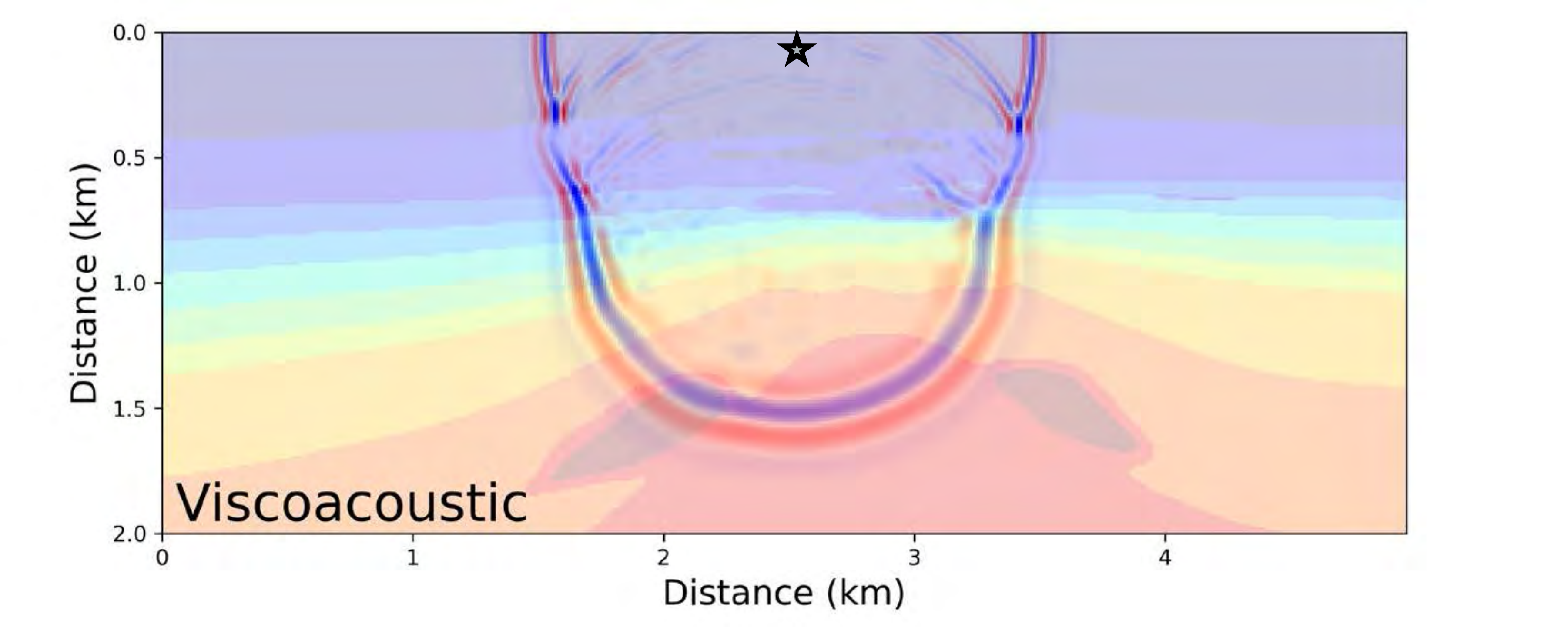
Xing and Zhu (2018) *SEG abstract*

Wavefield snapshot



Xing and Zhu (2018) *SEG abstract*

Wavefield snapshot



Xing and Zhu (2018) *SEG abstract*

Accomplishments to Date

Task 2.0

- Development of a simple formulation of time-domain viscoacoustic wave equation
- Building the numerical scheme and numerical code of solving the new wave equation
- Accuracy tests

Task 4.0

- The development of Frio flow models was initiated. A Frio flow model using the CMG simulator is being developed from the existing LBNL flow model which uses the TOUGH2 simulator.

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 joint Bayesian petrophysical inversion of seismic models and pressure data for providing and updating CO_2 saturation models; --- joint inversion framework (collab. with joint-inversion of (EM, acoustic etc.) projects)

Project Summary

- **Key findings:**
- Build our seismic modeling with attenuation code (Task 2.1)
  - A simple formulation of time-domain viscoacoustic wave equation
  - The numerical scheme and numerical code of solving the new wave equation
  - Accuracy tests

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

Dispersion-dominant

Loss-dominant

Next Step

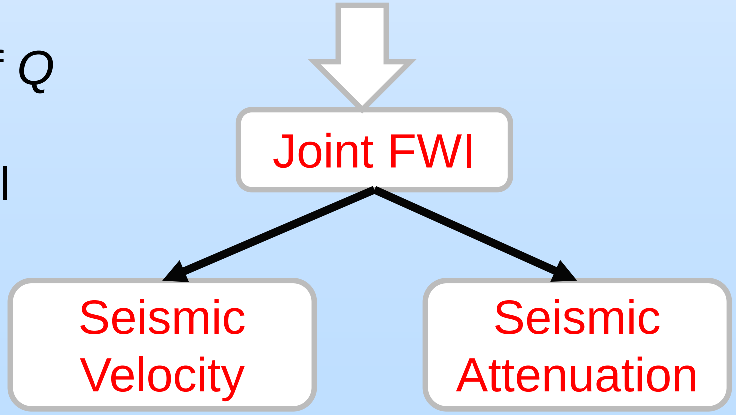
- *Subtask 2.2 – Theoretical development of joint full waveform inversion (FWI):*

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

Dispersion-dominant

Loss-dominant

The two-step studies include: (1) Use of *Q* tomography for processing data and estimating an initial *Q* model for the FWI input; and (2) Development of the joint FWI.



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)

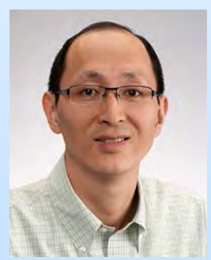
Sun (co-PI)

Daley

Postdoc & graduate student(s)

Leading task 4

Leading task 5



Task 4.2

Help on Frio and CASSM systems

BERKELEY LAB Lawrence Berkeley National Laboratory

PennState

BUREAU OF ECONOMIC GEOLOGY

Gantt Chart

		Budget Period 1								Budget Period 2							
Task	**Description**	**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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