Time-lapse poroelastic modelling for a carbon capture and storage (CCS) project in Alberta

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Outline

- Goals
- Biot’s theory
- Quest project
- Numerical examples
- Absorbing boundary condition (ABC)
- Time-lapse modelling of the Quest project
- Conclusion
- Acknowledgement

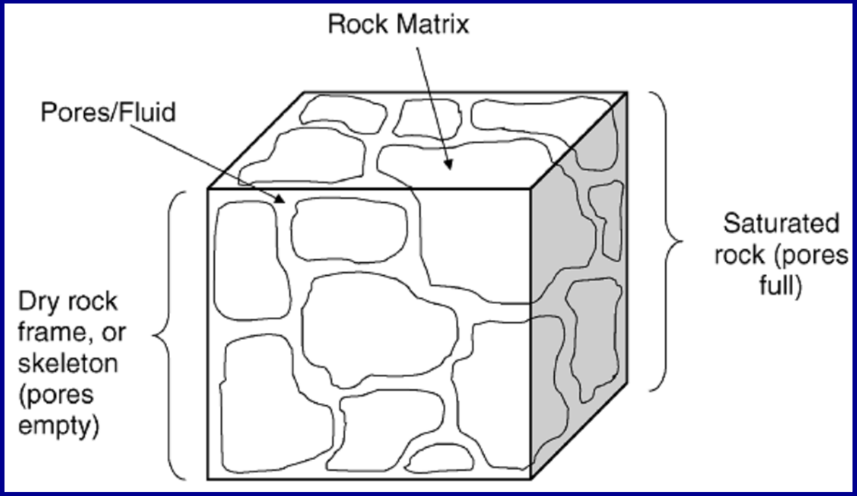
Goals

- To develop a finite difference program for modeling the wave propagation in the fluid saturated media based on the Biot's theory of poroelasticity.

- To investigate the theoretical detectability of the CO_2 for the Quest carbon capture and storage project using a poroelastic approach.

Biot’s Theory of poroelasticity (1962)

- Useful in geophysical applications in which the fluid content of the rock is of interest.
- Poroelastic medium is composed of two phases: the porous rock frame and the viscous fluid within the pore space.
- The poroelastic theory (Biot) predicts a slow P-wave generated due to the relative movement of the fluid with respect to the rock frame.



(Russell et al., 2003)

- Partial differential equations for isotropic porous media saturated with viscous fluid (Biot, 1962):

Stress-strain relations:

$$\begin{cases} \dfrac{\partial \tau_{ij}}{\partial t} = 2\mu \dfrac{\partial e_{ij}}{\partial t} + \left(\lambda_c \dfrac{\partial e_{kk}}{\partial t} + \alpha M \dfrac{\partial \varepsilon_{kk}}{\partial t}\right) \delta_{ij} \\ \dfrac{\partial P}{\partial t} = -\alpha M \dfrac{\partial e_{kk}}{\partial t} - M \dfrac{\partial \varepsilon_{kk}}{\partial t} \end{cases}$$

Velocity-stress relations:

$$\begin{cases} \dfrac{\partial W_i}{\partial t} = A \dfrac{\partial \tau_{ij}}{\partial x_j} + B \dfrac{\partial P}{\partial x_i} + C W_i \\ \dfrac{\partial V_i}{\partial t} = D \dfrac{\partial \tau_{ij}}{\partial x_j} + E \dfrac{\partial P}{\partial x_i} + F W_i \end{cases}$$

Coupling Modulus $M = [\frac{\phi}{K_{Fluid}} + \frac{(\alpha - \phi)}{K_{Solid}}]$

$$\alpha = 1 - \frac{K_{Dry}}{K_{Solid}}$$

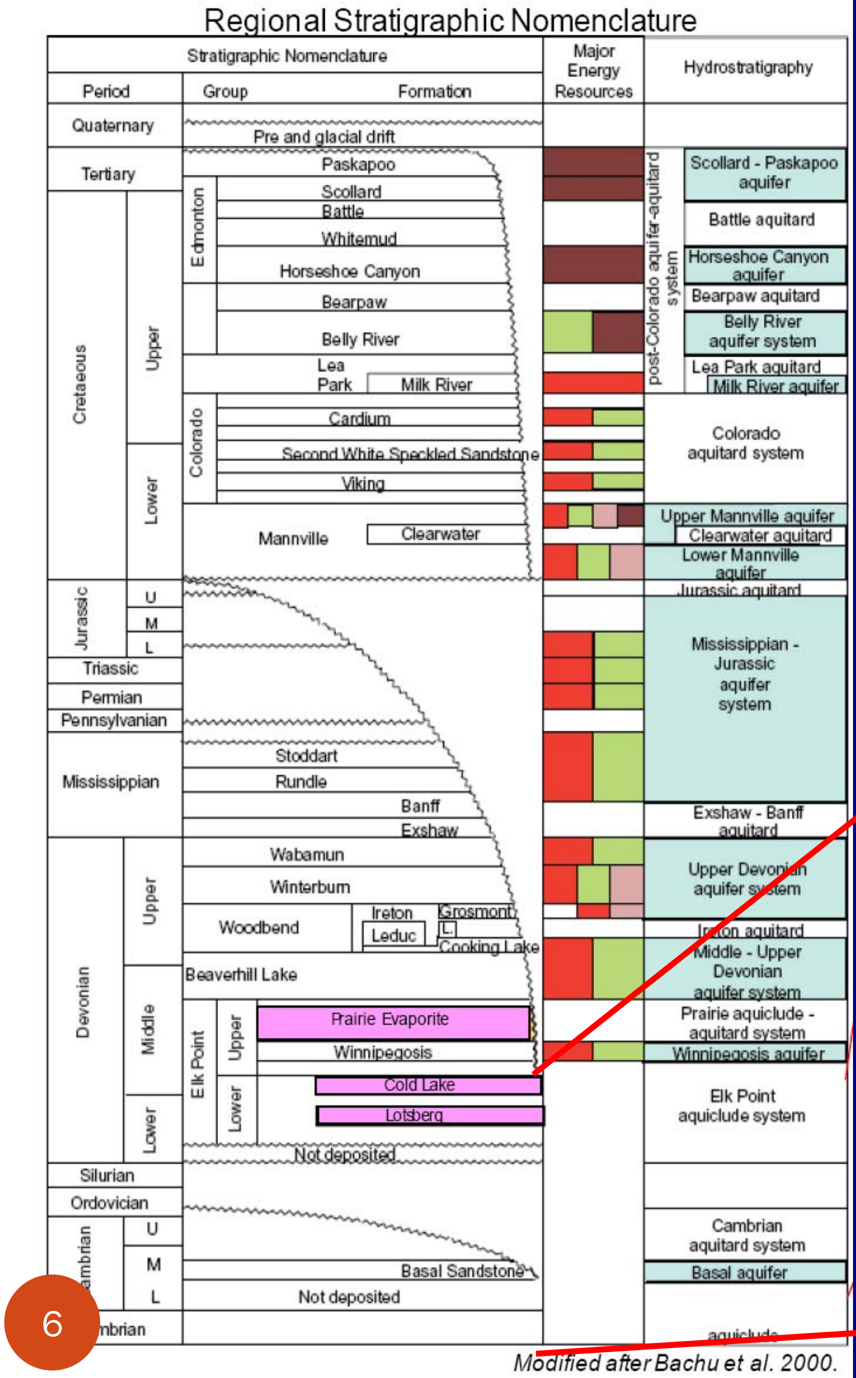
$A, B, C,$ D, E, F Density dependant coefficients

$$W = \frac{\partial (u - U)}{\partial t}$$

$$V = \frac{\partial u}{\partial t}$$

u : Solid Particle Displacement

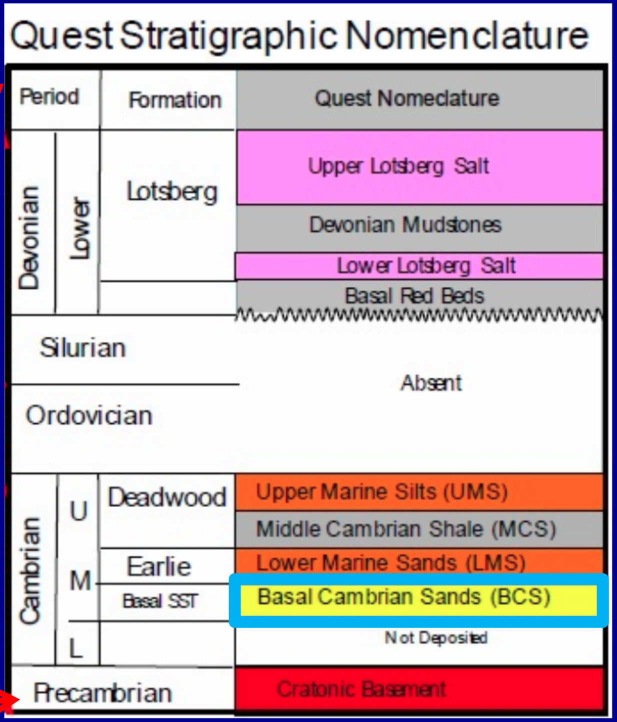
U : Fluid Particle Displacement



Modified after Bachu et al. 2000.

QUEST Project

- CO_2 storage in Basal Cambrian Sands or BCS, which is a saline aquifer within Western Canadian Sedimentary Basin (WCSB)



Quest Stratigraphic Nomenclature

Period		Formation	Quest Nomeclature
Devonian	Lower	Lotsberg	Upper Lotsberg Salt
			Devonian Mudstones
			Lower Lotsberg Salt
			Basal Red Beds
Silurian			Absent
Ordovician			
Cambrian	U	Deadwood	Upper Marine Silts (UMS)
			Middle Cambrian Shale (MCS)
	M	Earlie	Lower Marine Sands (LMS)
		Basal SST	Basal Cambrian Sands (BCS)
	L		Not Deposited
Precambrian			Cratonic Basement

- Logs from well

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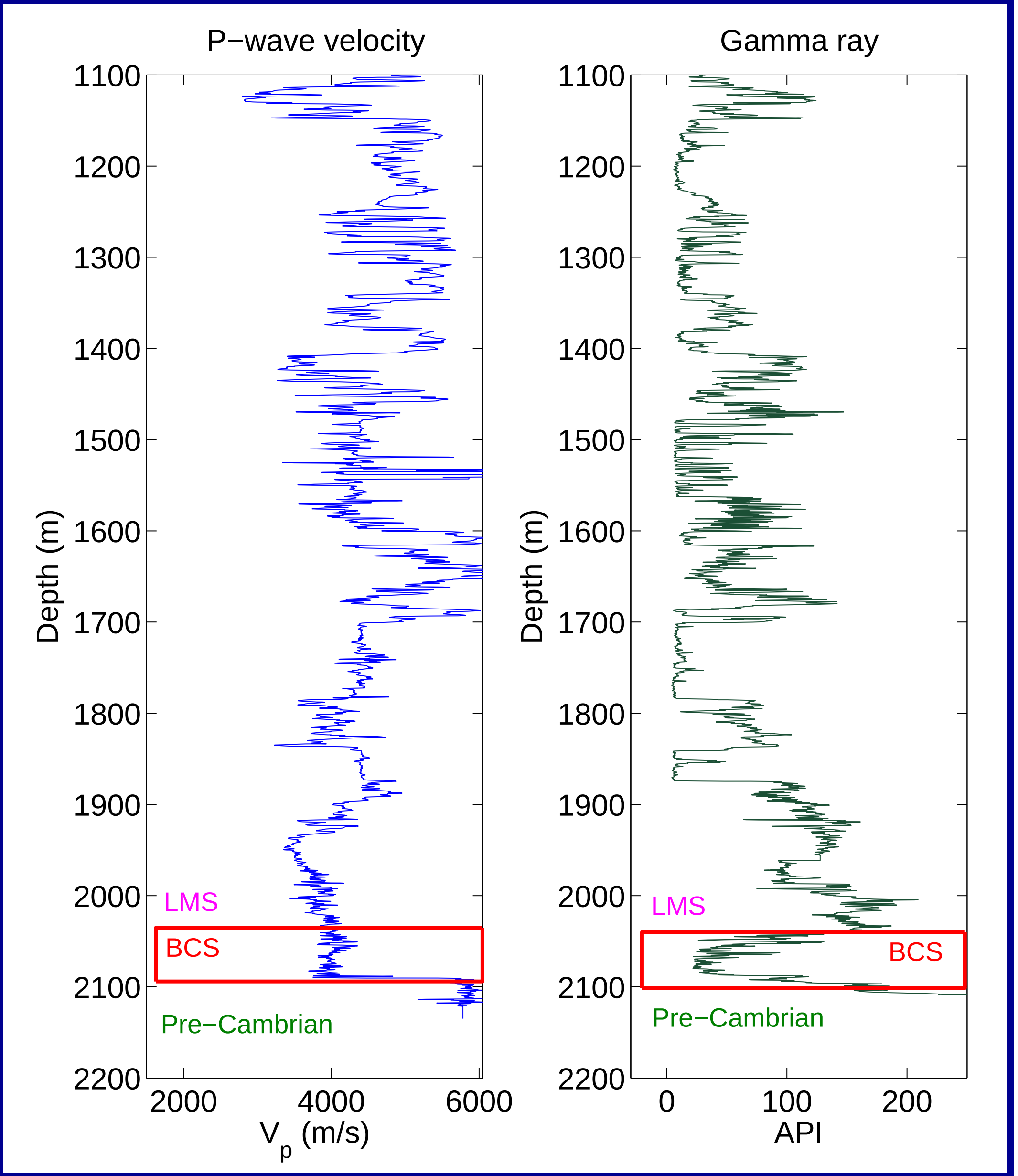


Finite-difference approximation

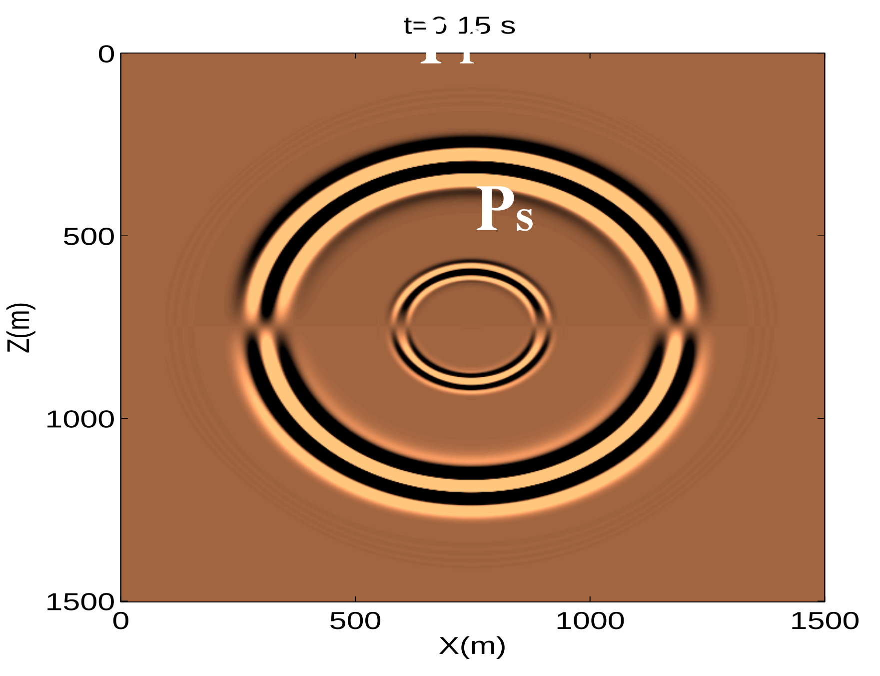
- 2D Staggered-grid velocity-stress finite difference scheme.
- Fourth order in space and second order in time.
- The stability condition is the same as the one in the elastic case (Zhu:1991) $\Delta t \leq \frac{\Delta x}{(V_p^2 - V_s^2)^{1/2}}$

$$\Delta x = 2m \qquad \Delta t = 0.2\ ms$$

- Explosive buried source: Ricker wavelet with dominant frequency 40 Hz

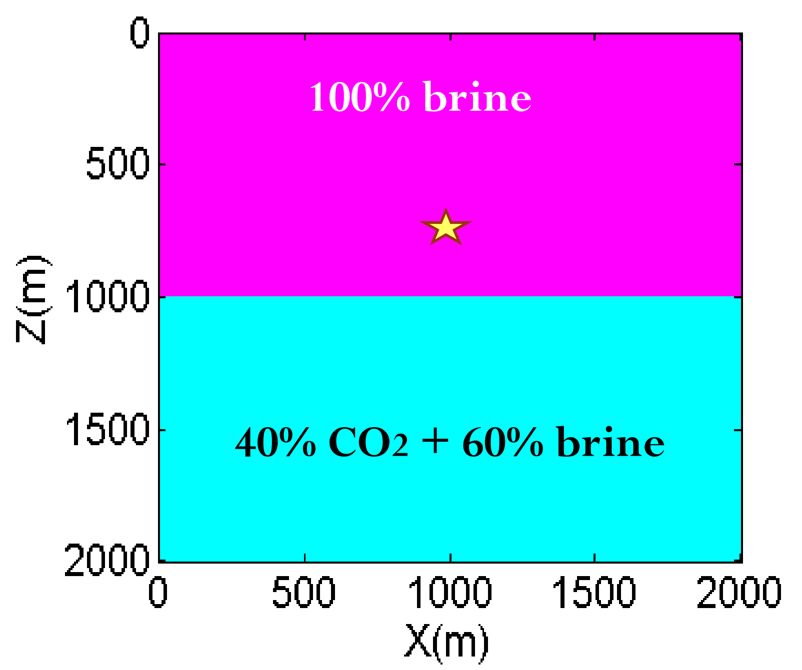
Single layer model

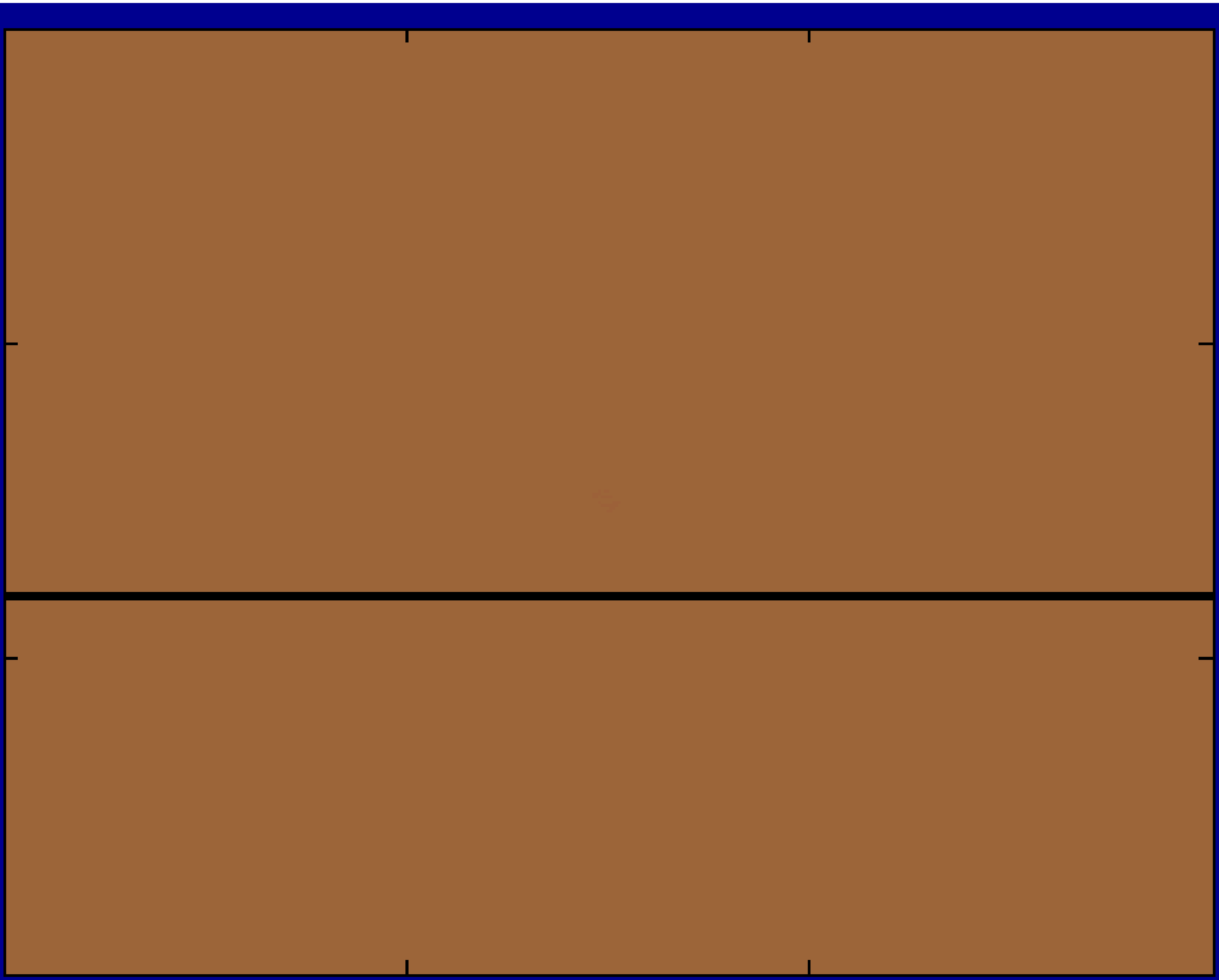
Vertical particle velocity of the solid:



Two layer model

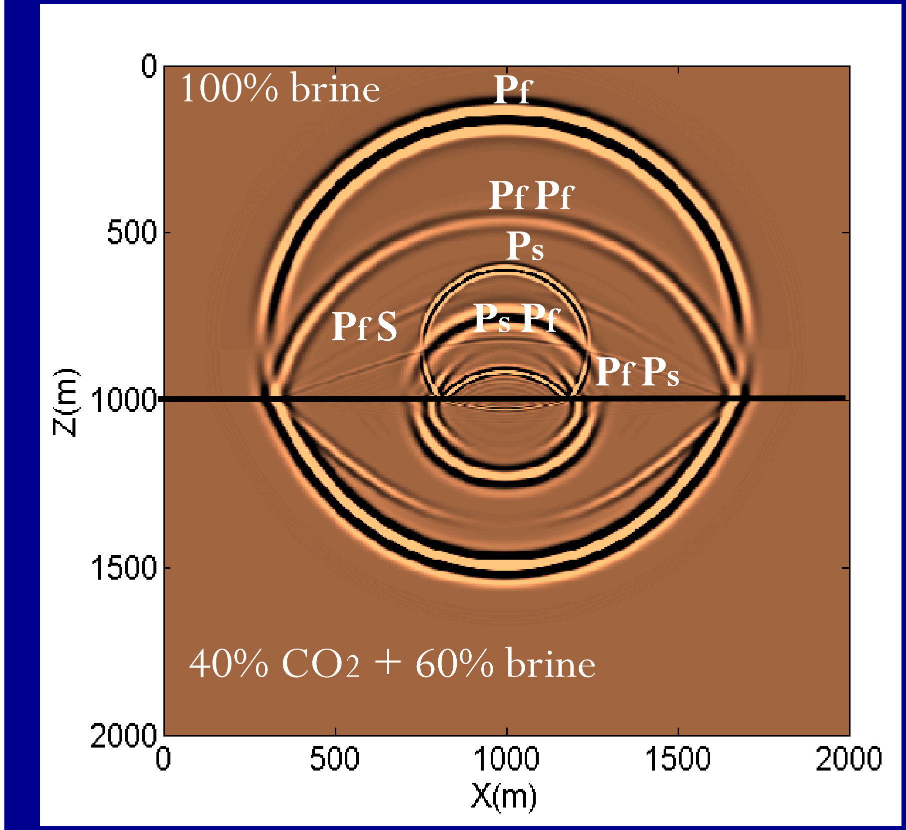
	Top Layer	**Bottom Layer**
ρ_f	$1070\ (kg/m^3)$	$937\ (kg/m^3)$
ρ	$2400\ (kg/m^3)$	$2370\ (kg/m^3)$
V_p	$4100(m/s)$	$3800\ (m/s)$
V_s	$2390(m/s)$	$2400\ (m/s)$
ϕ	16%	16%
η	0	0



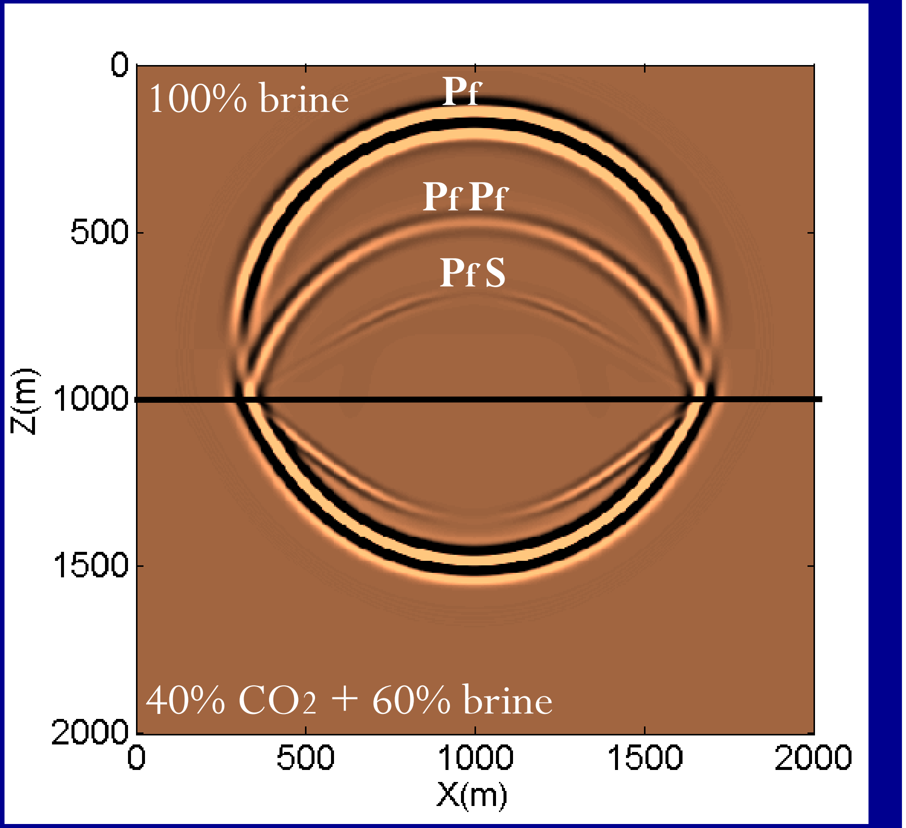


Two layer model

Poroelastic



Elastic



Perfectly matched layer (PML):

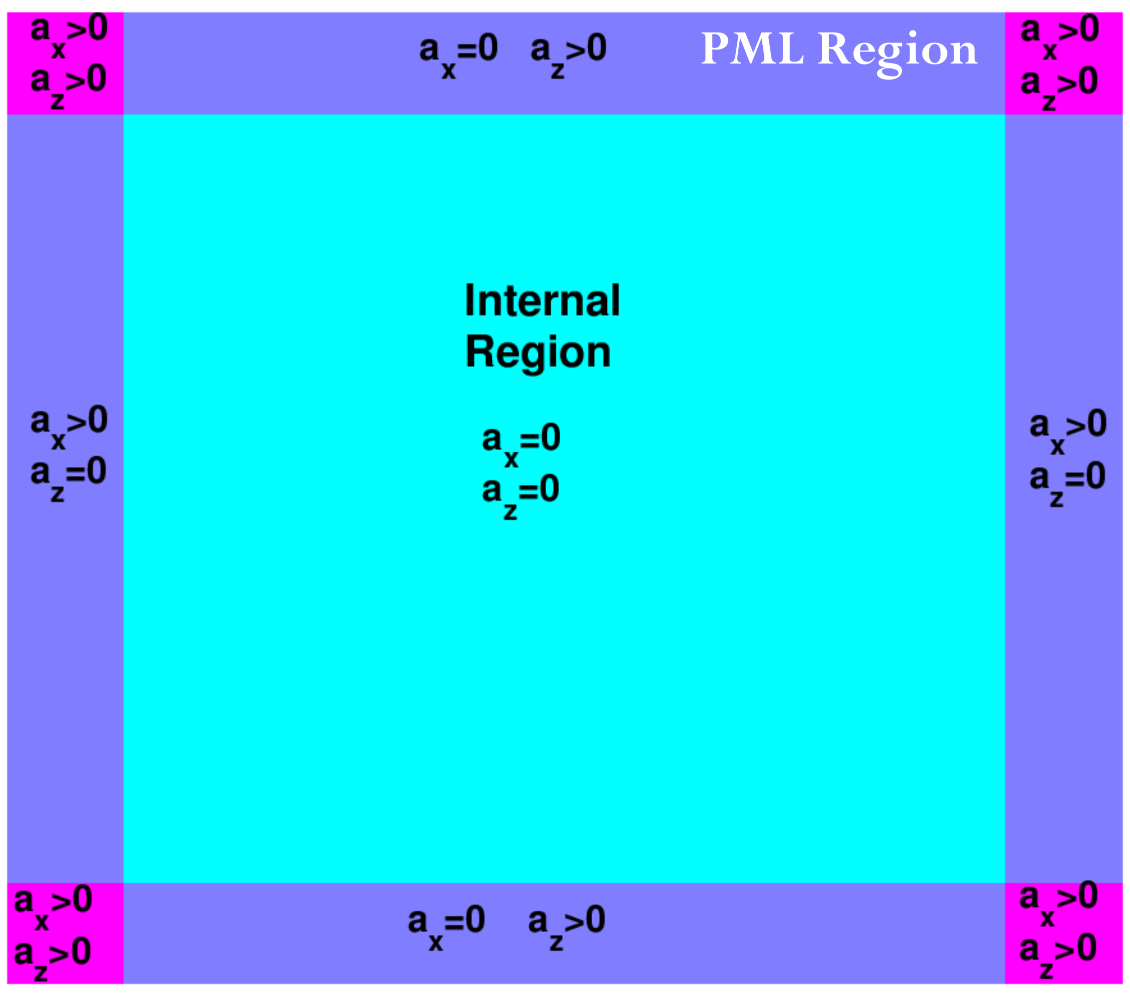
- Berenger, 1994: Electromagnetic waves
- Chew and Liu, 1996: Elastic waves
- Collino (2001).

$$a_x = log\left(\frac{1}{R}\right)\left(\frac{3V_p}{2}\right)\left(\frac{x^2}{L^3_{PML}}\right)$$

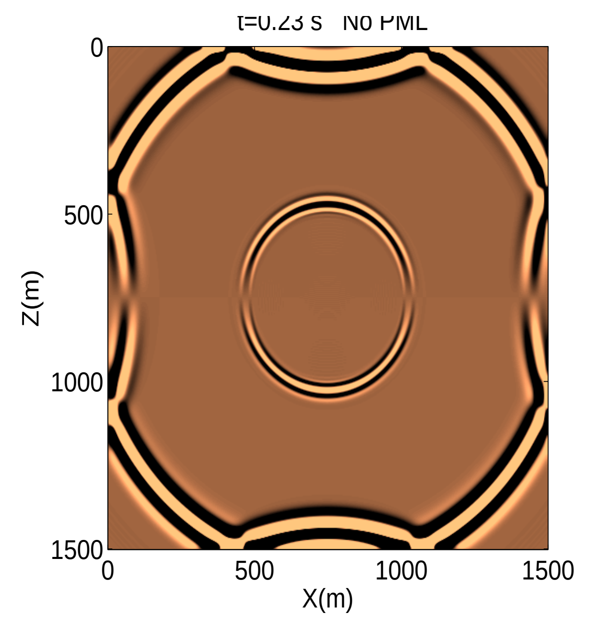
R : Theoretical reflection coefficient

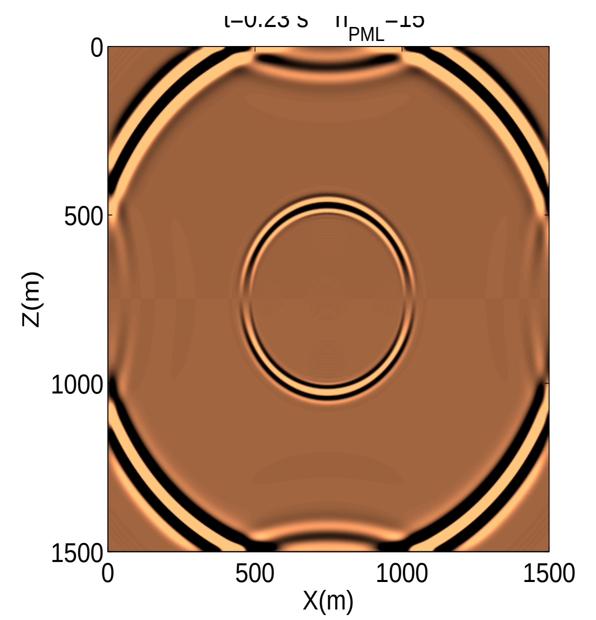
L_{PML} : Thickness of the PML region

x : distance from the PML boundary



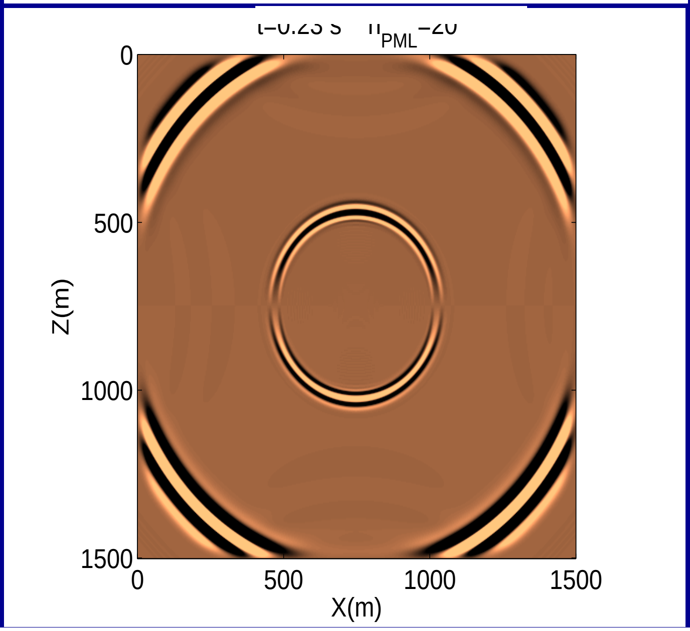
No PML

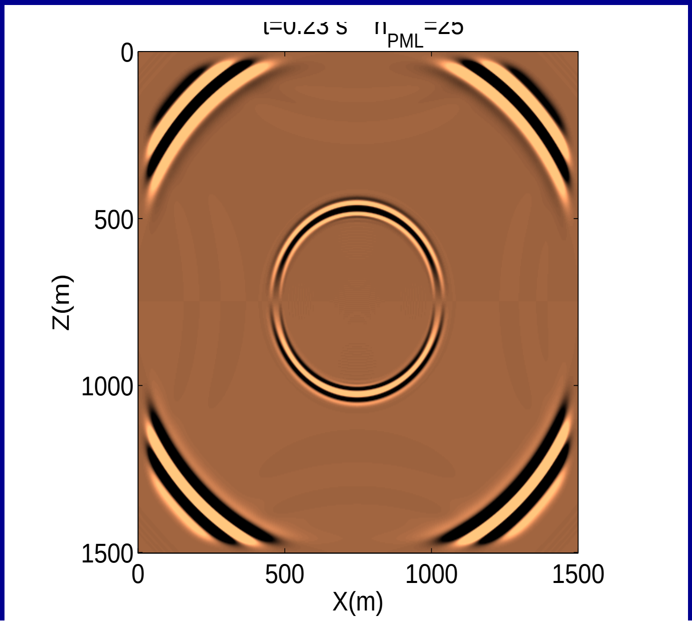




PML: 15 grid-points

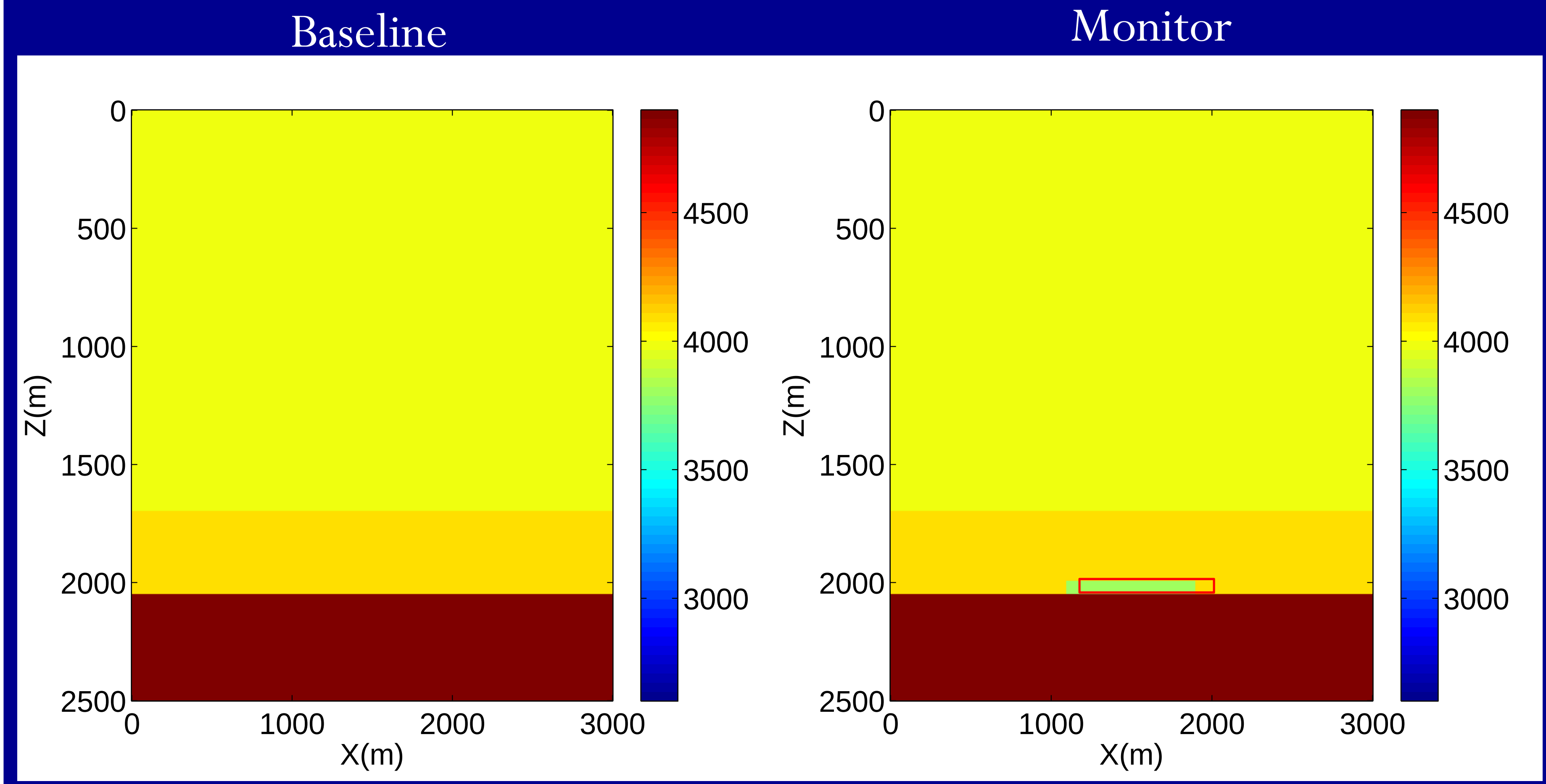
PML: 20 grid-points





PML: 25 grid-points

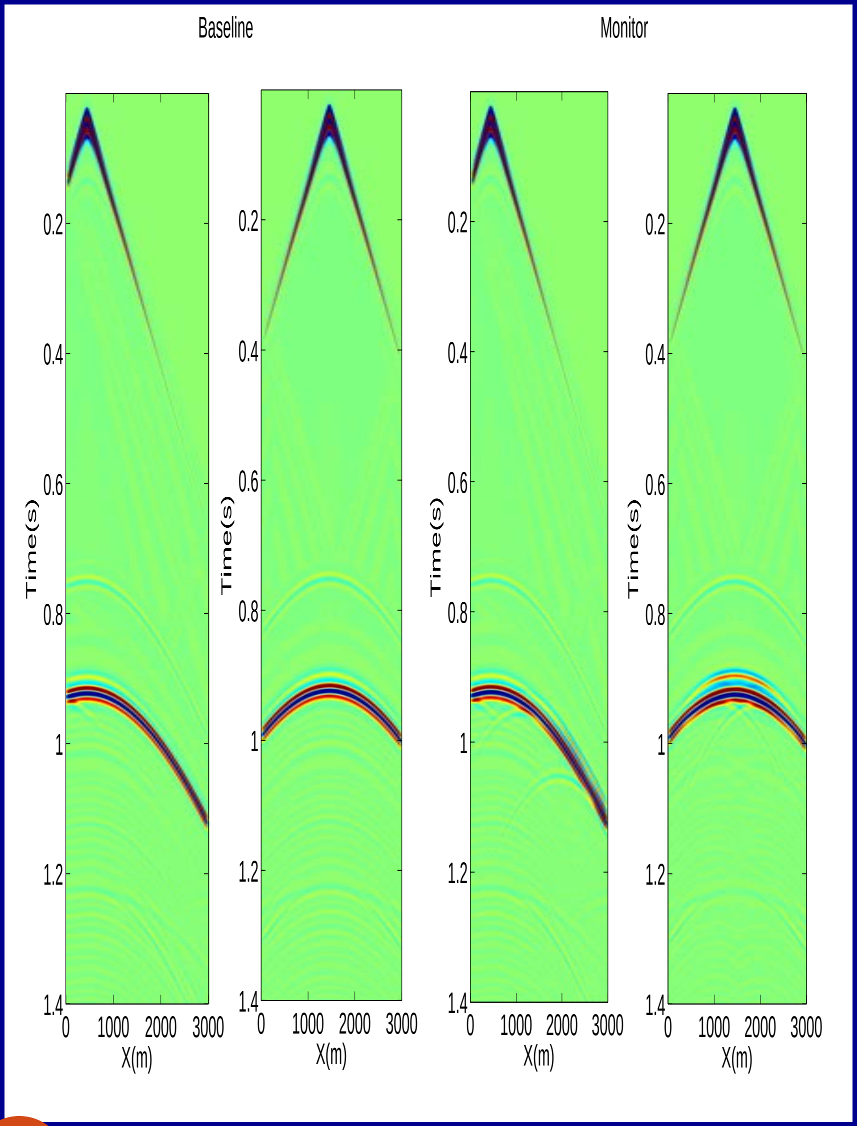
Time-lapse modelling

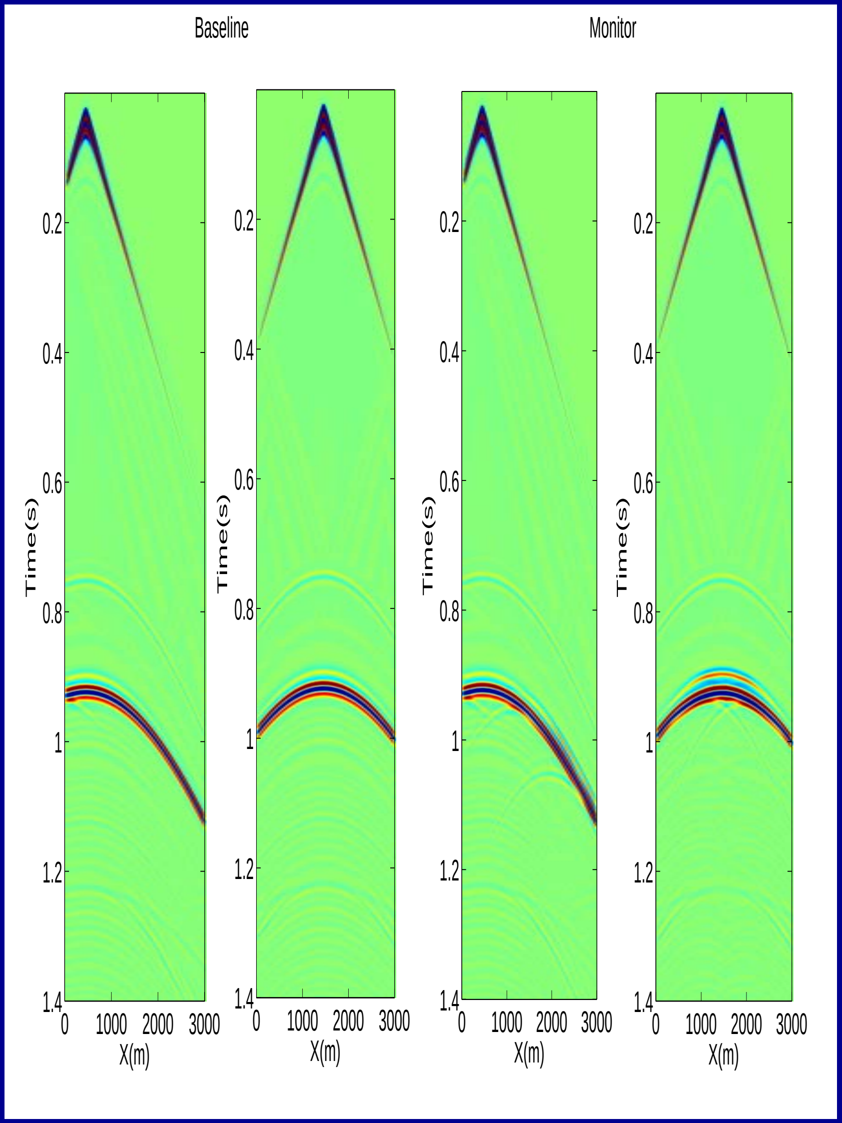


CO2 plume:

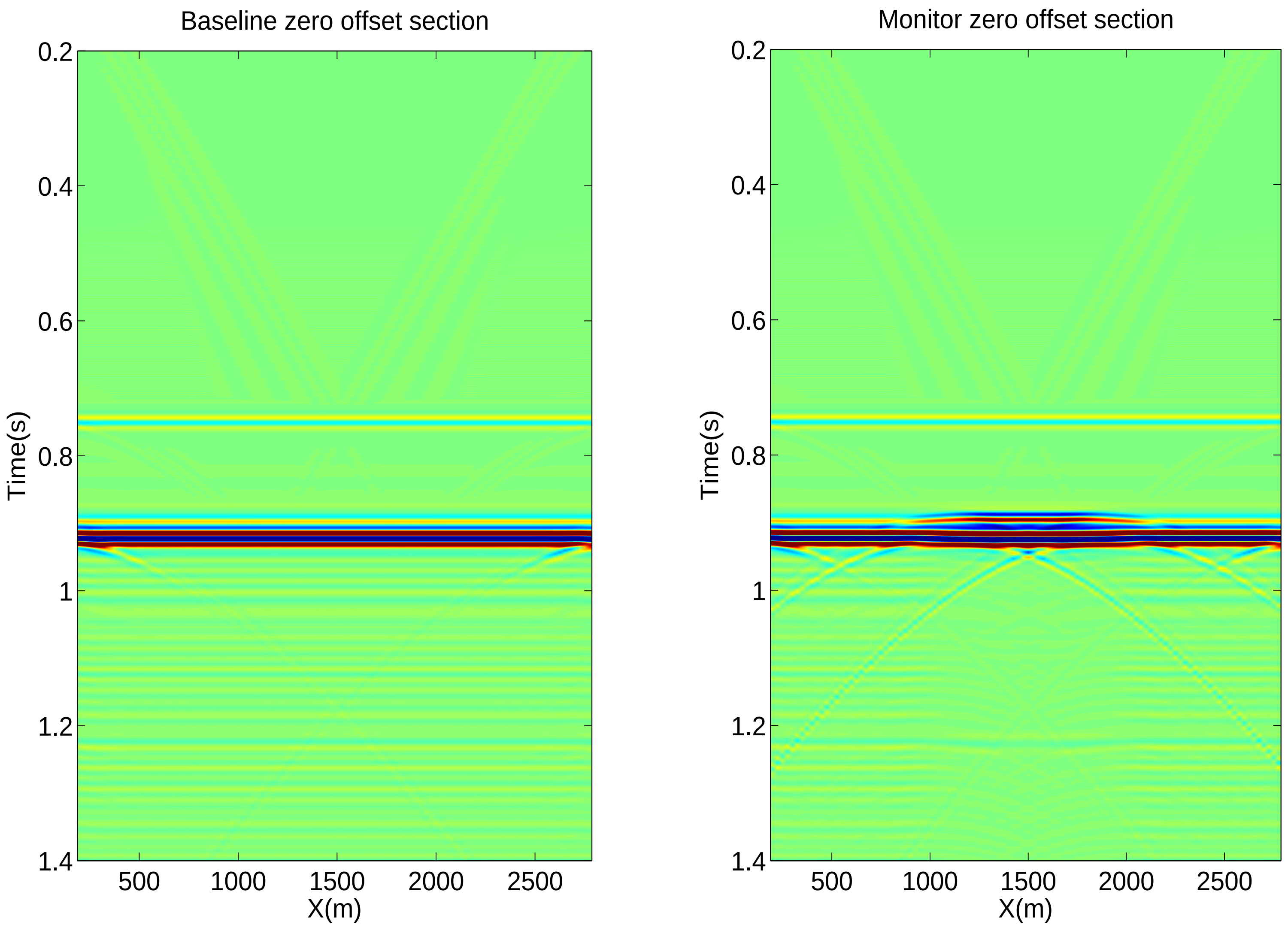
- 1.2 million tonnes CO2
- CO2 saturation 40%
- Porosity 16%

Shot gathers: Poroelastic

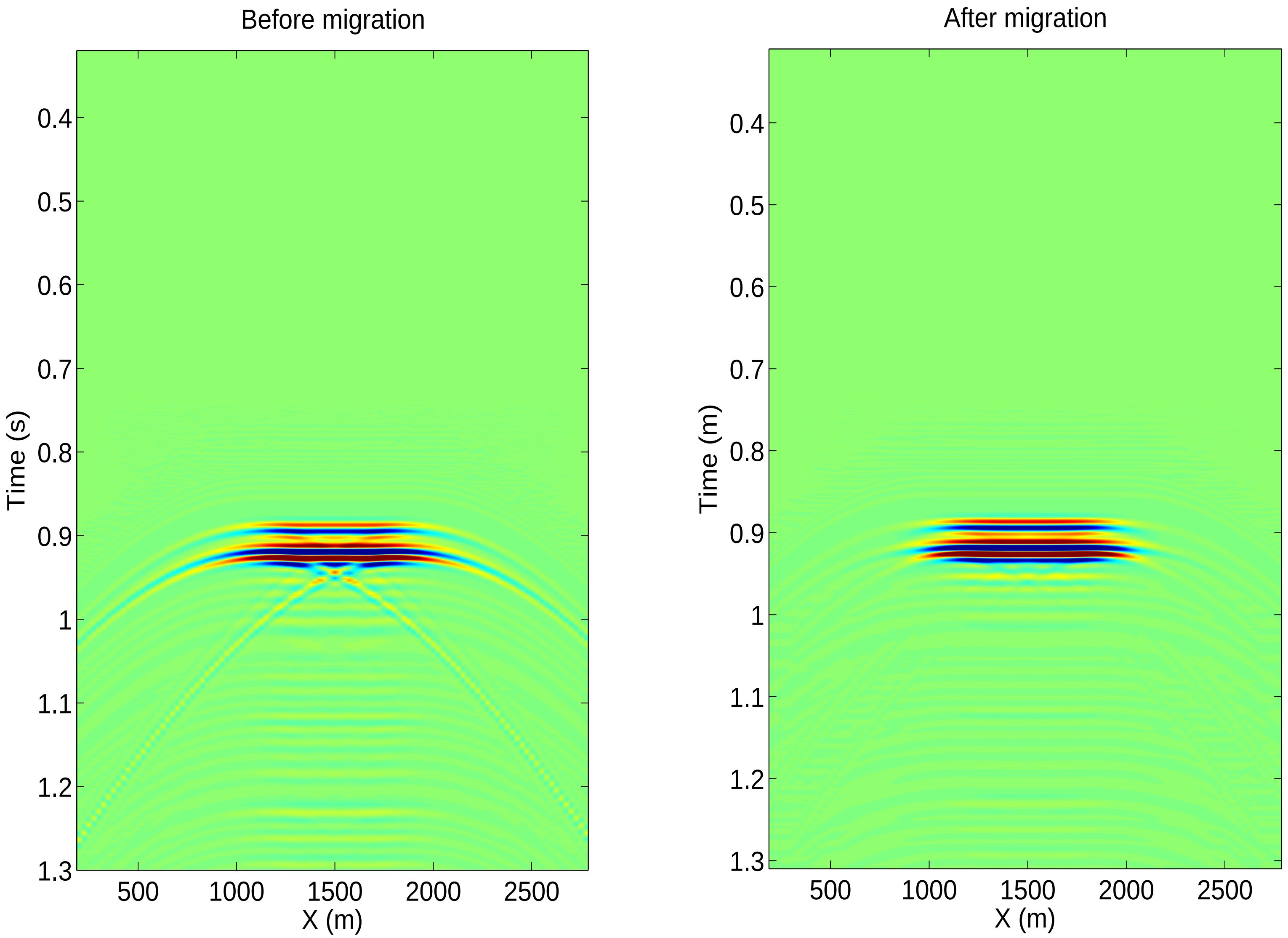




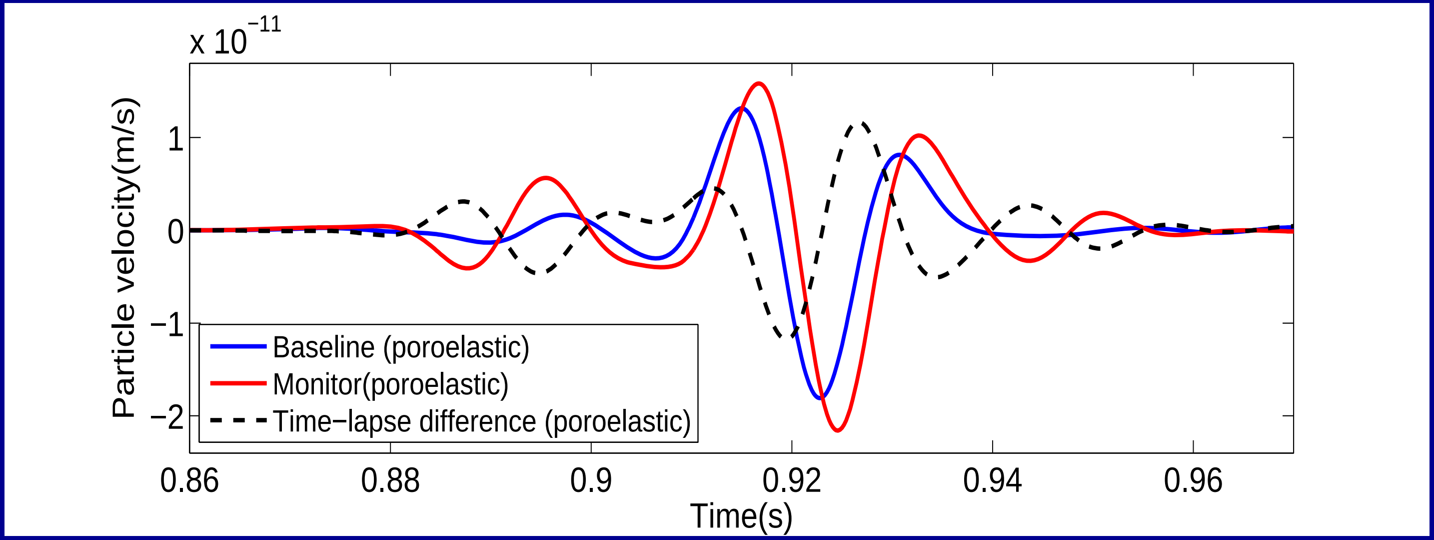
Zero offset sections: Poroelastic



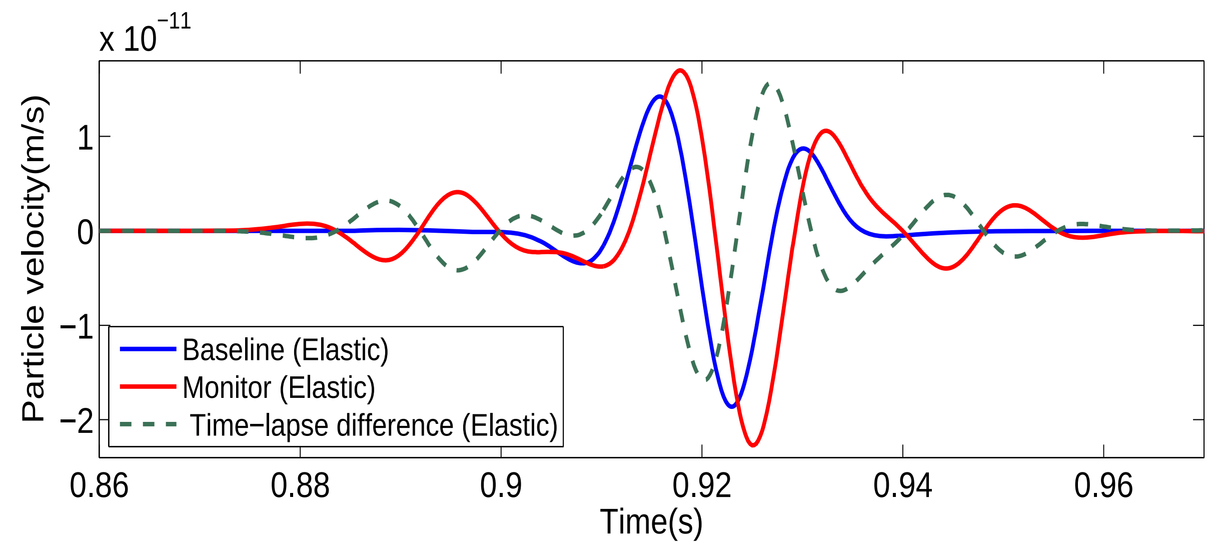
Time-lapse difference: Poroelastic



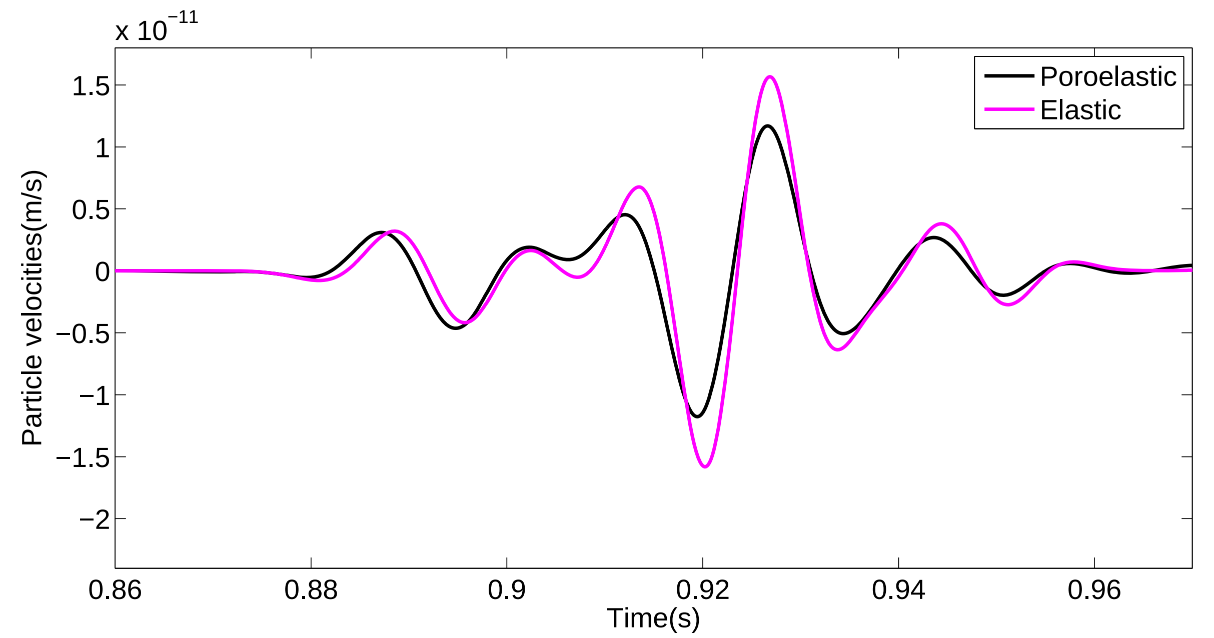
Poroelastic



Elastic



Time-lapse differences



Conclusions

- We showed that the fluid induced flow even in cases of low viscosity effects the seismic response of the fluid saturated medium.
- Perfectly matched layers were used as boundary condition that effectively absorbed the reflections from the computational boundaries.
- This means that the CO_2 plume could be detected in the seismic data providing the data have good bandwidth and a high signal to noise ratio.
- The difference between the elastic and poroelastic algorithms are considerable and we need to take the poroelastic effects into account.

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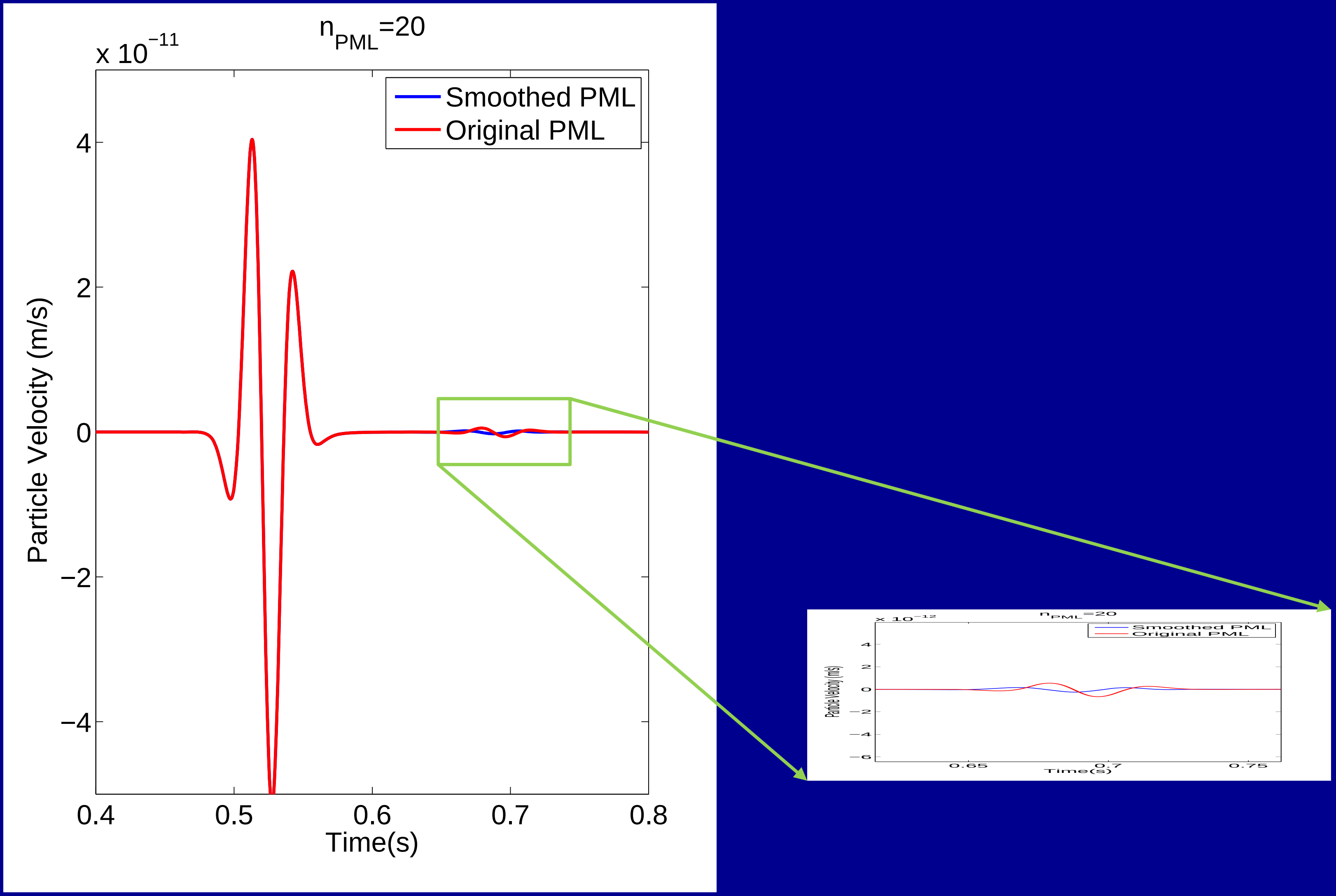
- Juan Santos from Purdue University



n_{PML}=20
x 10^{-11}
Smoothed PML
Original PML
4
2
0
−2
−4
Particle Velocity (m/s)
0.4
0.5
0.6
0.7
0.8
Time(s)
n_{PML}=20
x 10^{-12}
Smoothed PML
Original PML
4
2
0
−2
−4
−6
Particle Velocity (m/s)
0.65
0.7
0.75
Time(s)

Absorbing boundary condition (ABC)

In 2D case:

$$\frac{\partial V_z}{\partial t} = A\left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{zz}}{\partial z}\right) + B\frac{\partial S}{\partial z} + CW_z$$

$$\Downarrow$$

$$\left(\frac{\partial}{\partial t} + a_x\right) V_z^x = A\left(\frac{\partial \tau_{xz}}{\partial x}\right) + C\left(W_z^x + a_x \int_{-\infty}^{t} W_z^x \, dt\right)$$

$$\left(\frac{\partial}{\partial t} + a_z\right) V_z^z = A\left(\frac{\partial \tau_{zz}}{\partial z}\right) + B\frac{\partial S}{\partial z} + C\left(W_z^z + a_z \int_{-\infty}^{t} W_z^z \, dt\right)$$

$$V_z = V_z^x + V_z^z$$

Biot’s Theory(1962)

Assumptions :

- Elastic rock frame
- Connected pores
- Seismic wavelength $\gg$ average pore size
- Small deformations
- Statistically isotropic medium

Staggered-grid finite difference

Levander (1988)

$X: \tau_{xx}, \tau_{zz}$ and P

$Y: V_x$ and W_x

$Z: V_z$ and W_z

$O: \tau_{xz}$