SEISMIC MONITORING OF CARBON DIOXIDE FLUID FLOW

J. E. Santos[1], G. B. Savioli[2], J. M. Carcione[3], D. Gei[3]

[1] CONICET, IGPUBA, Fac. Ing., UBA
and Univ. Nac. de La Plata, ARGENTINA
and Department of Mathematics, Purdue University, USA
[2] IGPUBA - Fac. Ing., UBA, ARGENTINA

[3] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS),
Trieste, ITALY

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Introduction. I

- Storage of CO_2 in geological formations is a procedure employed to reduce the amount of greenhouse gases in the atmosphere to slow down global warming.
- Geologic sequestration involves injecting CO_2 into a target geologic formation at depths typically >1000 m where pressure and temperature are above the critical point for CO_2 (31.6C, 7.38 MPa).
- First industrial scale CO_2 injection project: Sleipner gas field (North Sea).

Introduction. II

- CO_2 is separated from natural gas produced and is currently being injected into the Utsira Sand, a saline aquifer at the Sleipner field, some 26000 km^2 in area.
- Injection started in 1996 and is planned to continue for about 20 years, at a rate of about one million tonnes per year.
- Time-lapse seismic surveys aim to monitor the migration and dispersal of the CO_2 plume after injection.
- Very little is known about the effectiveness of CO_2 sequestration over very long periods of time.

Introduction. III

- The analysis of CO_2 underground storage safety in the long term is a current area of research.
- We present a methodology integrating numerical simulation of CO_2-brine flow and seismic wave propagation to model and monitor CO_2 injection.
- The model of the formation is based on the porosity and clay content distribution considering the variation of properties at the site with fluid pressure and saturation.

Presentation Outline

- Present the two-phase fluid flow equations used to simulate CO_2 injection.
- Describe a viscoelastic model for wave propagation
- Present a petrophysical model of a shaly sandstone based on fractal porosity and clay content, considering the variation of properties with pressure and saturation.
- Show numerical simulations of CO_2 injection and time-lapse seismics to monitor the migration and dispersal of CO_2 after injection in the Utsira formation at the Sleipner field in the North Sea.

The Black-Oil formulation

- **The simultaneous flow of brine and CO_2 is described by the well-known Black-Oil formulation applied to two-phase, two component fluid flow.**
- **In the Black-Oil model employed, brine is NOT present, OIL is identified with brine and CO_2 is identified with GAS.**
- **Also, CO_2 may dissolve in brine (OIL) but brine (OIL) is not allowed to vaporize into the CO_2 phase.**
- **This formulation uses, as a simplified thermodynamic model, the quantities R_s, B_b and B_{CO2} as PVT data:**

The Black-Oil formulation of two-phase flow in porous media. I

- $R_s = \frac{V_{dCO2}^{SC}}{V_b^{SC}}$: **$CO_2$ solubility in brine**
- $B_{CO2} = \frac{V_{CO2}^{res}}{V_{CO2}^{SC}}$: **$CO_2$ formation volume factor**
- $B_b = \frac{(V_{dCO2}^{res} + V_b^{res})}{V_b^{SC}}$: **brine formation volume factor**

To estimate the above PVT data we used an algorithm developed by Hassanzadeh (2008).

The Black-Oil equations for two-phase flow in porous media are obtained combining conservation of mass of each component with two-phase Darcy's law.

The Black-Oil formulation of two-phase flow in porous media. II

$$\nabla \cdot \left[\frac{\underline{\kappa} k_{rCO2}}{B_{CO2}\eta_{CO2}} (\nabla p_{CO2} - \rho_{CO2} g \nabla D) + \frac{\underline{\kappa} R_s k_{rb}}{B_b \eta_b} (\nabla p_b - \rho_b g \nabla D) \right]$$

$$+q_{CO2} = \frac{\partial \left[\phi \left(\frac{S_{CO2}}{B_{CO2}} + \frac{R_s S_b}{B_b} \right) \right]}{\partial t}$$

$$\nabla \cdot \left[\frac{\underline{\kappa} k_{rb}}{B_b \eta_b} (\nabla p_b - \rho_b g \nabla D \right] + q_b = \frac{\partial \left[\phi \frac{S_b}{B_b} \right]}{\partial t}$$

Two algebraic equations complete the system:

$$S_b + S_{CO2} = 1, \qquad p_{CO2} - p_b = P_C(S_b)$$

Numerical solution of the Black-Oil formulation of two-phase flow in porous media.

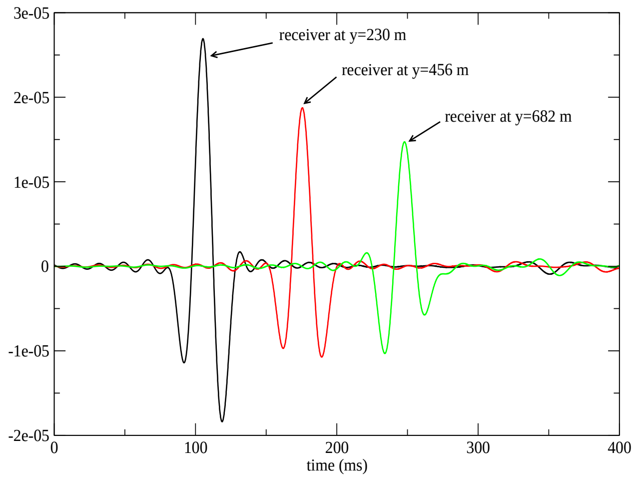
The unknowns for the Black-Oil fluid-flow model are the **fluid pressures** p_{CO2}, p_b and the **saturations** S_{CO2}, S_b for the CO_2 and brine phases.

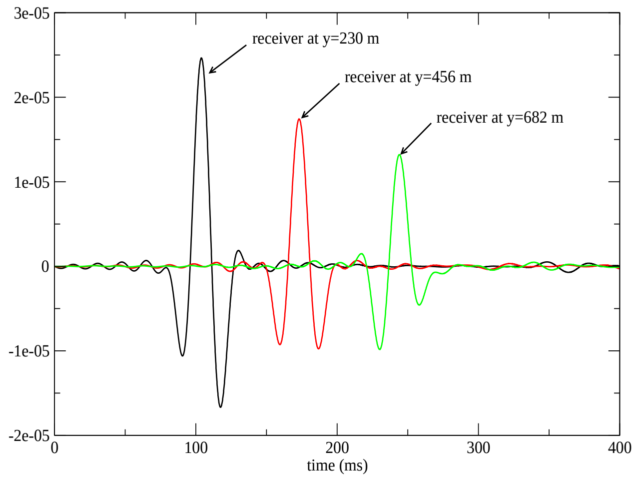
They were computed using the public domain software **BOAST**, which solves the differential equations applying **IMPES**, a finite difference technique.

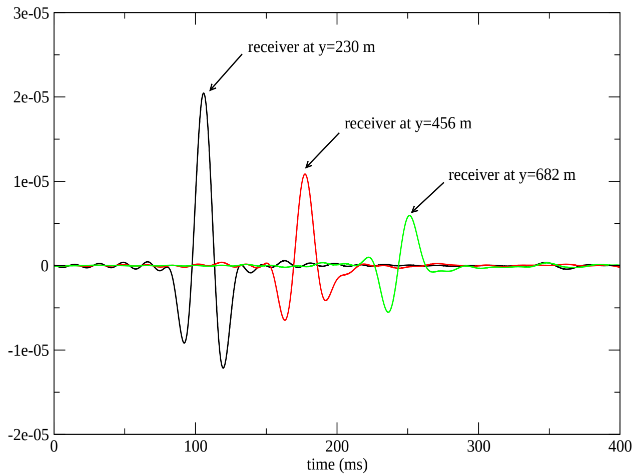
Seismic modeling. Mesoscopic attenuation effects. I

- An important mechanisms of P-wave attenuation and dispersion at seismic frequencies is known as mesoscopic loss, due to heterogeneities larger than the pore size but much smaller than the predominant wavelengths (mesoscopic-scale heterogeneities).
- These effects are due to the equilibration of wave-induced fluid pressure gradients via a slow-wave diffusion process (Type II Biot waves).
- White et al. (1975) were the first to introduce the mesoscopic-loss mechanism in the framework of Biot's theory, which is illustrated in the next figures.

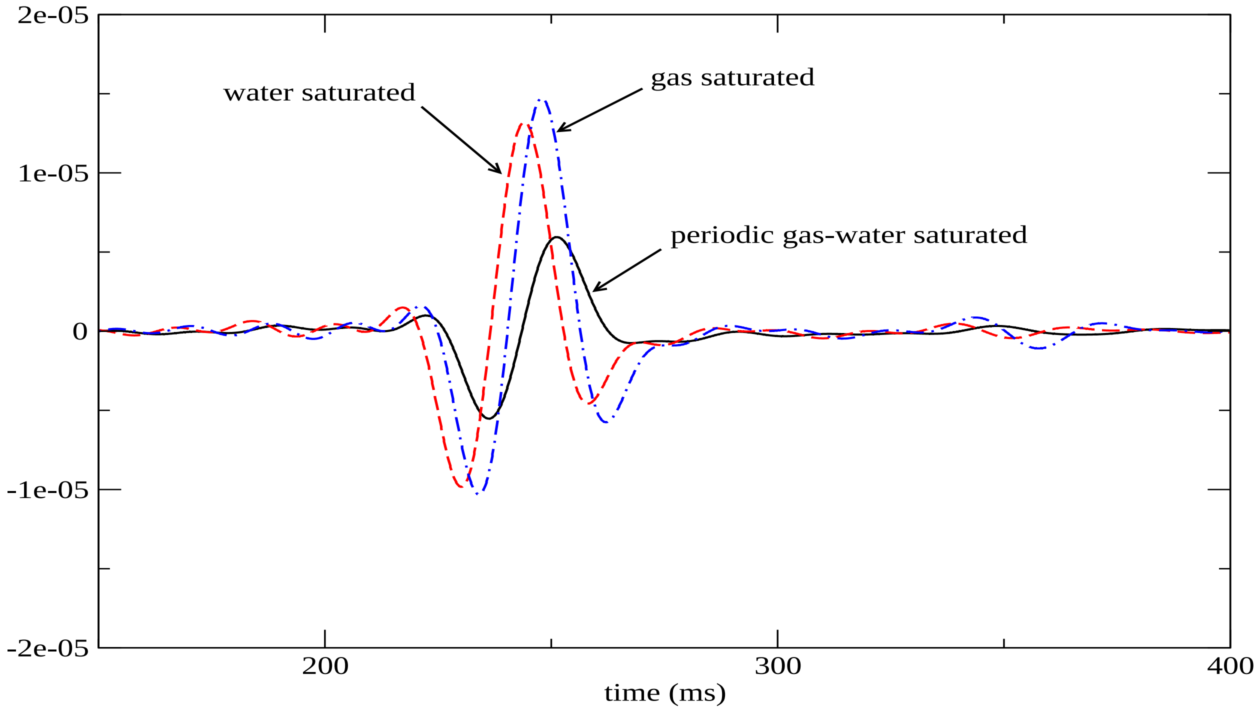
Traces of waves travelling through a porous media saturated by gas (top left), water (top right) and periodic gas-water (bottom)





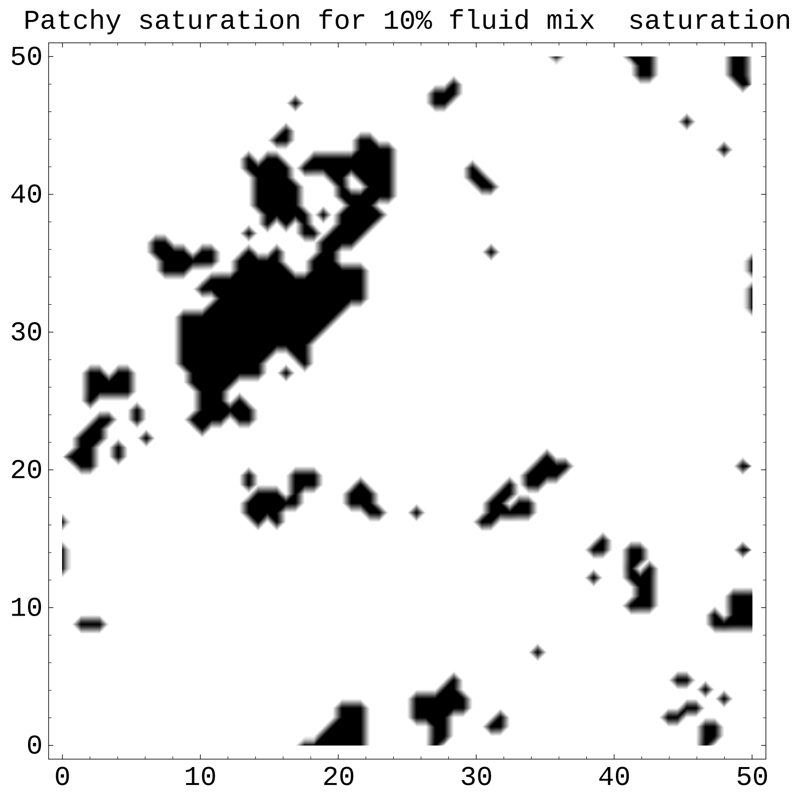


Traces of waves for the gas, water and periodic gas-water saturation cases



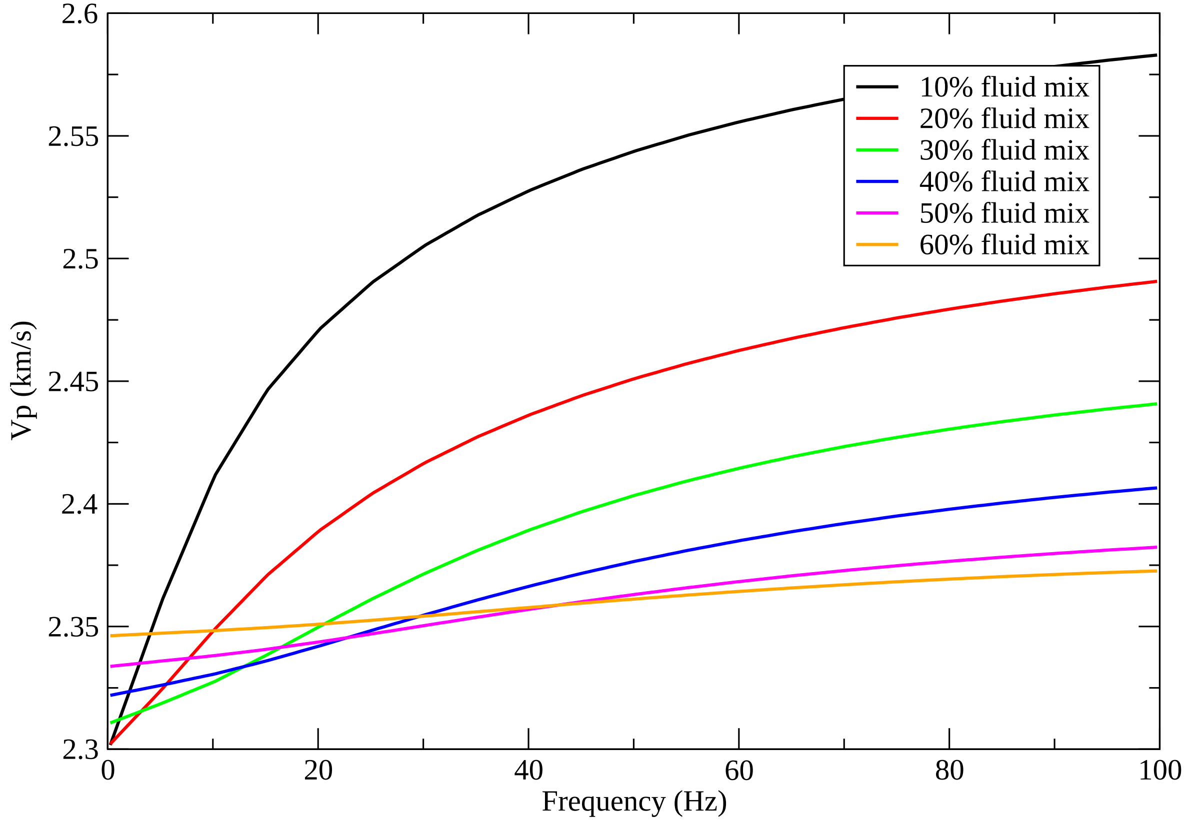
The delay in the arrival time in the periodic case is due to the velocity dispersion caused by the mesoscopic scale heterogeneities. Attenuation and dispersion in the periodic gas-water case is in perfect agreement with that predicted by White's theory.

Representative sample for 10% fluid mixture CO_2 patchy saturation.



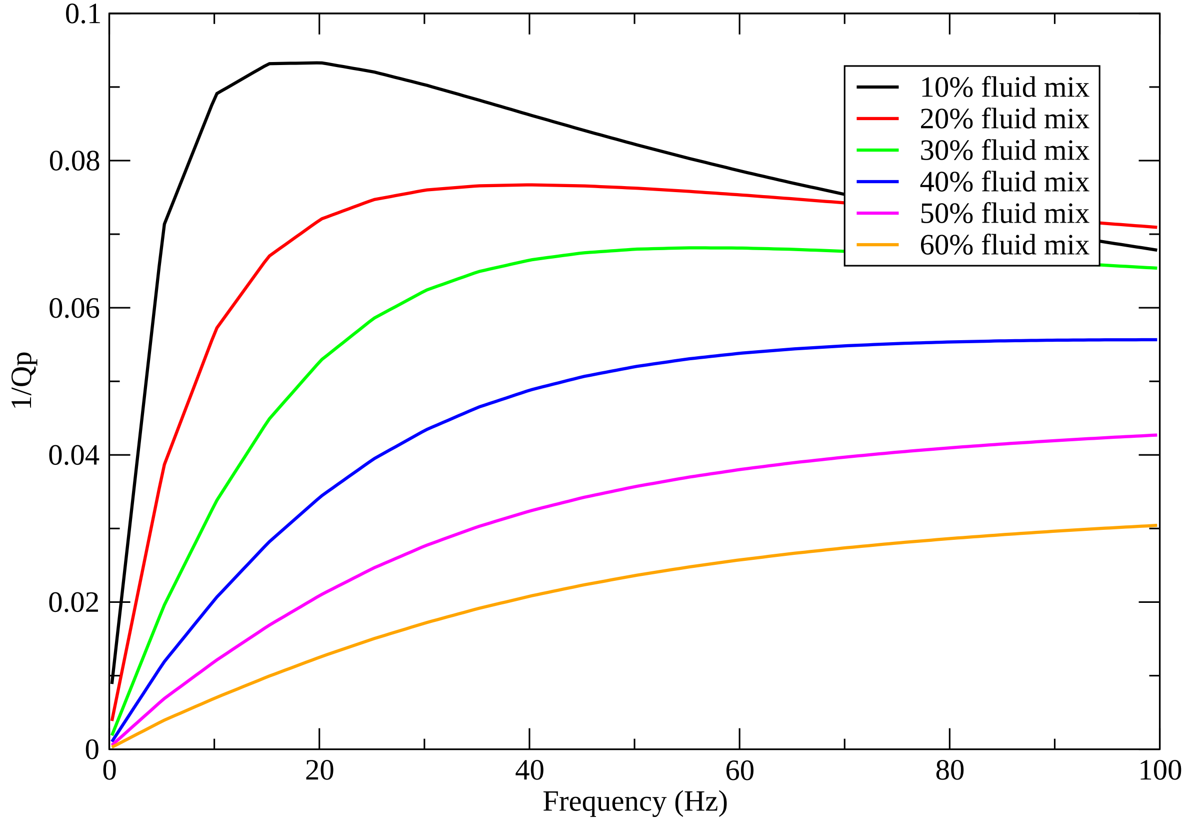
Side length 50 cm, fractal dimension D=2.5, correlation length a = 5cm. Black zones: pure CO_2 saturation, white zones: pure brine saturation.

Computed Vp (P-wave phase velocity) as function of CO_2 patchy saturation



CO_2 is in gaseous state, fractal dimension D=2.5, correlation length a = 5 cm

Computed inverse quality factor as function of fluid mixture CO_2 patchy saturation



CO_2 is in gaseous state, fractal dimension D=2.5, correlation length a = 5 cm

Seismic modeling. Mesoscopic attenuation effects. II

- Due to the extremely fine meshes needed to properly represent these type of media, numerical simulations at the macroscale is very expensive or even not feasible.
- Our approach: employ an upscaling procedure to include the mesoscale effects in the macroscale.

Seismic modeling. Mesoscopic attenuation effects. III

- Within the Utsira formation, determine complex and frequency dependent P-wave modulus

$$E(\omega) = \lambda(\omega) + 2\mu(\omega)$$

  at the mesoscale using White's theory for patchy saturation.
- $\lambda(\omega), \mu(\omega)$: Lamé coefficients
- ω : angular frequency

Seismic modeling. Mesoscopic attenuation effects. IV

- Shear wave attenuation is taken into account using another relaxation mechanism related to the P-wave White mechanism to make the shear modulus

$$\mu(\omega)$$

complex and frequency dependent.

- These complex moduli define an equivalent viscoelastic model at the macroscale that take into account dispersion and attenuation effects occuring at the mesoscale.

Seismic modeling.

- Outside the Utsira formation and zones where only brine is present, the complex bulk and shear moduli as function of frequency were determined using a Zener model.

The dimensionless complex modulus of a Zener element is

$$Z(\omega) = \frac{\tau_\sigma}{\tau_\epsilon} \left[\frac{1 + i\omega\tau_\epsilon}{1 + i\omega\tau_\sigma} \right] \qquad \tau_\epsilon, \tau_\sigma : \text{relaxation times.}$$

The Zener model

The associated quality factor is

$$Q(\omega) = \frac{\mathbf{Re}(Z(\omega))}{\mathbf{Im}(Z(\omega))}$$

Its minimum value is equal to

$$Q_0 = \frac{2x}{x^2 - 1}, \qquad x = \left(\frac{\tau_\epsilon}{\tau_\sigma}\right)^{1/2} \tag{1}$$

and is located at $\omega_0 = \frac{1}{(\tau_\sigma \tau_\epsilon)^{1/2}}$.

If ω_0 **and** Q_0 **are chosen as data, then**

$$\tau_\epsilon = \frac{x}{\omega_0}, \qquad \tau_\sigma = \frac{x^{-1}}{\omega_0}, \quad \textbf{where } x \textbf{ solves} (1)$$

Seismic modeling. Constitutive Relations

$u = u(\omega) = (u_x(\omega), u_z(\omega))$: **Time-Fourier transform of the displacement vector**

Stress-strain relations in the space-frequency domain:

$$\sigma_{jk}(u) = \lambda(\omega)\nabla \cdot u\delta_{jk} + 2\mu(\omega)\varepsilon_{jk}(u),$$

$\sigma_{jk}(u)$: **stress tensor** $\varepsilon_{jk}(u)$: **strain tensor**

δ_{jk}: **Kroenecker delta**

$\lambda(\omega), \mu(\omega)$: **complex Lamé coefficients determined using White's theory.**

Seismic modeling. Phase velocities and attenuation coefficient.

For isotropic viscoelastic solids, the frequency dependent phase velocities $v_t(\omega)$ and quality factors $Q_t(\omega)$, $t = p, s$ are defined by the relations

$$v_t(\omega) = \left[\mathrm{Re}\left(\frac{1}{vc_t(\omega)}\right)\right]^{-1}, \; Q_t(\omega) = \frac{\mathbf{Re}(vc_t(\omega)^2)}{\mathbf{Im}(vc_t(\omega)^2)}, \quad t = p, s$$

$vc_p(\omega), vc_s$**: complex and frequency dependent compressional and shear velocities defined as**

$$vc_p(\omega) = \sqrt{\frac{E(\omega)}{\rho}}, \quad vc_s(\omega) = \sqrt{\frac{\mu(\omega)}{\rho}}$$

ρ**: bulk density.**

Seismic modeling. A viscoelastic model for wave propagation. I

Equation of motion in a 2D isotropic viscoelastic domain Ω with boundary $\partial\Omega$:

$$\omega^2 \rho u + \nabla \cdot \sigma(u) = f(x,\omega), \quad \Omega$$

First-order absorbing boundary condition:

$$-\sigma(u)\nu = i\omega \mathcal{D} u, \quad \partial\Omega,$$

$f(x,\omega)$ **external source**

Numerical Solution - Finite Element Method.

- The FE was computed at a selected number of frequencies in the range of interest using an iterative finite element domain decomposition procedure.
- The time domain solution was obtained using a discrete inverse Fourier transform.
- To approximate each component of the solid displacement vector we employed a nonconforming finite element space which generates less numerical dispersion than the standard bilinear elements.
- The error measured in the energy norm is of order $h^{1/2}$, where h is the size of the computational mesh.

A petrophysical model of the Utsira formation.

We consider a 2D model of the Utsira formation constructed using an initial porosity ϕ_0 (at hydrostatic pore pressure) and the clay content C of the formation.

The model was constructed using iteratively a wave propagation simulator to fit the avalaible seismic data. It has 400 m thickness (top at 800 m and bottom 1200 m b.s.l.).

Within the formation, there are several mudstone layers which act as barriers to the vertical motion of the CO_2.

A petrophysical model considering pressure and saturation variations. I

Our shaly sand model was generated using fractal realizations of the porosity ϕ_0 at hydrostatic pressure p_H and clay content C.

- **To determine the porosity ϕ as function of the fluid pressure p_f (obtained from the flow simulator) we solved the nonlinear equation:**

$$\frac{(1-\phi_c)}{K_s}(p_f - p_H) = \phi_0 - \phi + \phi_c \ln \frac{\phi}{\phi_0},$$

ϕ_c : **critical porosity**

A petrophysical model considering pressure and saturation variations. II

- The bulk modulus of the dry matrix was determined using a Krief model ($A = 4.5$):

$$K_m = K_s (1 - \phi)^{A/(1-\phi)}.$$

  Here K_s denote the bulk modulus of the solid grains.

- Assuming a Poisson medium the shear modulus of the solid grains is $\mu_s = 3K_s/5$ and the following relation gives the shear modulus of the dry matrix

$$\mu_m = \mu_s (1 - \phi)^{A/(1-\phi)}.$$

A petrophysical model considering pressure and saturation variations. III

- **Horizontal κ_x and vertical permeability κ_z,**

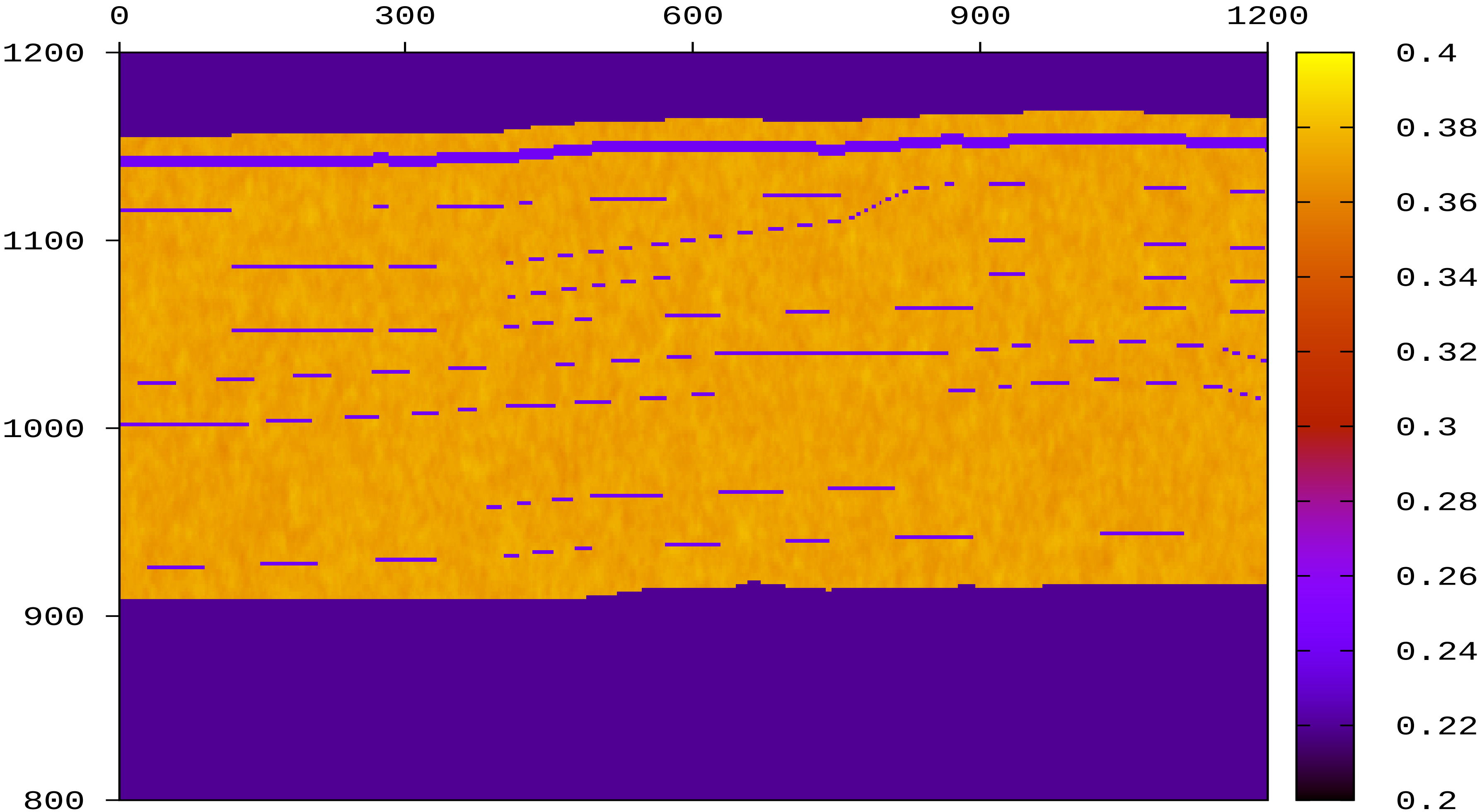
$$\frac{1}{\kappa_x} = \frac{45(1-\phi)^2}{\phi^3}\left(\frac{(1-C)^2}{R_q^2} + \frac{C^2}{R_c^2}\right)$$

R_q, R_c: average radii of sand and clay particles

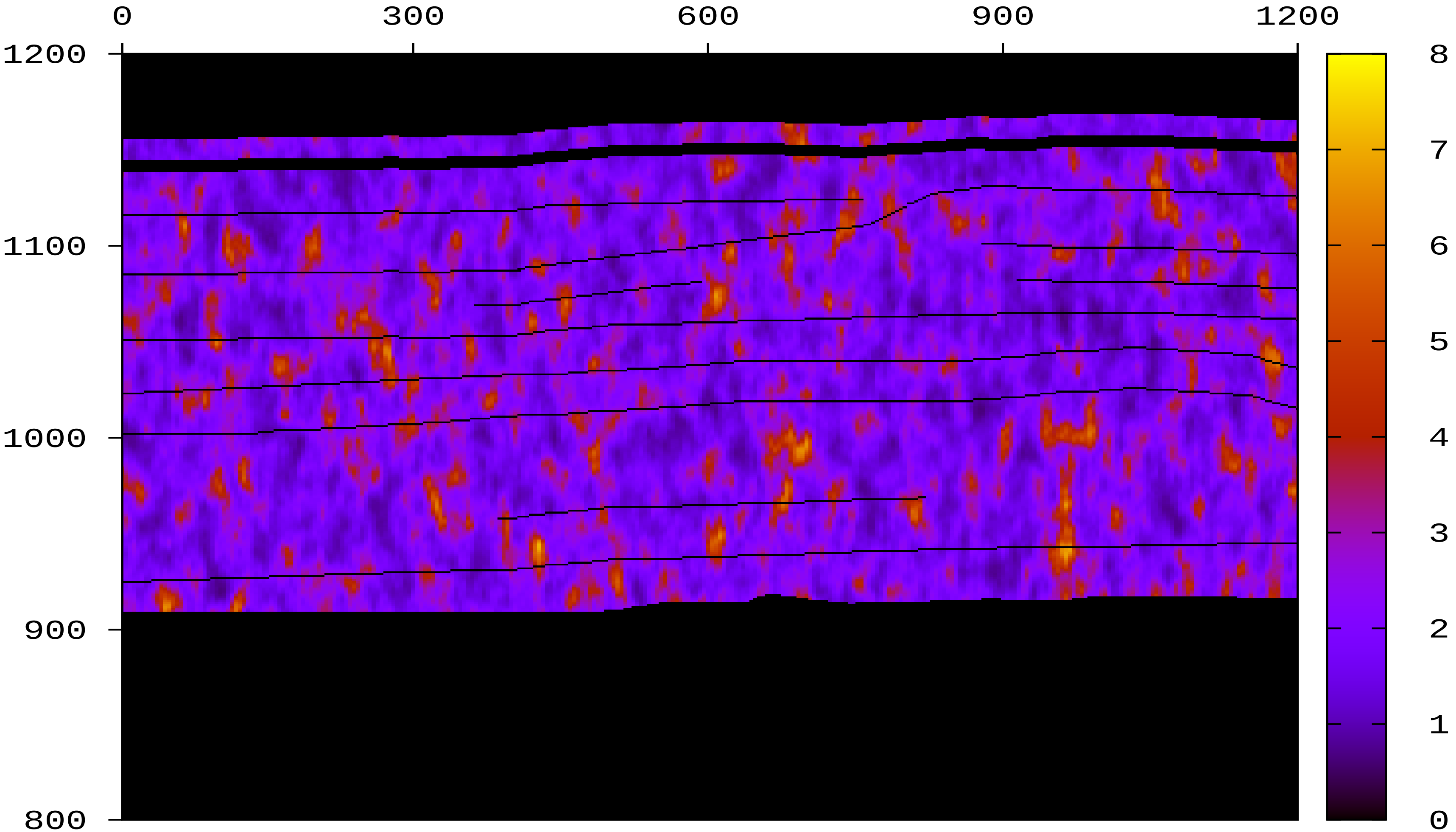
$$\frac{\kappa_x}{\kappa_z} = \frac{1-(1-0.3a)\sin\pi S_b}{a(1-0.5\sin\pi S_b)}$$

a: permeability-anisotropy parameter

Porosity map of the formation.



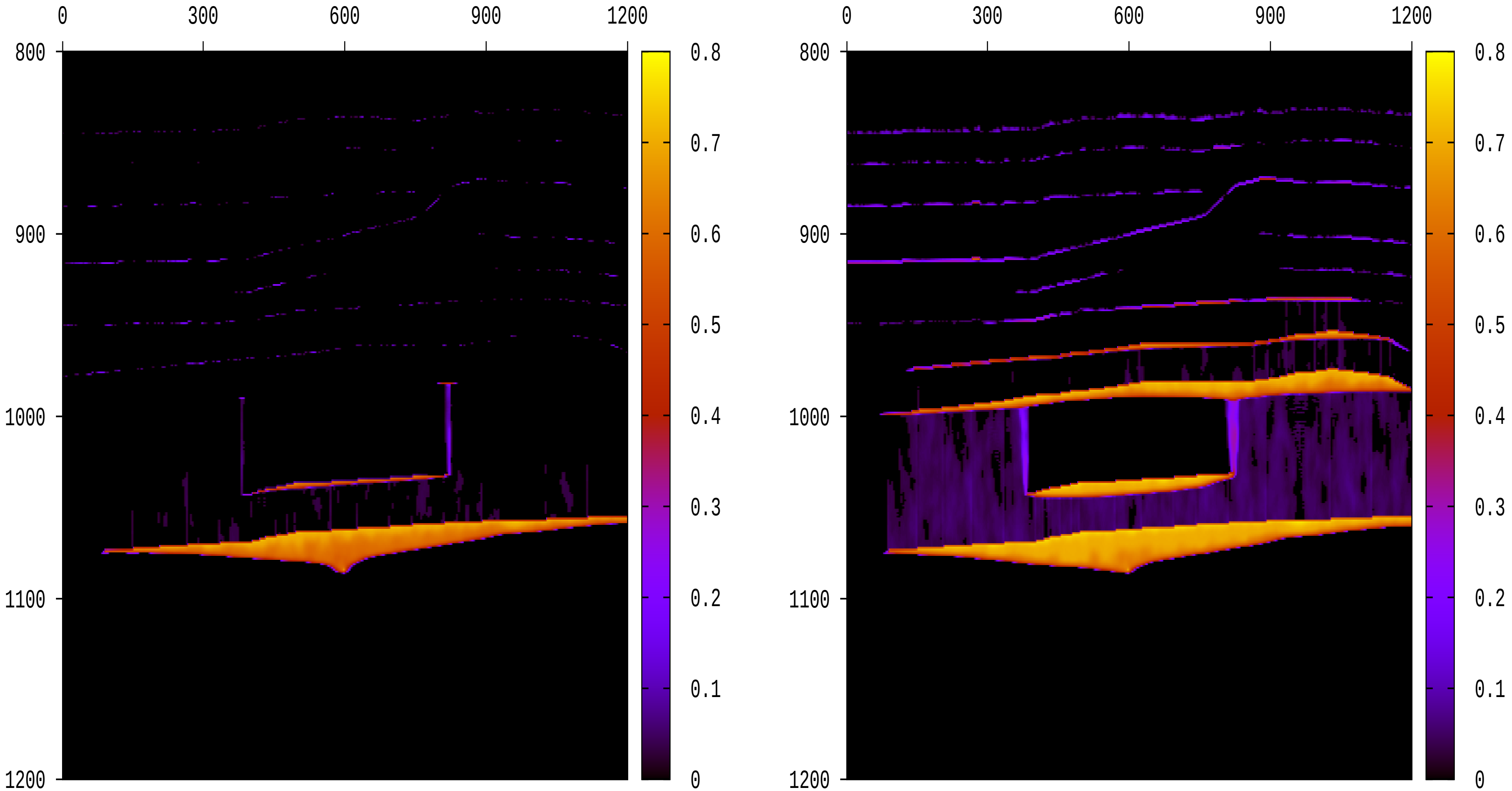
Permeability map (Darcy units) of the formation.



CO_2 Injection model. I

- At the Utsira formation CO_2 is injected at a constant flow rate of one millon tons per year.
- The injection point is located at the bottom of the Utsira formation: $x = 600$ m, $z = 1060$ m.
- The viscosity, density and bulk modulus of CO_2 needed for the flow simulator were obtained from the Peng-Robinson equations as a function of temperature and pore pressure.

Injection Modeling. II

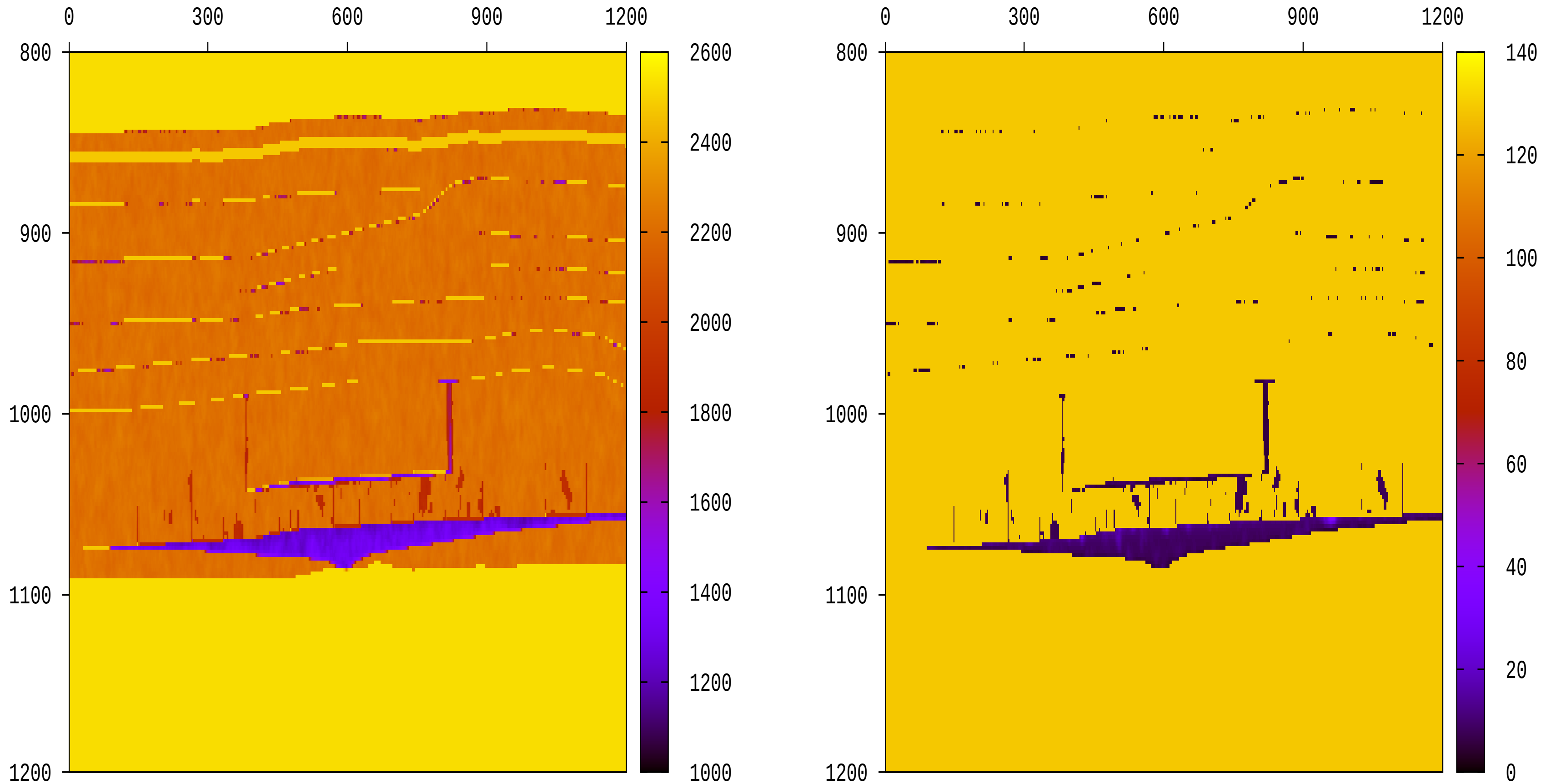


CO_2 saturation distribution after 2 years (left) and 6 years(right) of CO_2 injection

Seismic Model.

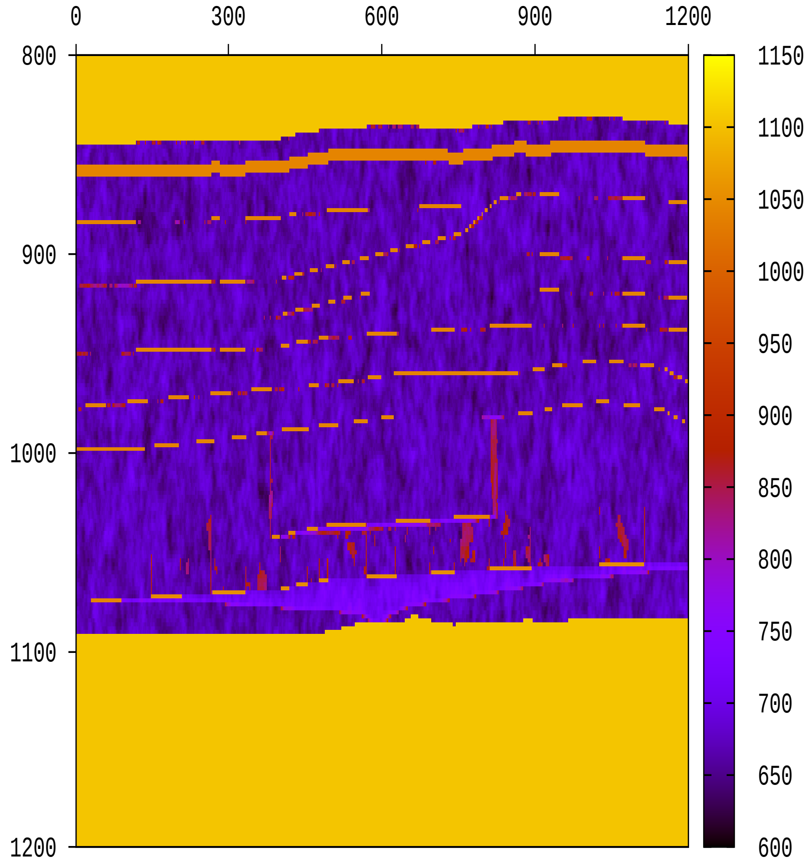
- The equivalent viscoelastic model, determined using White's model for patchy saturation, assumes an effective single-phase fluid.
- Effective fluid density, viscosity and bulk modulus were obtained using the properties of the CO_2 and brine weighted by the corresponding saturations computed by the BOAST flow simulator.
- The next Figure displays maps of of P-wave phase velocity $v_p(\omega)$ and attenuation coefficient $Q_p(\omega)$ at 50 Hz after 2 years of CO_2 injection.

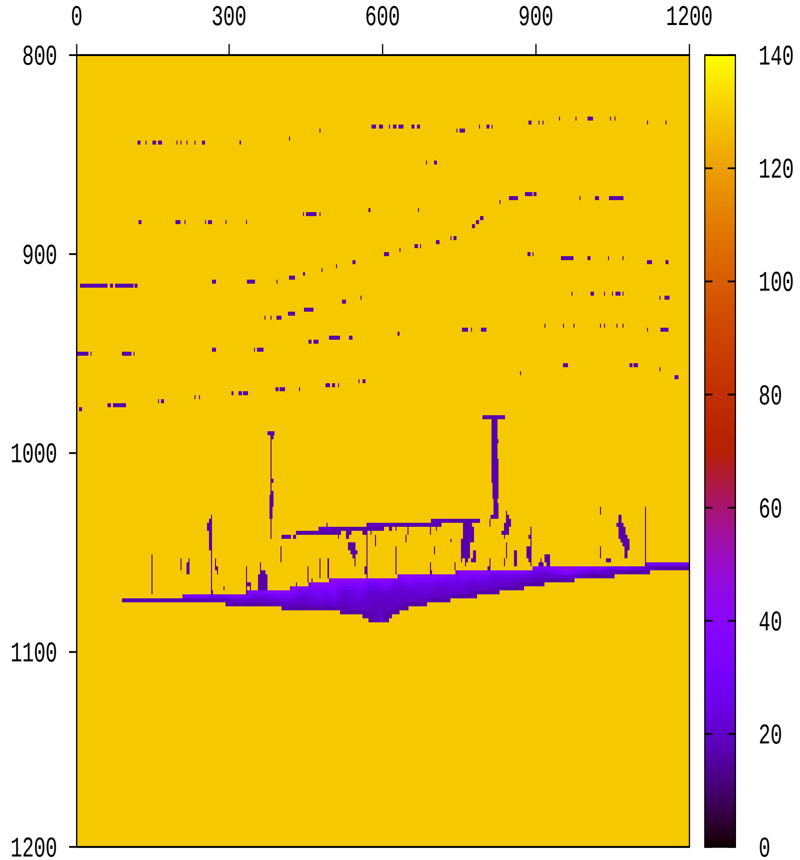
P-wave phase velocity $v_p(\omega)$(m/s) (left) and attenuation coefficient $Q_p(\omega)$ (right) at 50 Hz.



Observe a decrease in P- wave velocity in zones of CO_2 accumulation (left) and a corresponding decrease in attenuation coeefficient Q_p (right) .

S-wave phase velocity $v_s(\omega)$(m/s) (left) and attenuation coefficient $Q_s(\omega)$ (right) at 50 Hz.



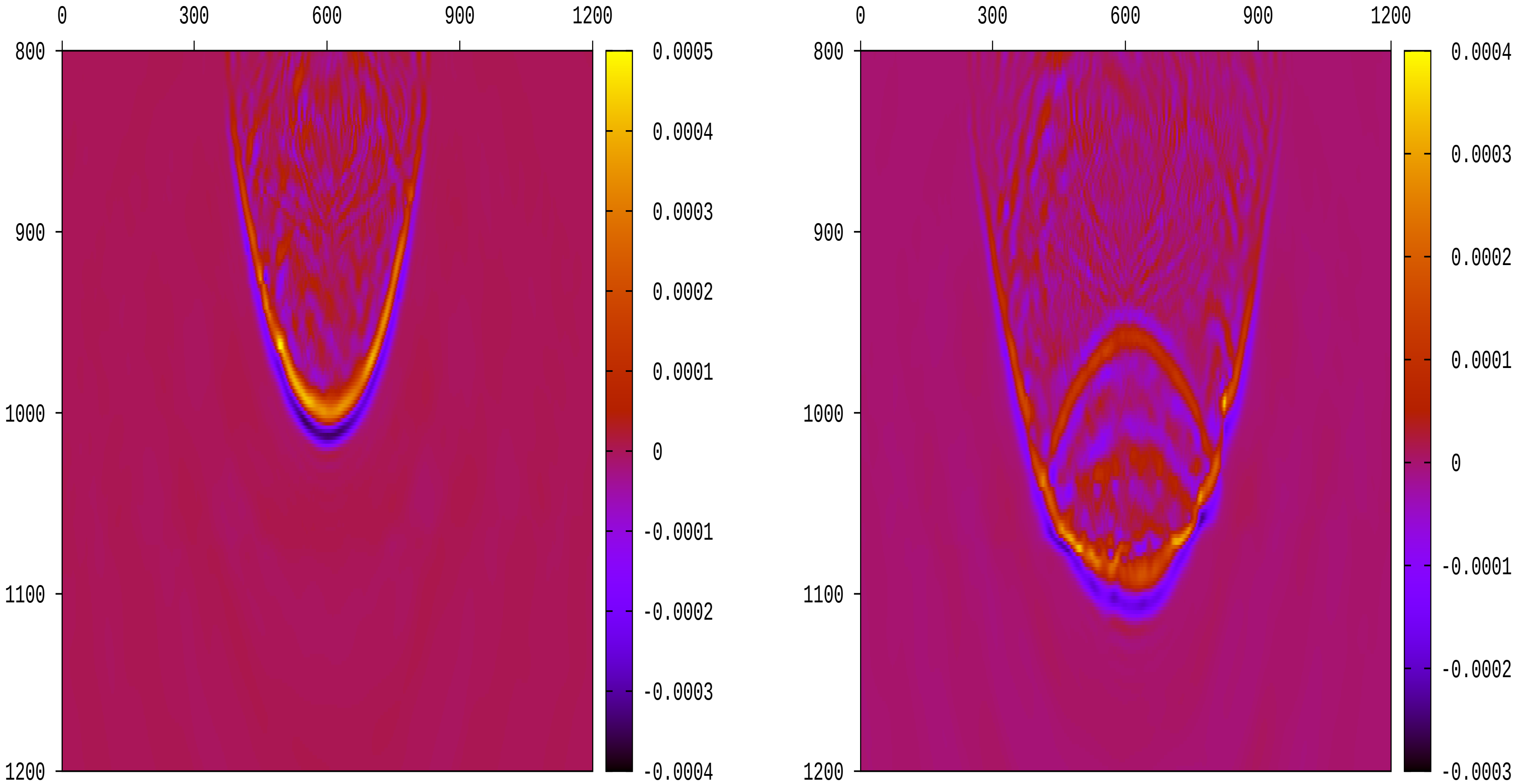


Observe a decrease in S- wave velocity in zones of CO_2 accumulation (left) and a corresponding decrease in attenuation coeefficient Q_s (right) .

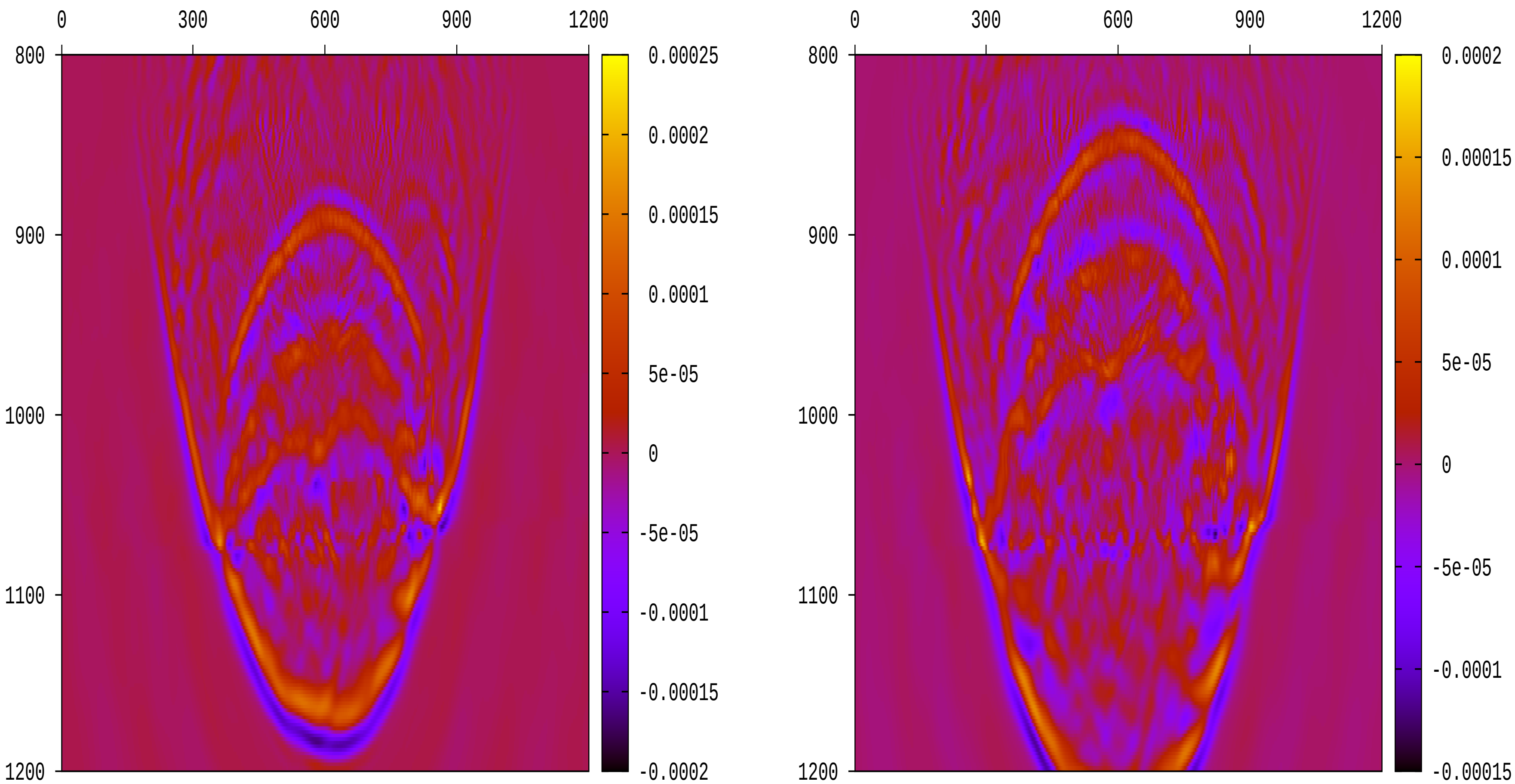
Seismic Monitoring.

- To analyze the capability of seismic monitoring to identify zones of CO_2 accumulation, the model was excited with compressional point and line sources located at the top of the model (800 m depth) with central frequency 50 Hz.
- The viscoelastic wave equation was solved for 200 frequencies. The time domain solution was obtained using an inverse Fourier transform.
- The next Figures display snapshots at several steps of the simulations. Other Figures show time histories before and after 2 and 6 years of CO_2 injection.

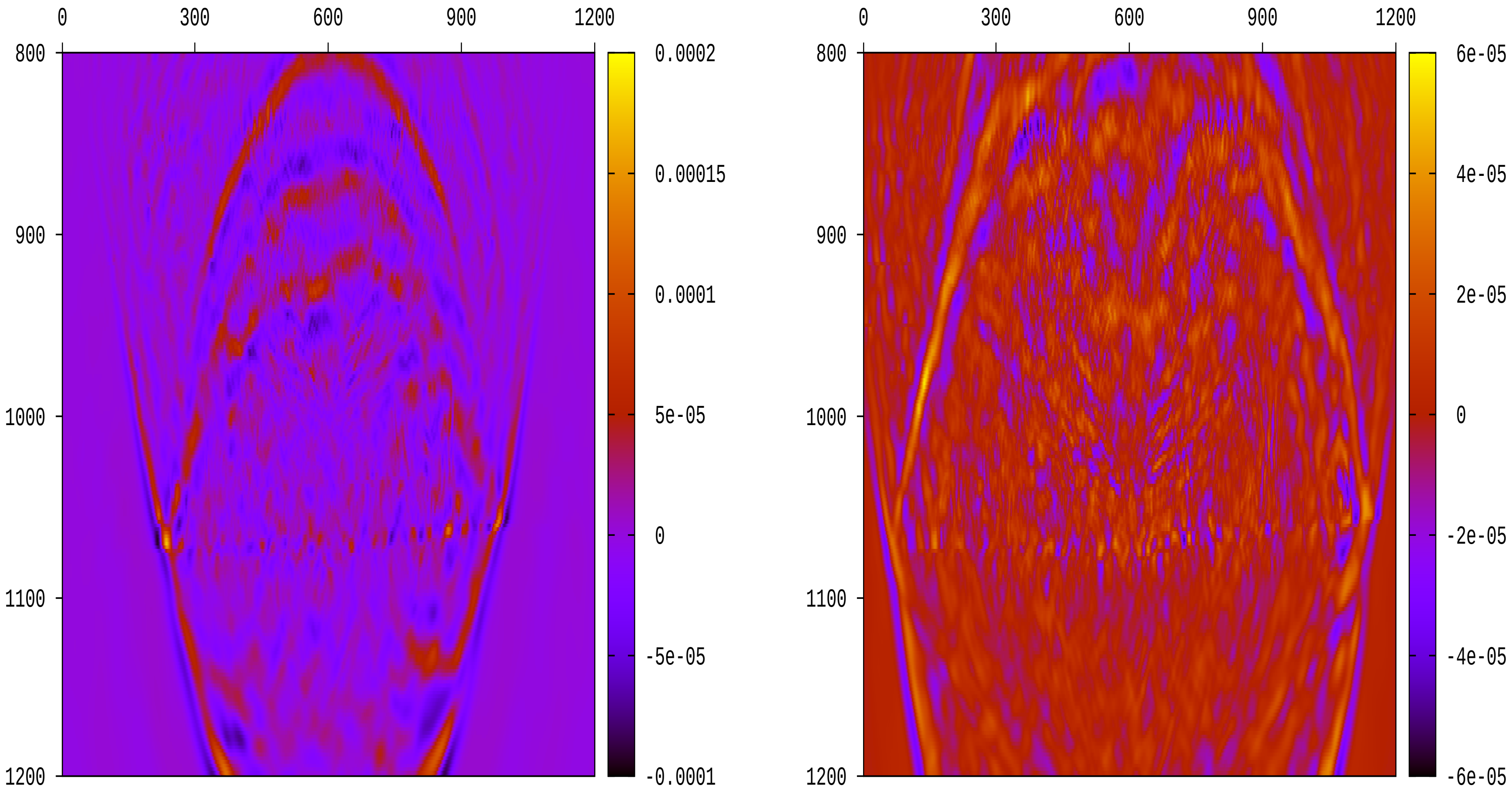
Snapshots of z-component of particle velocity at 100 ms (left) and 150 ms (right). Point Source.



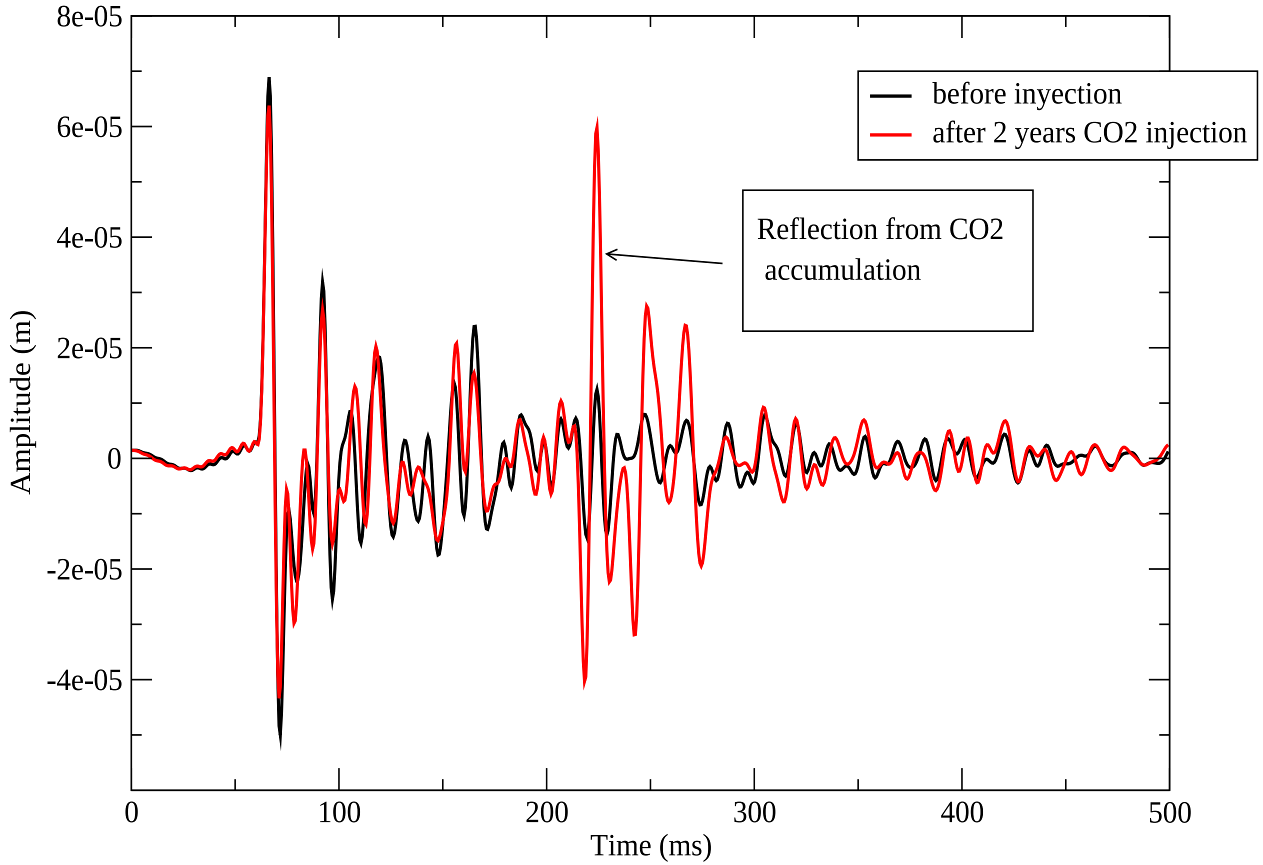
Snapshots of z-component of particle velocity at 180 ms (left) and 200 ms (right). Point Source.



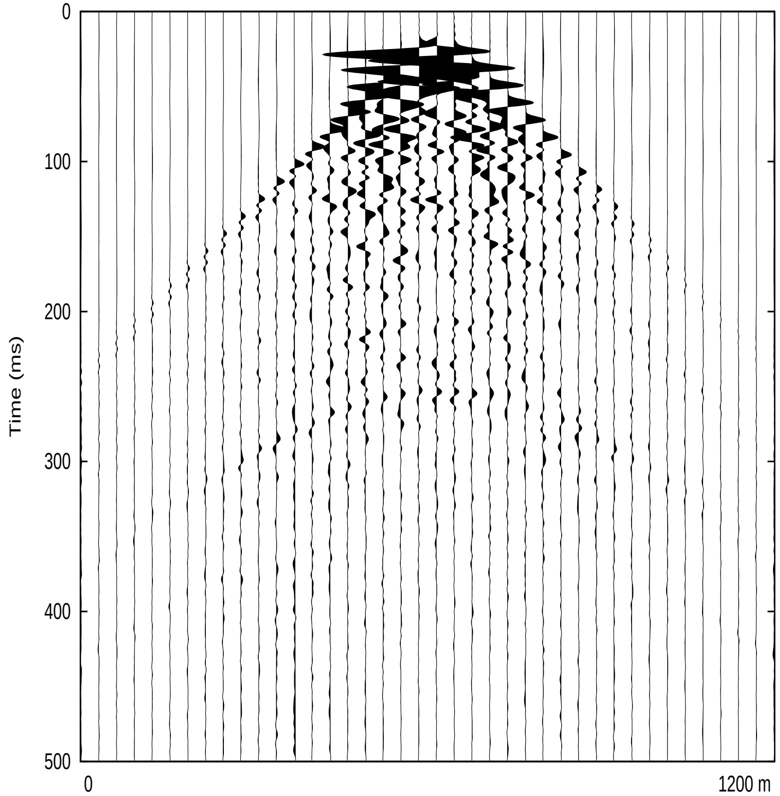
Snapshots of z-component of particle velocity at 220 ms (left) and 280 ms (right). Point Source.

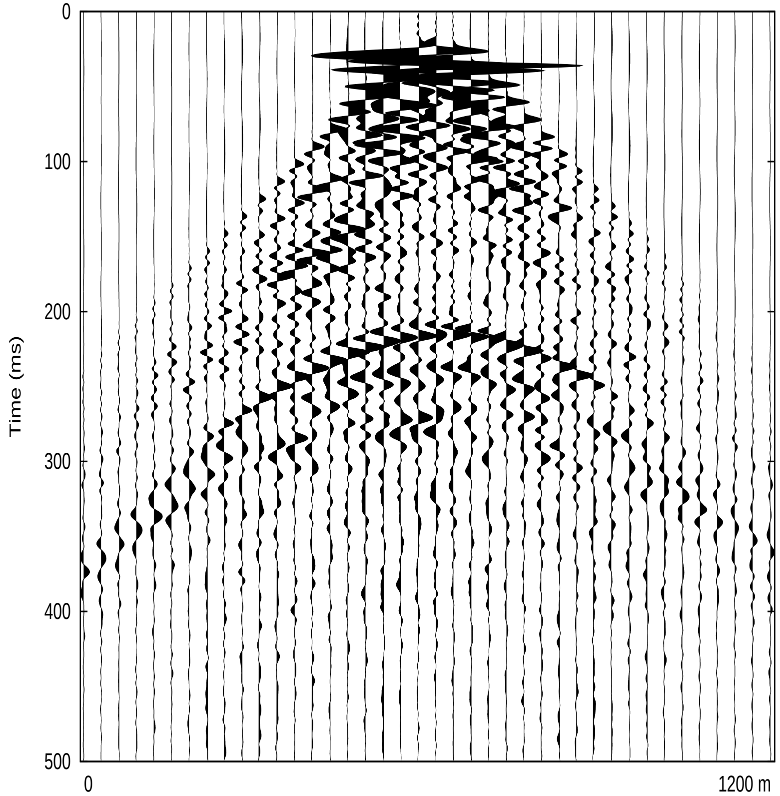


Time histories of the z-component of the particle velocity measured at the top of the model before and after 2 years of CO_2 injection. Point Source



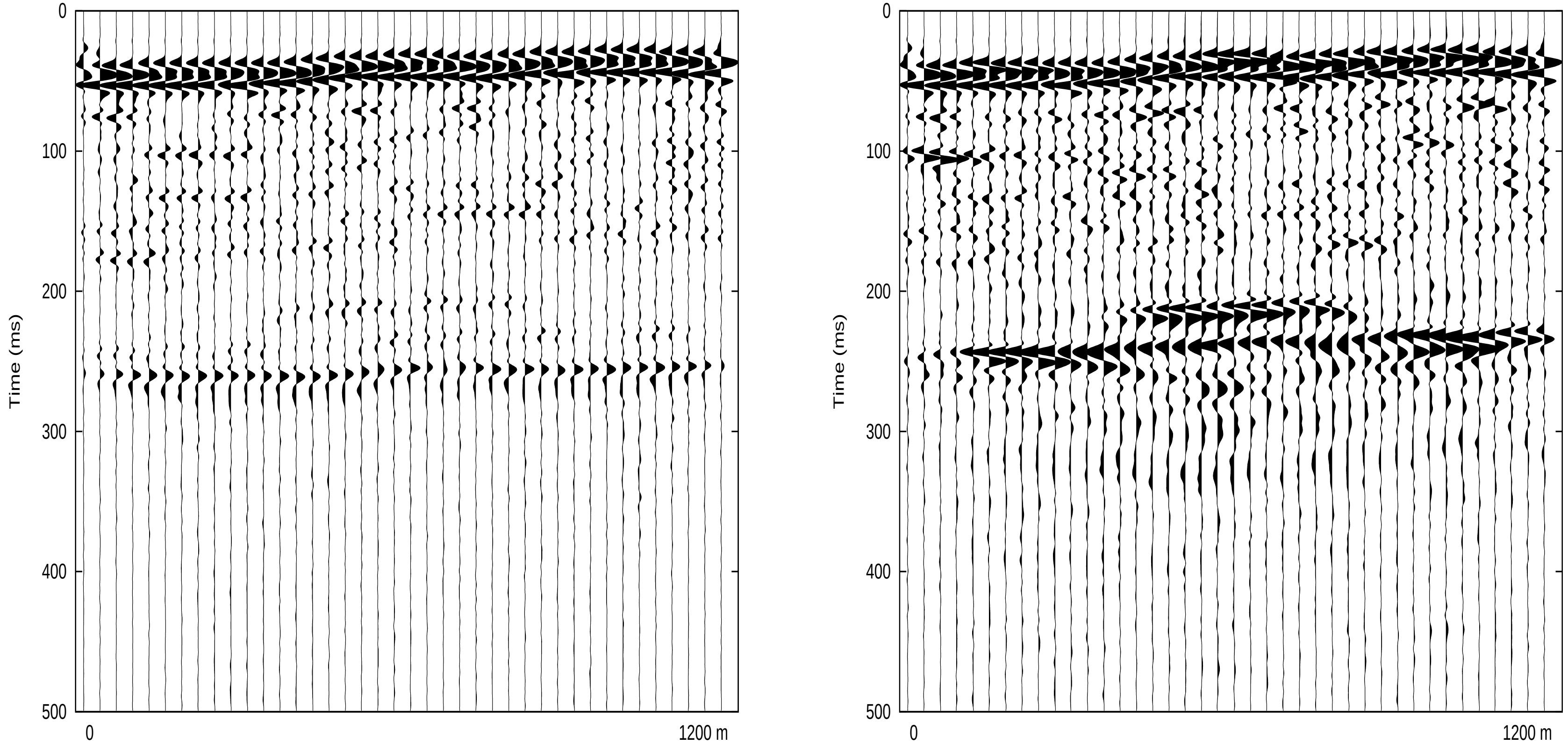
Time histories before and after 2 years of CO_2 injection. Point Source. Both figures are shown with the SAME SCALE





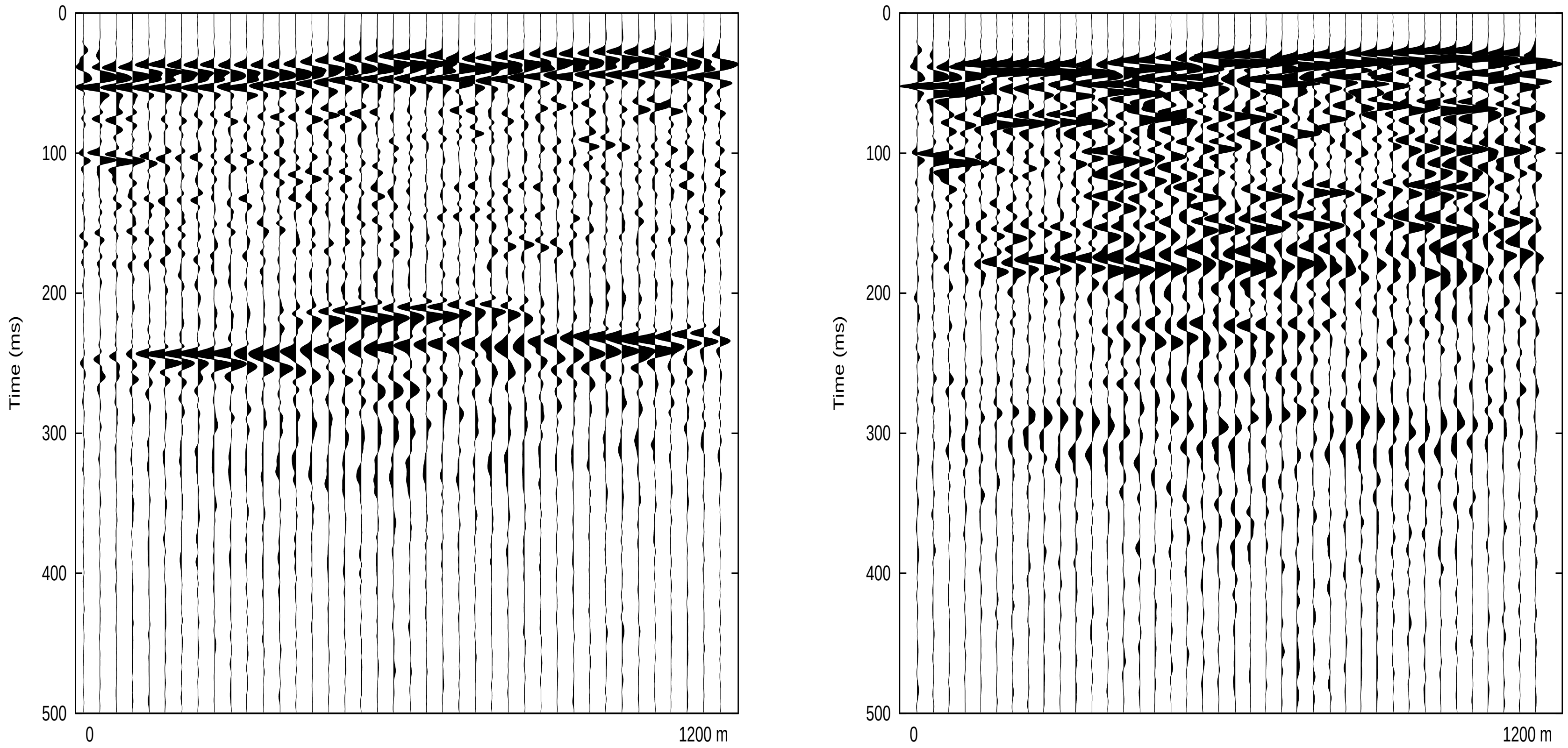
Traces of the z-component of the velocity before (left) and after 2 years (right) CO_2 injection. The first strong and second weak arrivals seen on the left Figure come from the base and top of the Utsira. The strong later arrivals seen on the right Figure are due to P-waves reflected at the CO_2 accumulations and the base of the Utsira.

Time histories before and after 2 years of CO_2 injection. Line Source. Both figures are shown with the SAME SCALE



Traces of the z-component of the particle velocity before (left) and after 2 years (right) CO_2 injection. The two arrivals seen on the left Figure come from the base and top of the Utsira. The strong later arrivals seen on the right Figure are due to P-waves reflected at CO_2 accumulations and the base of the Utsira.

Time histories before and after 2 and 6 years of CO_2 injection. Line Source



Traces of the z-component of the particle velocity after 2 years (left) and 6 years (right) of CO_2 injection. The earlier arrivals on the right Figure are due to waves reflected at the CO_2 accumulations below the shalow mudstone layers.

CONCLUSIONS

- The numerical examples show the effectiveness of combining multiphasic flow simulators in porous media with seismic monitoring to map the spatio-temporal distribution of CO_2 after injection.
- The wave propagation model includes attenuation and dispersion effects due to mesoscopic scale heterogeneities using White's theory.
- This methodology constitutes a valuable tool to monitor the migration and dispersal of the CO_2 plume and to analyze storage integrity, providing early warning should any leakage occurs.

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THANKS FOR YOUR ATTENTION !!!!!!