Multiphase fluid flow and time lapse seismics

UNLP, 11 Octubre de 2012

.

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.

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 pressure and saturation.

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 this model, CO_2 may dissolve in the brine but the brine 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

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

An algorithm developed by Hassanzadeh (2008) can be used to estimate the above PVT data.

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

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

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

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

Two algebraic equations complete the system:

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

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

- One important mechanisms of P-wave attenuation and dispersion in fluid-saturated porous media at seismic frequencies (1-100 Hz) is known as mesoscopic loss.
- It is caused by heterogeneities in the solid frame and saturant fluids larger than the pore size but much smaller than the predominant wavelengths (mesoscopic-scale heterogeneities).
- These effects are caused by equilibration of wave-induced fluid pressure gradients via a slow-wave diffusion process (Type II Biot waves).

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: 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. III

- 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 occurring at the mesoscale.

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

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

$vc_t(\omega)$**: 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.

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 solution of the viscoelastic wave equation with the given absorbing boundary condition was obtained at a finite 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 generate **less numerical dispersion than the standard bilinear elements**.
- The error associated with this numerical procedure measured in the energy norm is of order $h^{1/2}$, where h is the size of the computational mesh.

A model of the Utsira formation. I

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

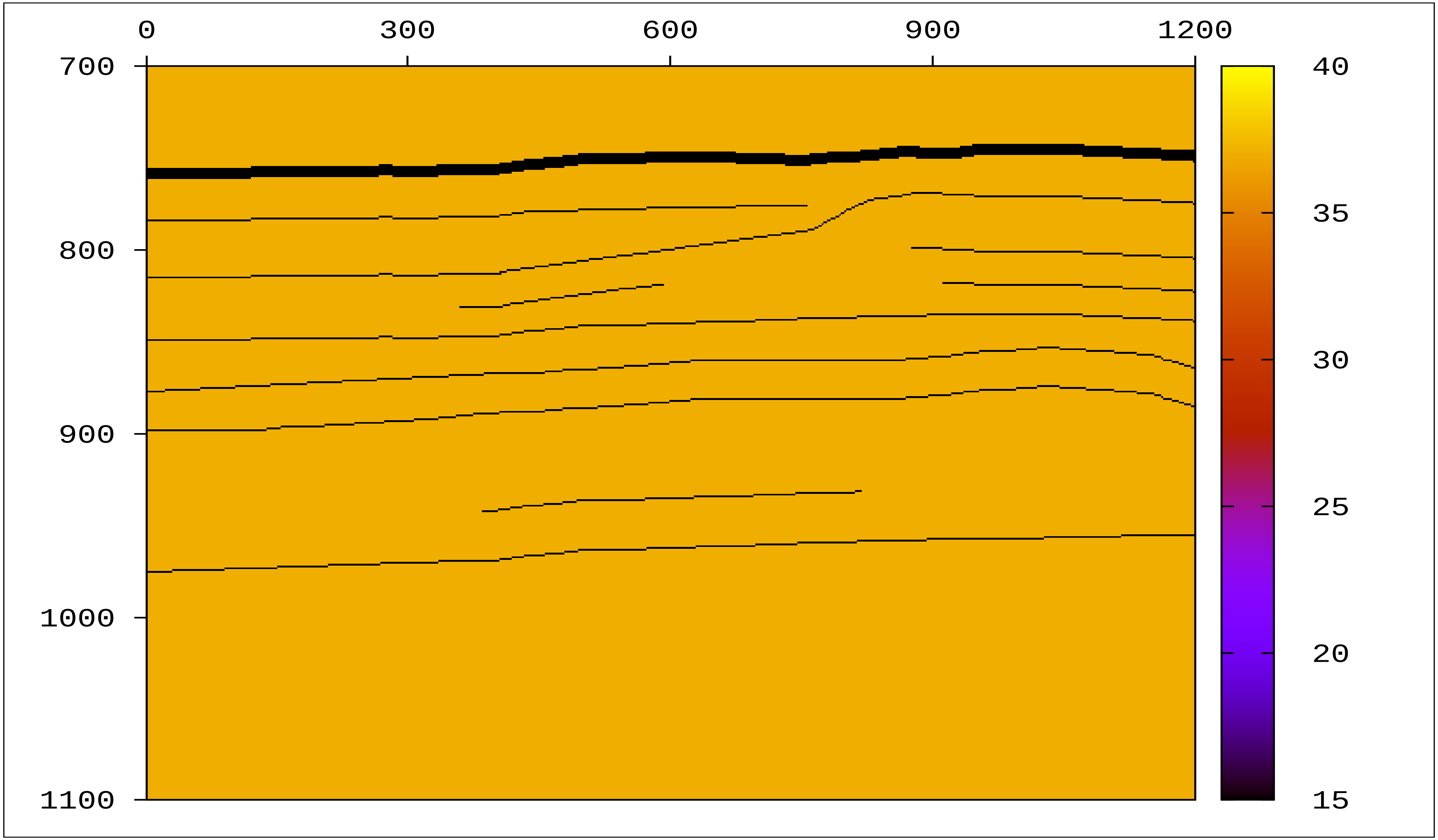
The model was constructed using iteratively a wave propagation simulator to fit the avalaible seismic data. It has 400 m thickness (top at 700 m and bottom 1100 m b.s.l.).

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

A model of the Utsira formation. II

- Extraction or injection of fluids in underground formations results in pore pressure changes and associated changes in effective stress.
- To take into account these effects, as a first step we used an uncoupled fluid-flow and geomechanics approach as follows.
- The porosity and dry bulk and shear modulus of the formation were obtained using a pore pressure-porosity relationship, combined with the Krief model assuming a Poisson medium (with an initial hydrostatic pore presure).
- For the anisotropic permeability, we computed the horizontal permeability $\kappa_{\mathbf{x}}$ and the vertical permeability $\kappa_{\mathbf{z}}$ using a model depending on porosity and clay content.
- The next Figure displays a map of the initial porosity of the formation.

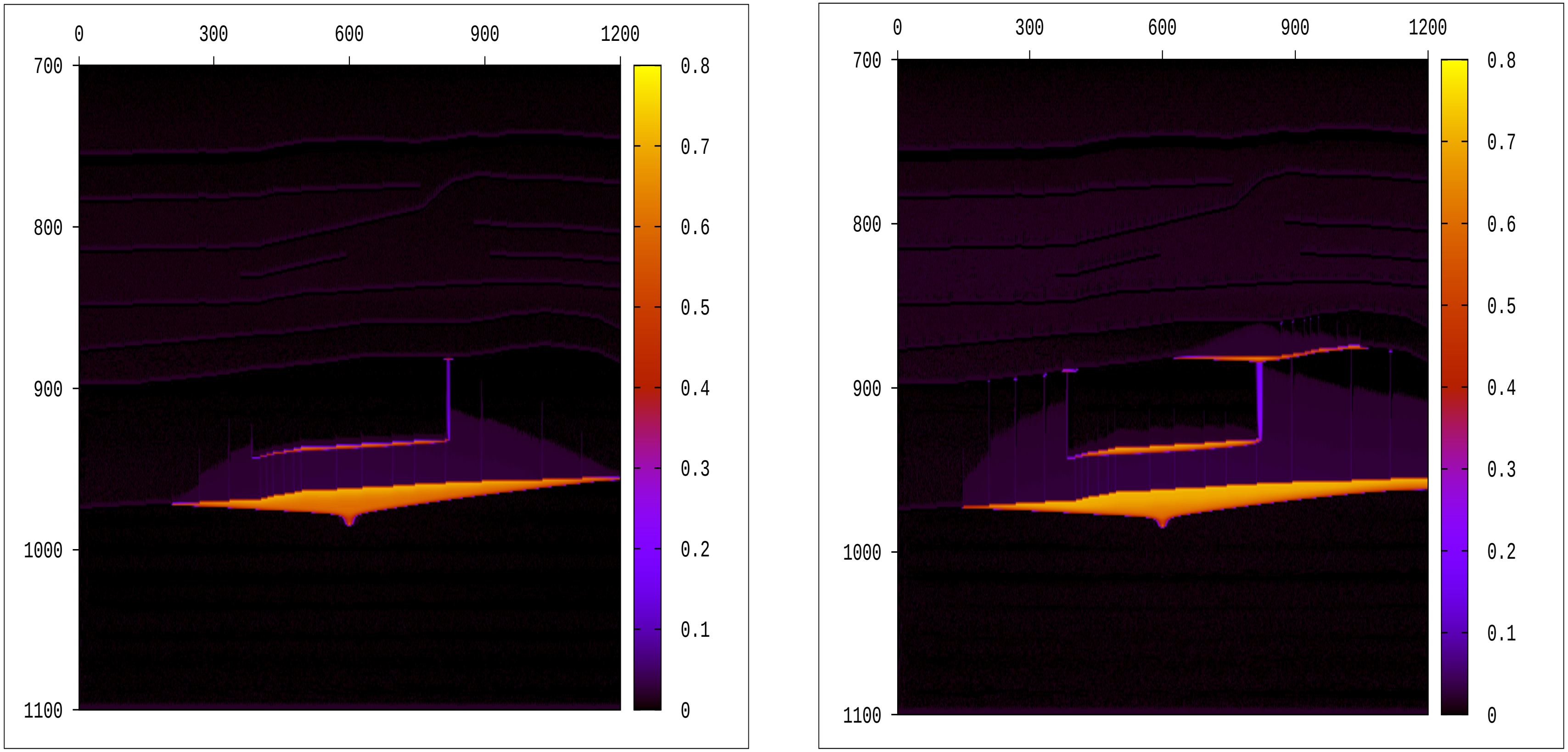
Porosity map of the Utsira formation.



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

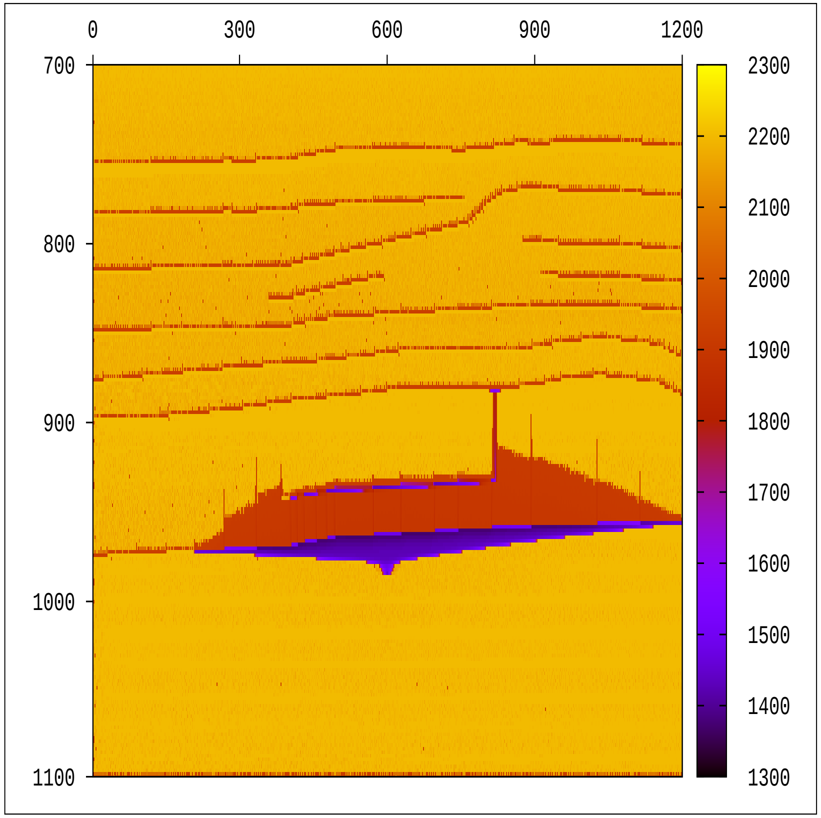


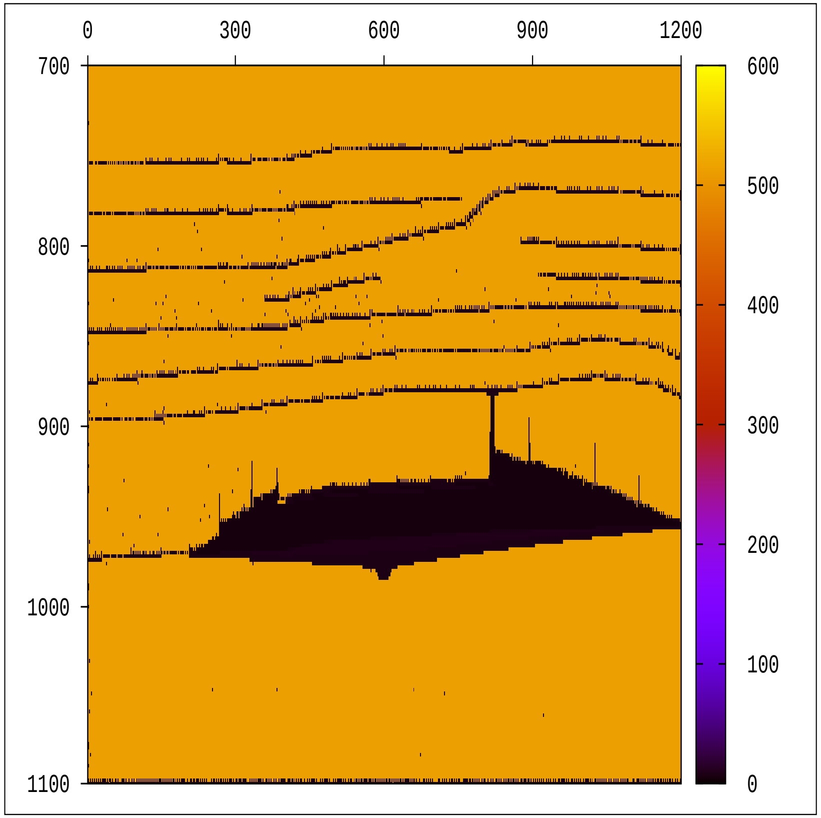
CO_2 saturation distribution after 2 years (left) and 4 years(right) of CO_2 injection

The 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 P-wave phase velocity v_p (left) and attenuation coefficient $1000/Q_p$ (right) at 75 Hz after 2 years of CO_2 injection.

Phase velocity v_p and attenuation coefficient $1000/Q_p$ at 75 Hz.



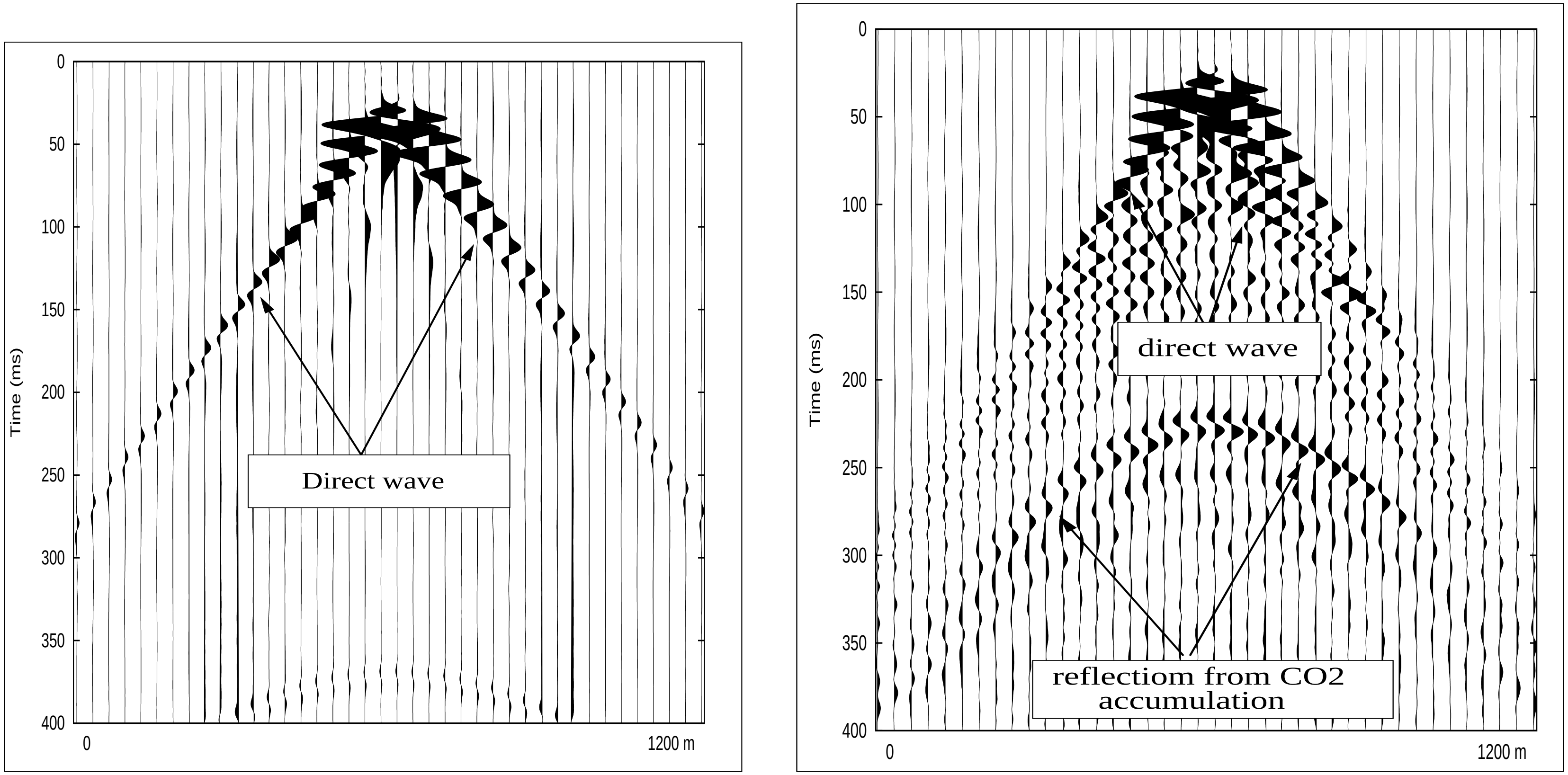


Observe a decrease in P- wave velocity v_p in zones of CO_2 accumulation (left) and a corresponding increase in attenuation coefficient $1000/Q_p$ (right) .

Seismic Monitoring.

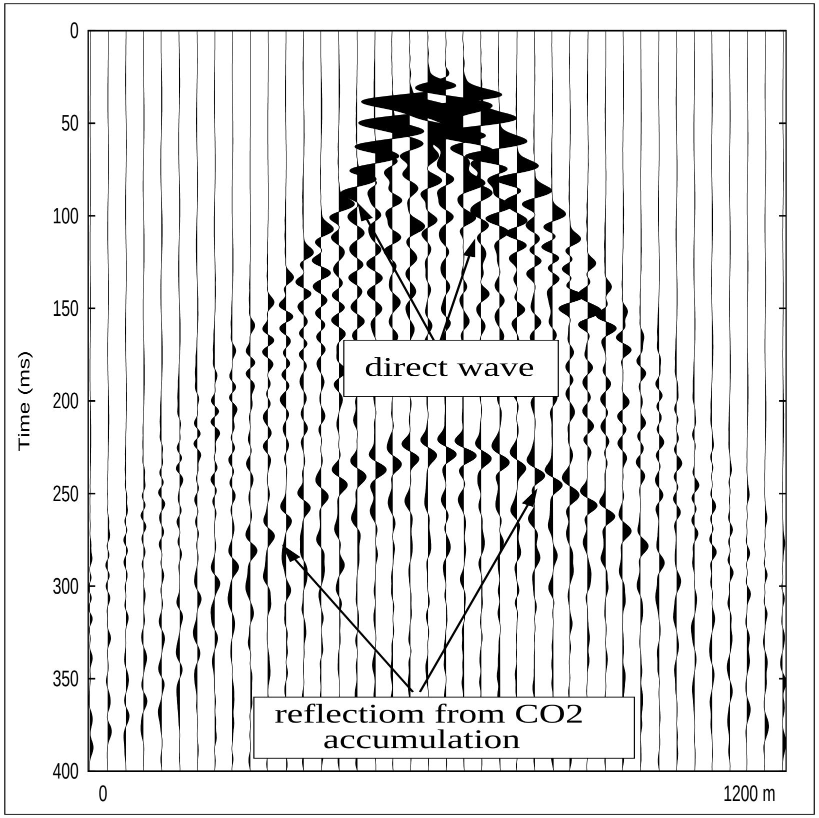
- To analyze the capability of seismic monitoring to identify zones of CO_2 accumulation, the model is excited with a compressional point source located at $x = 600$ m, $z = 710$ m, with central frequency 75 Hz and highest frequency 150 Hz.
- The viscoelastic wave equation is solved for 150 frequencies, and the time histories were obtained using an approximate inverse Fourier transform.
- The next Figures display time histories measured near the surface before and after 2 an 4 years of CO_2 injection.

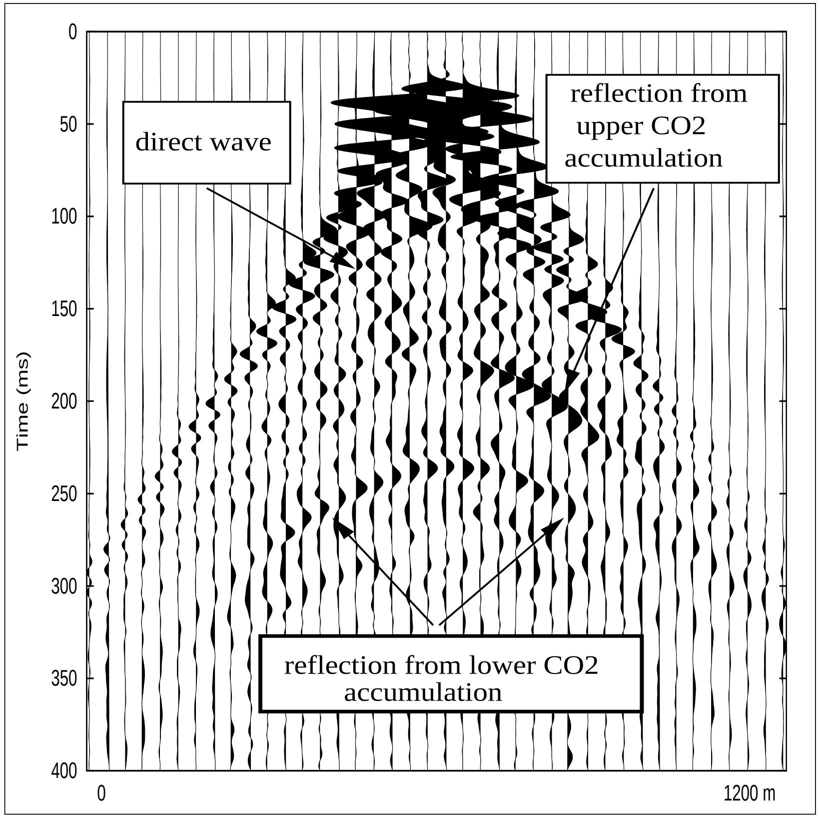
Time histories before and after 2 years of CO_2 injection



Traces of the z-component of the displacement before (left) and after 2 years (right) of CO_2 injection. The upper reflection is due to the direct wave coming from the point source. The second reflection is due to the CO_2 accumulation below the deepest mudstone layer.

Time histories before and after 2 and 4 years of CO_2 injection





Traces of the z-component of the displacement after 2 years (left) and 4 years (right) of CO_2 injection. The lower reflection is due to the deepest CO_2 accumulation. The earlier reflection to the right is due to the upper CO_2 accumulation

CONCLUSIONS.

- The numerical examples show the effectiveness of combining multiphase flow simulators in porous media with seismic monitoring to map the spatio-temporal distribution of CO_2 after injection.
- The flow simulator takes into account porosity and permeability changes associated to pore pressure changes caused by the fluid injection.
- The wave propagation model includes attenuation and dispersion effects due to mesoscopic scale heterogeneities using White's theory.

FUTURE WORK.

- Future work includes the inclusion of coupled fluid flow and deformation process since the pore compressibility

$$C_{pp} = \frac{1}{\phi}\left(\frac{1}{K_m} - \frac{1+\phi}{K_s}\right).$$

is not sufficient to take into account all geomechanical effects (see for example Gutierrez, J. Engrg. Mechanics, 2002).