Società Italiana di Fisica
101° Congresso Nazionale

Roma 21 – 25 Settembre 2015

Numerical modeling and tomographic inversion for CO_2 monitoring in a saline aquifer

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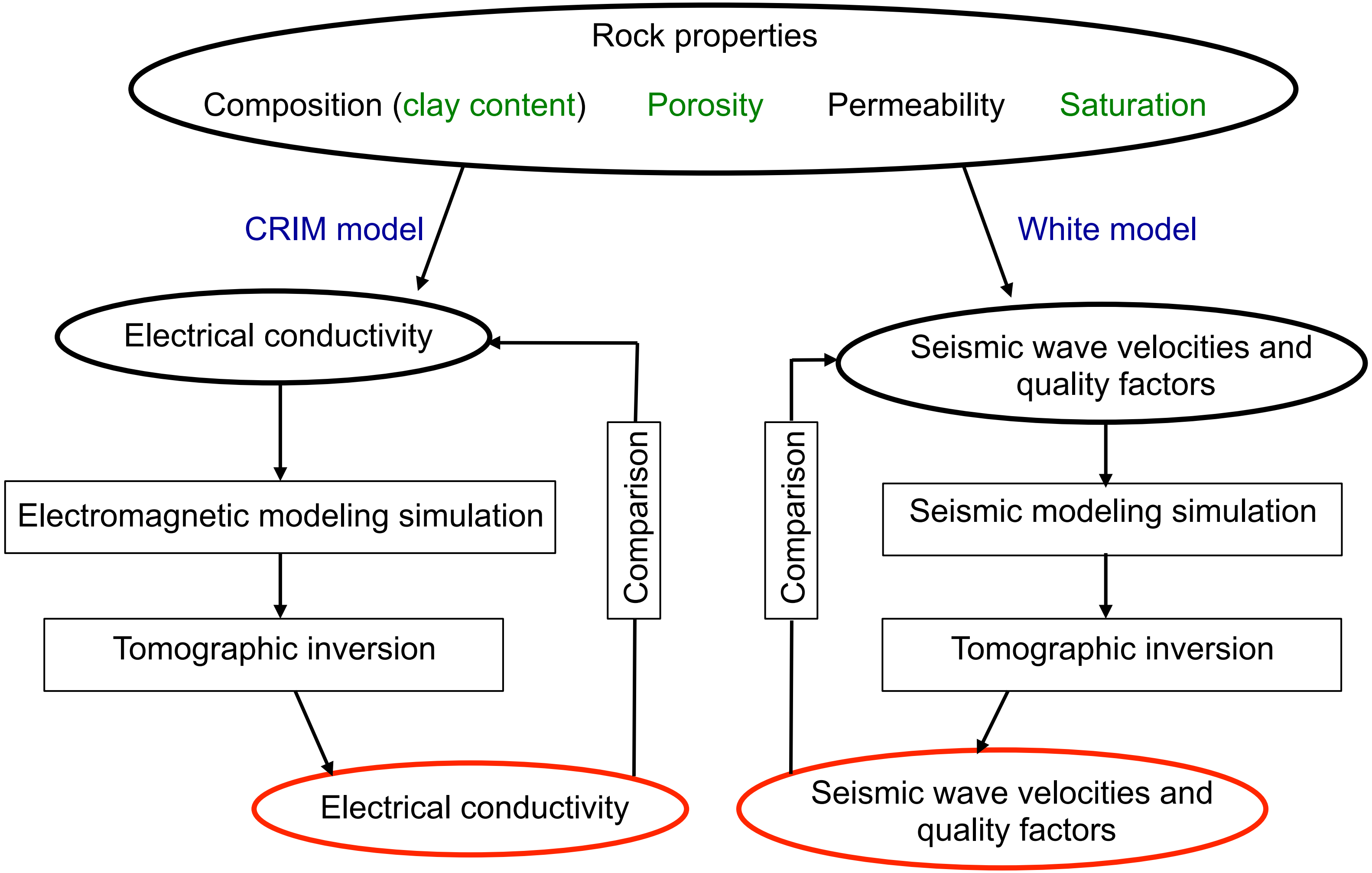
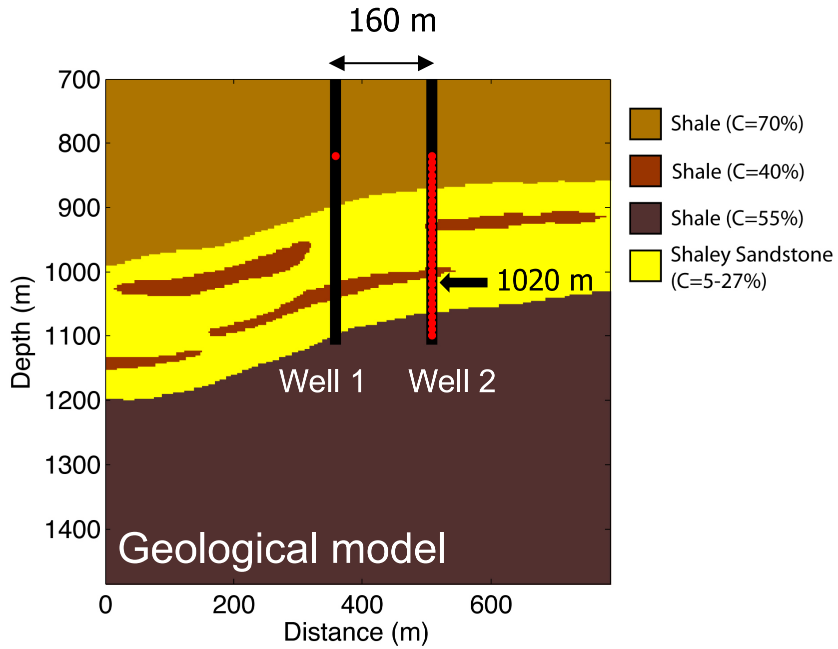
Methodology

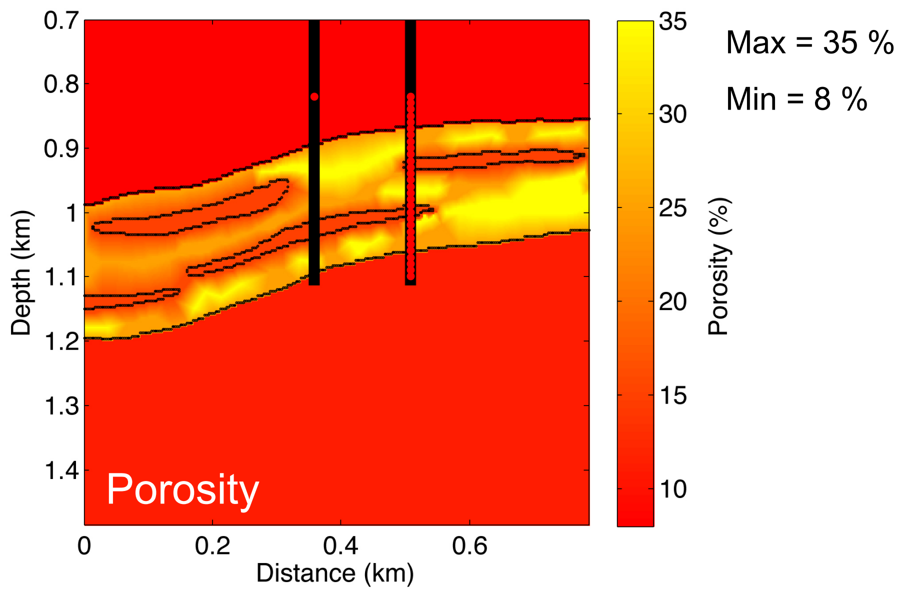
We present an combined rock-physics methodology of electromagnetic (EM) and seismic wave propagation for the detection and monitoring of CO_2 in cross-well experiments.

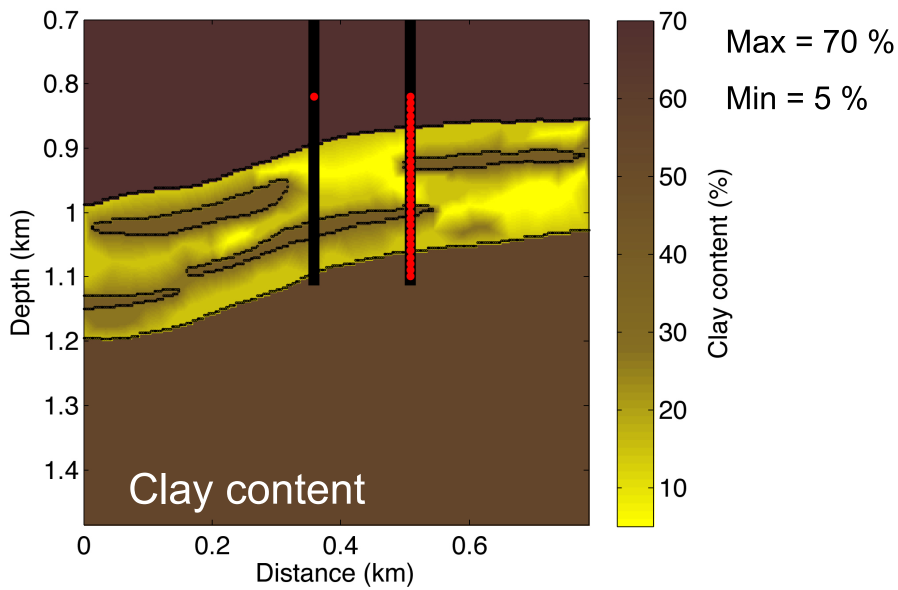


Assumed models



Aquifer depth: 900 – 1200 m
Aquifer thickness: ≈ 200 m
Well 1: 15 sources (dz =20 m)
Well 2: injection and 29 receivers (dz =10 m)





Permeability

Rock composition
(clay content)

Porosity

Permeability

$$\kappa_q = \frac{R_q^2\phi^3}{45(1-\phi)^2(1-C)} \qquad \kappa_c = \frac{R_c^2\phi^3}{45(1-\phi)^2 C},$$

$$\frac{1}{\kappa} = \frac{1-C}{\kappa_q} + \frac{C}{\kappa_c} = \frac{(1-\phi)^2}{A\phi^3}\left[(1-C)^2 + C^2B^2\right]$$

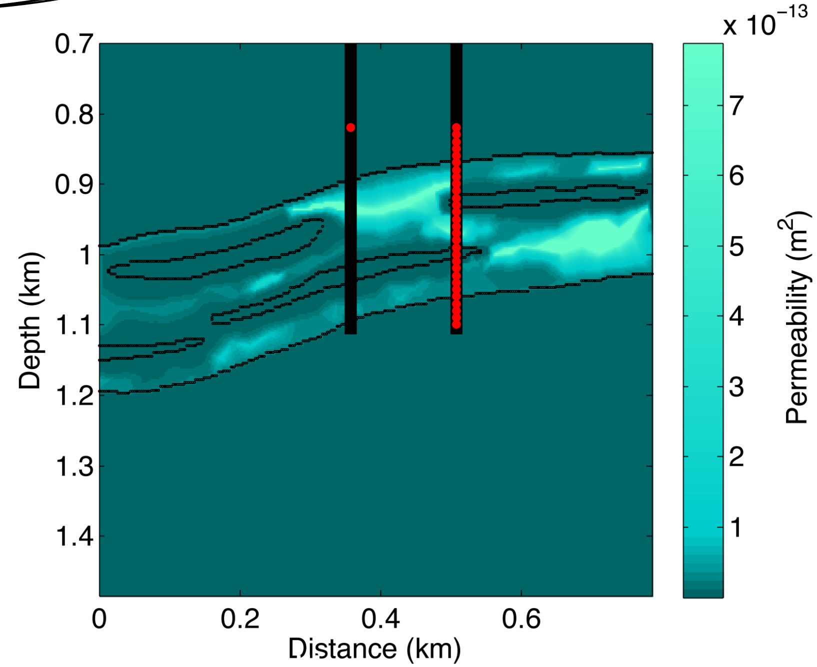
$$A = R_q^2/45 \qquad B = R_q/R_c$$

κ_q, κ_c = sandy and shaly matrices partial permeabilities

R_q, R_c = average radii of sand and clay particles

C = clay content

ϕ = porosity



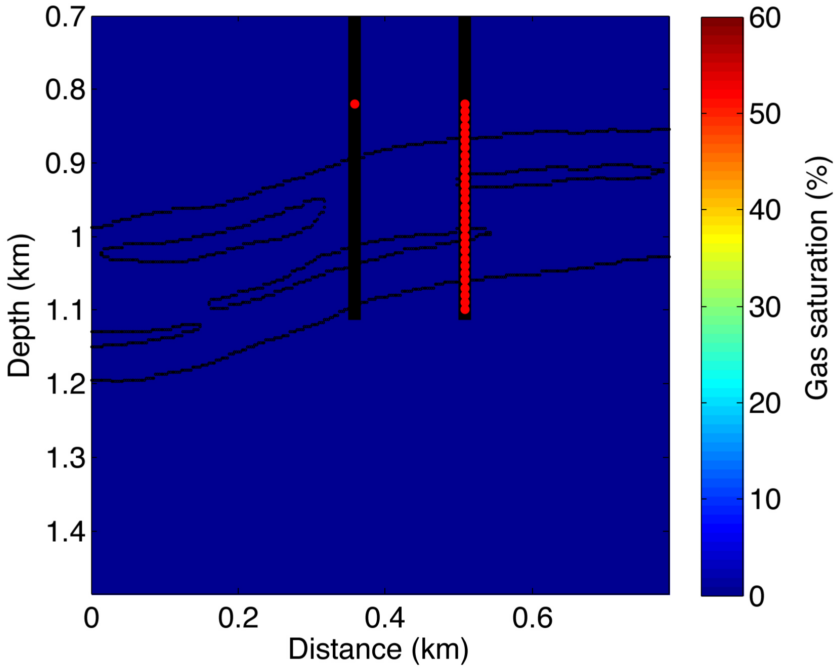
Max =7.8822e^{-13} m^2

Min = 2.7432e^{-17} m^2

(from Carcione et al., 2000)

Saturation

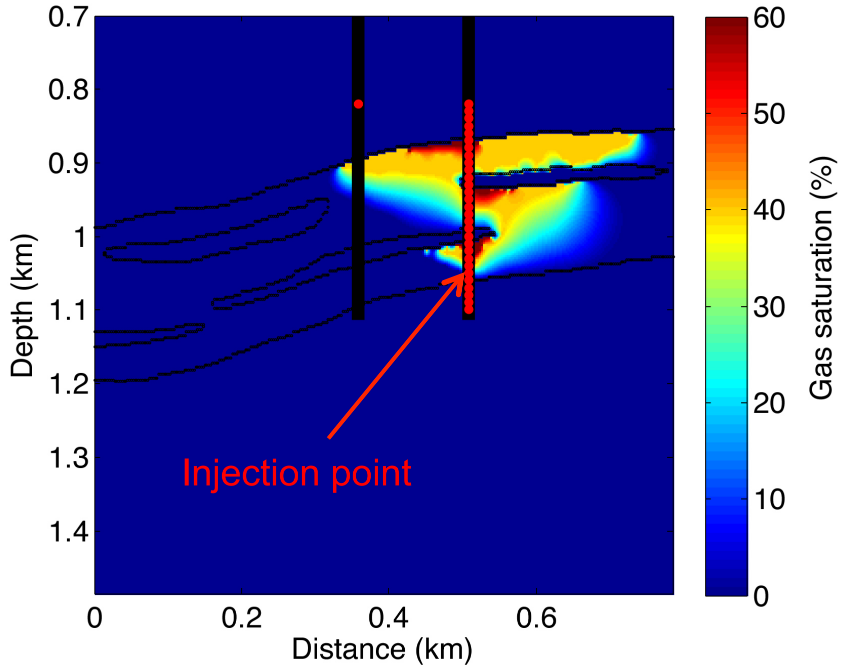
Gas saturation before CO_2 injection



Max = 0 %

Min = 0 %

Gas saturation after CO_2 injection (assumed)



Max = 60 %

Min = 0 %

Conductivity

Complex Refractive Index Method (CRIM)*

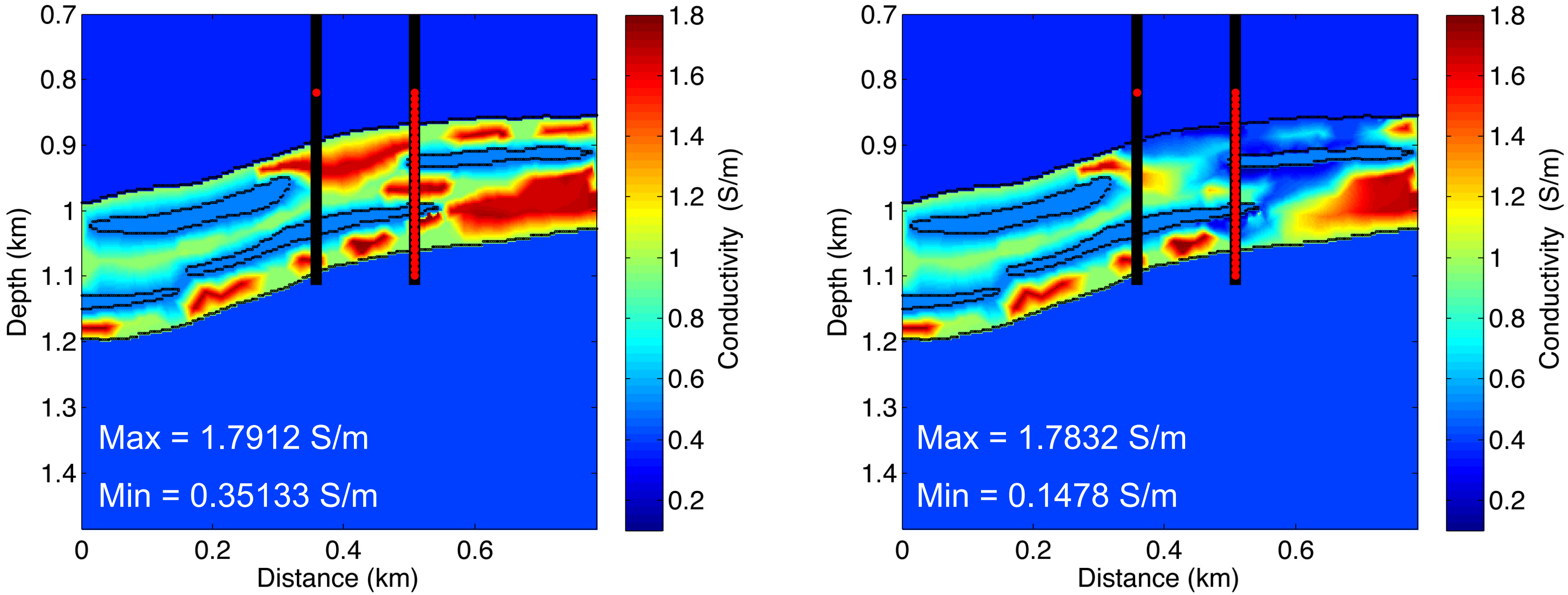
Conductivity of a shaly sandstone with negligible permittivity and partially saturated with gas:

$$\sigma = \left[(1-\phi)(1-C)\sigma_q^\gamma + (1-\phi)C\sigma_c^\gamma + \right.$$
$$\left. + \phi(1-S_g)\sigma_b^\gamma + \phi S_g \sigma_g^\gamma\right]^{1/\gamma}, \qquad \gamma = 1/2$$

C = clay content
S_g = gas saturation
σ_q = quartz conductivity
σ_c = clay conductivity
σ_g = gas conductivity
σ_b = brine conductivity
ϕ = porosity

Conductivity before CO_2 injection

Conductivity after CO_2 injection



*(e.g. Schön, 1996)

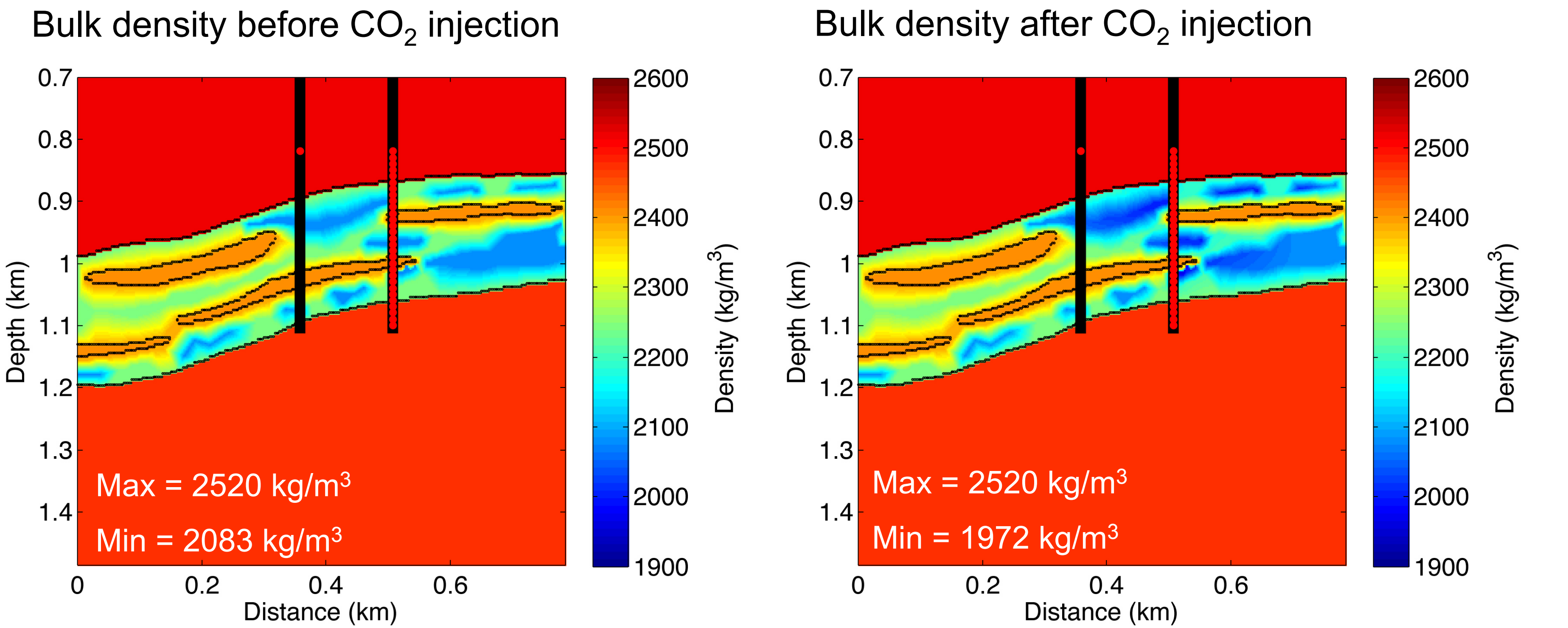
Bulk density

The density of a shaly sandstone partially saturated with gas can be computed with:

$$\rho_f = S_g \rho_g + (1 - S_g)\rho_b$$

$$\rho = (1 - \phi)[(1 - C)\rho_q + C\rho_c] + \phi\rho_f$$

C = clay content
S_g = gas saturation
ρ_q = density of quartz particles
ρ_c = density of clay particles
ρ_g = density of gas (CO_2)
ρ_b = density of brine
ϕ = porosity



Bulk and shear moduli of saturated rocks

Dry-rock bulk modulus (Krief model)

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

Dry-rock shear modulus (assumed)

$$\mu_m = \frac{\mu_s}{K_s} K_m$$

K_m = dry rock bulk modulus
μ_m = dry rock shear modulus
K_S = bulk modulus of the grains
μ_S = shear modulus of the grains
ϕ = porosity
A = 3

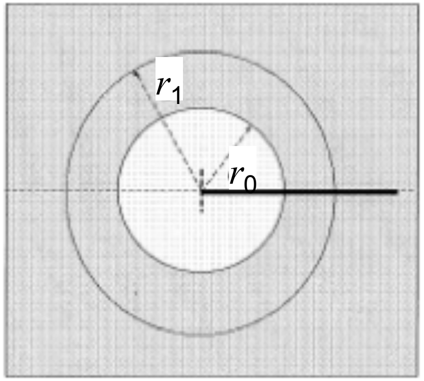
White model (1975) – patchy saturation

Complex bulk modulus as a function of frequency of a shaly sandstone partially saturated with gas:

$$K = \frac{K_\infty}{1 - K_\infty W}$$

$W\,(f,\, r_0,\, r_1,\, \eta_g,\, \eta_b,\, \kappa,\, \phi,\, K_m,\, \mu_m,\, K_b,\, K_g,\, K_s)$

$K_\infty\,(r_0,\, r_1,\, \phi,\, K_m,\, \mu_m,\, K_b,\, K_g)$



$$S_g = \frac{r_0^3}{r_1^3}$$

κ = permeability
K_m = dry rock bulk modulus
μ_m = dry rock shear modulus
K_b = brine bulk modulus
K_g = gas bulk modulus
K_s = grains bulk modulus

S_g = gas saturation
f = frequency
r_0 = inner radius (gas patch)
r_1 = outer radius
η_b = brine viscosity
η_g = gas viscosity

P- and S- wave velocities of saturated rocks

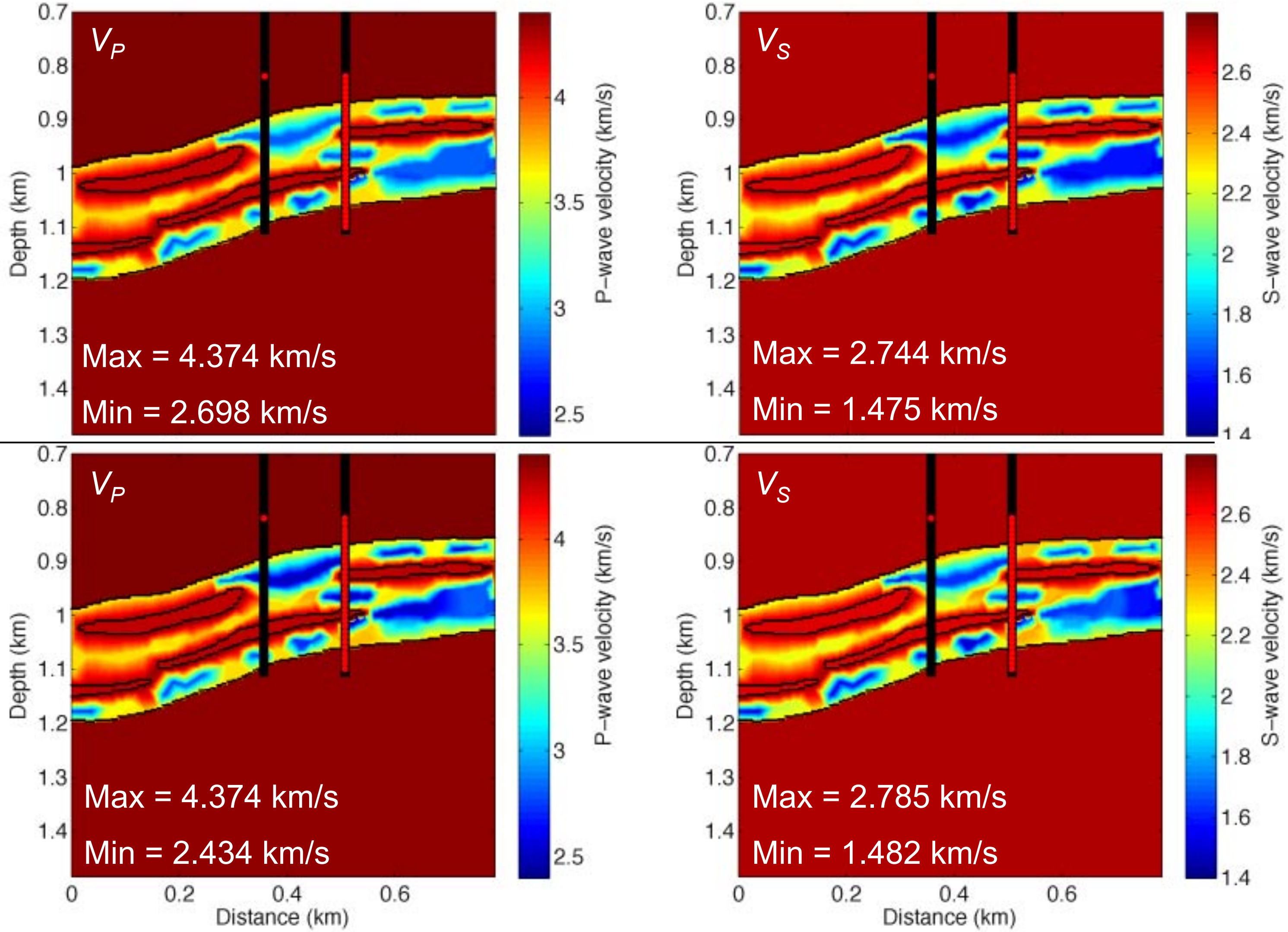
$$v_P = \sqrt{\left(K(f_0) + \frac{4}{3}\mu\right)/\rho} \qquad V_P = \left[Re\left(\frac{1}{v_P}\right)\right]^{-1}$$

$$v_S = \sqrt{(\mu_m + i\,\mu_m/Q_\mu)/\rho} \qquad V_S = \left[Re\left(\frac{1}{v_S}\right)\right]^{-1}$$

$K(f_0)$ = White complex bulk modulus
μ_m = dry rock shear modulus
μ = complex shear modulus
v_i = complex wave velocity (i=P, S)
V_i = real wave velocity (i=P, S)
Q_μ = *shear quality factor*

Before CO_2 injection

After CO_2 injection



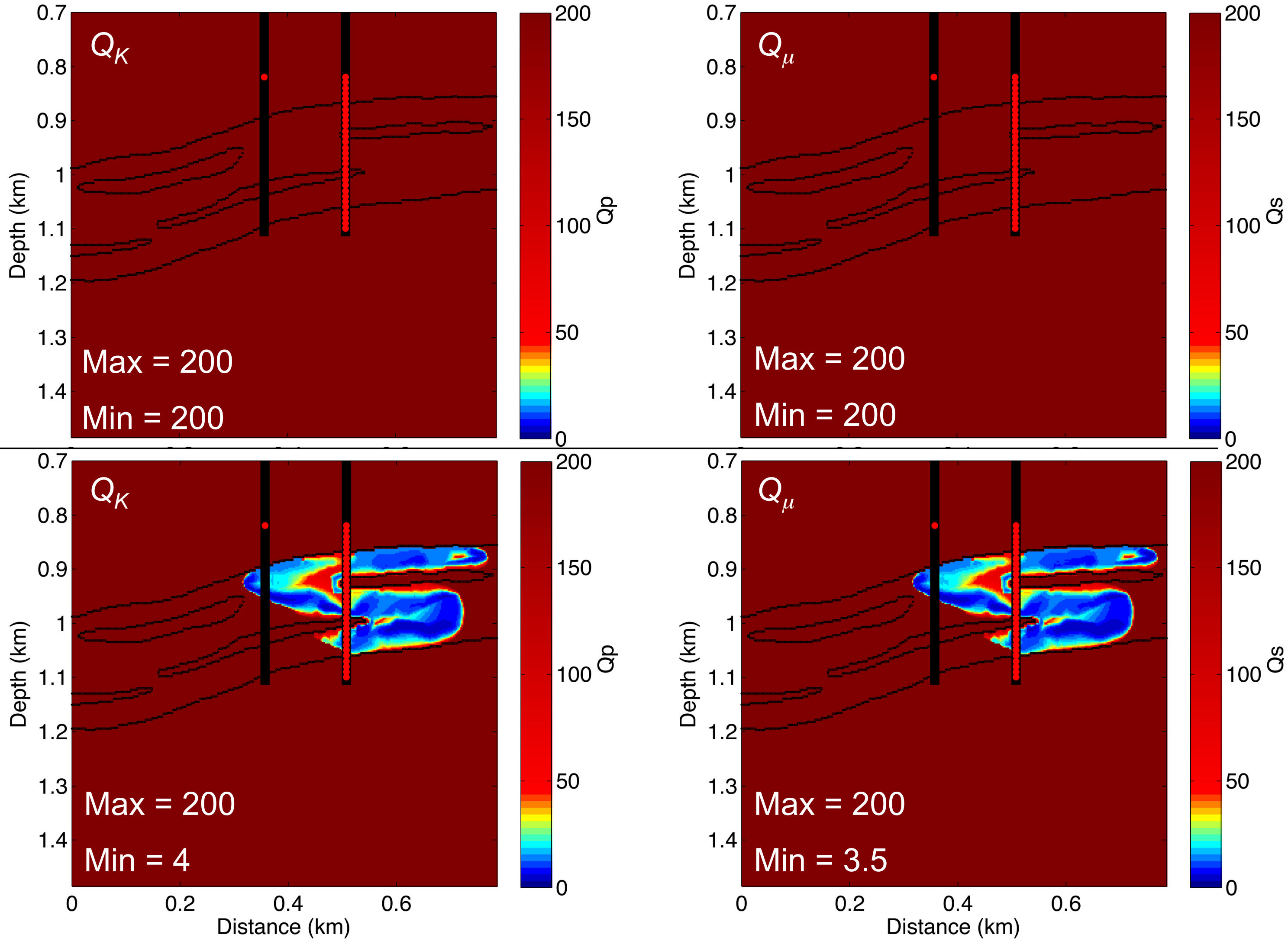
Quality factors of saturated rocks

$$Q_K = \frac{Re(K(f_0))}{Im(K(f_0))} \qquad Q_\mu = \frac{\mu_m}{Re[K(f_0)]} Q_K$$

$K(f_0)$ = White complex bulk modulus
μ_m = dry rock shear modulus
Q_K = quality factor associated with K
Q_μ = quality factor associated with μ

Before CO_2 injection

After CO_2 injection



EM numerical modelling

TM (transverse magnetic) equation

$$\mu_0 \dot{H}_y = (\sigma^{-1} H_{y,x})_{,x} + (\sigma^{-1} H_{y,z})_{,z} - \\ - \mu_0 \dot{M}_y + (J_{x,z} - J_{z,x})$$

μ_0 = magnetic permeability of vacuum
H_y = magnetic field
σ = electrical conductivity
M_y = magnetic source
J = electric sources

Regular grid (315 x 315; dx = dy = 2.5 m)

Spatial derivatives: pseudospectral (Fourier) method

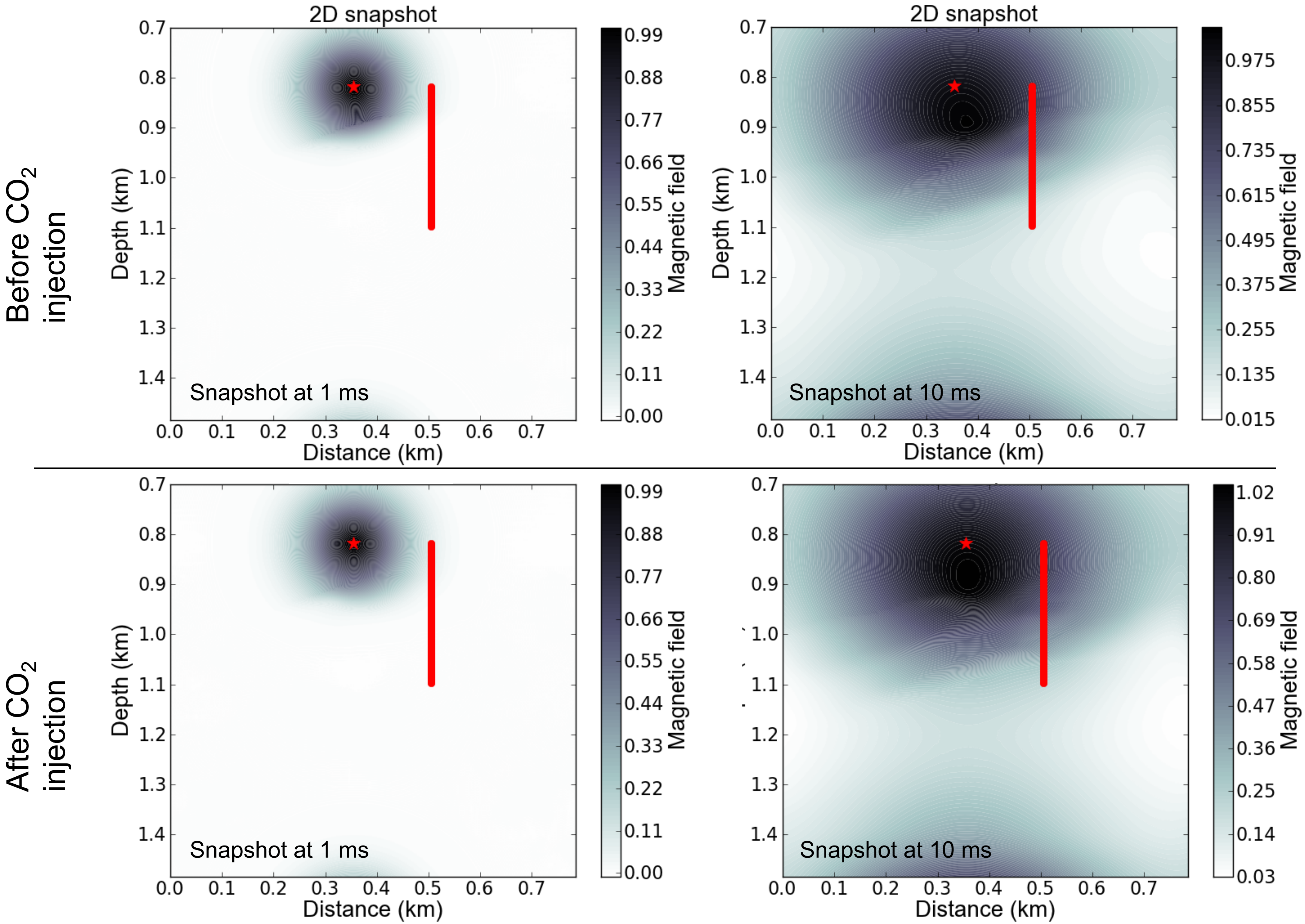
Time evolution: Chebyshev expansion

Boundary conditions: absorbing (sponge method)

Source time history: Dirac delta for H

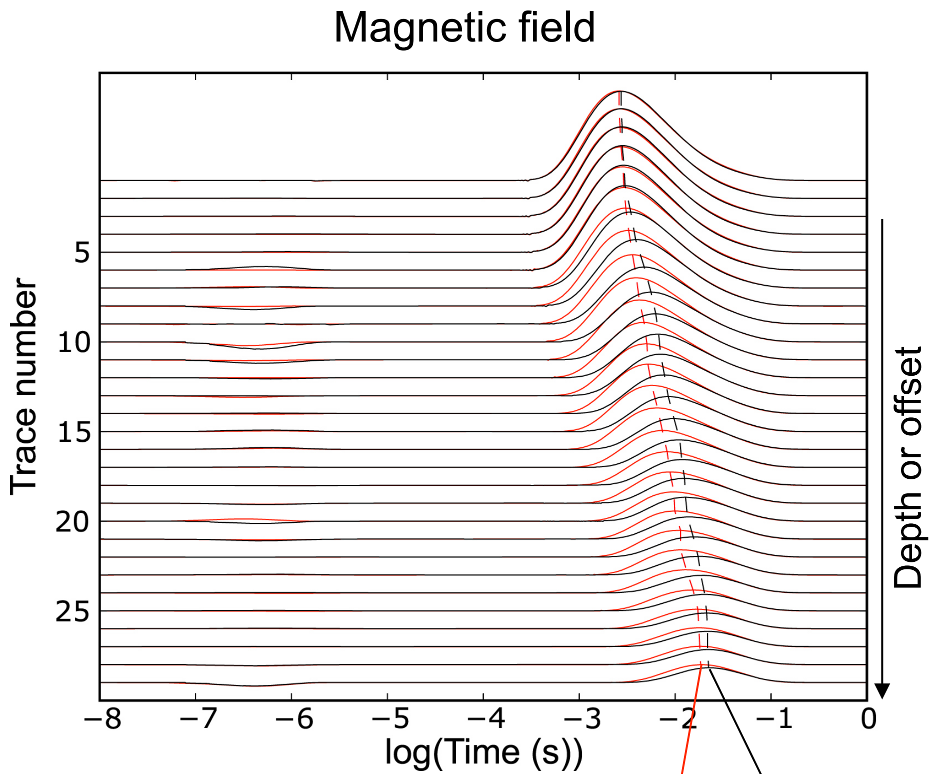
(Carcione 2006, 2007, 2010)

EM numerical modelling



EM numerical modelling

EM before-after CO2 injection



Picking of the maximum of the pulse: traveltimes of pre-injection data

Picking of the maximum of the pulse: traveltimes of post-injection data

Black= before CO_2 injection
Red = after CO_2 injection

Seismic numerical modelling

2D viscoelastic wave equation

Newton's equations

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} = \rho \frac{\partial v_x}{\partial t} + f_x$$
$$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = \rho \frac{\partial v_y}{\partial t} + f_y$$

Constitutive equations

$$\frac{\partial \sigma_{xx}}{\partial t} = (\lambda + 2\mu)\frac{\partial v_x}{\partial x} + \lambda \frac{\partial v_y}{\partial y} + (\lambda + \mu)\varepsilon_1 + 2\mu\varepsilon_2$$
$$\frac{\partial \sigma_{yy}}{\partial t} = \lambda \frac{\partial v_x}{\partial x} + (\lambda + 2\mu)\frac{\partial v_y}{\partial y} + (\lambda + \mu)\varepsilon_1 - 2\mu\varepsilon_2$$
$$\frac{\partial \sigma_{xy}}{\partial t} = \mu\left[\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) + \varepsilon_3\right]$$

Memory variables equations

$$\frac{\partial \varepsilon_1}{\partial t} = \frac{1}{\tau_\sigma^{(1)}}\left[\left(\frac{\tau_\sigma^{(1)}}{\tau_\varepsilon^{(1)}} - 1\right)\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z}\right) - \varepsilon_1\right]$$
$$\frac{\partial \varepsilon_2}{\partial t} = \frac{1}{2\tau_\sigma^{(2)}}\left[\left(\frac{\tau_\sigma^{(2)}}{\tau_\varepsilon^{(2)}} - 1\right)\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z}\right) - 2\varepsilon_2\right]$$
$$\frac{\partial \varepsilon_3}{\partial t} = \frac{1}{\tau_\sigma^{(2)}}\left[\left(\frac{\tau_\sigma^{(2)}}{\tau_\varepsilon^{(2)}} - 1\right)\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z}\right) - \varepsilon_3\right]$$

Material relaxation time

$$\tau_\varepsilon^{(\upsilon)} = \frac{\tau_0}{Q_\upsilon}\left[\sqrt{Q_\upsilon^2 + 1} + 1\right], \quad \tau_\sigma^{(\upsilon)} = \frac{\tau_0}{Q_\upsilon}\left[\sqrt{Q_\upsilon^2 + 1} - 1\right]$$

Regular grid (315 x 315; dx = dy = 2.5 m)

Spatial derivatives: pseudospectral (Fourier) method

Time evolution: fourth order Runge-Kutta scheme

Attenuation: viscoelastic model (Zener)

Boundary conditions: absorbing (sponge method)

Source time history: Ricker wavelet

v_x, v_y	= particle velocities
$\sigma_{xx}, \sigma_{yy}, \sigma_{xy}$	= stress component
ρ	= density
f_x, f_y	= body forces
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	= memory variables
λ, μ	= Lamé constants

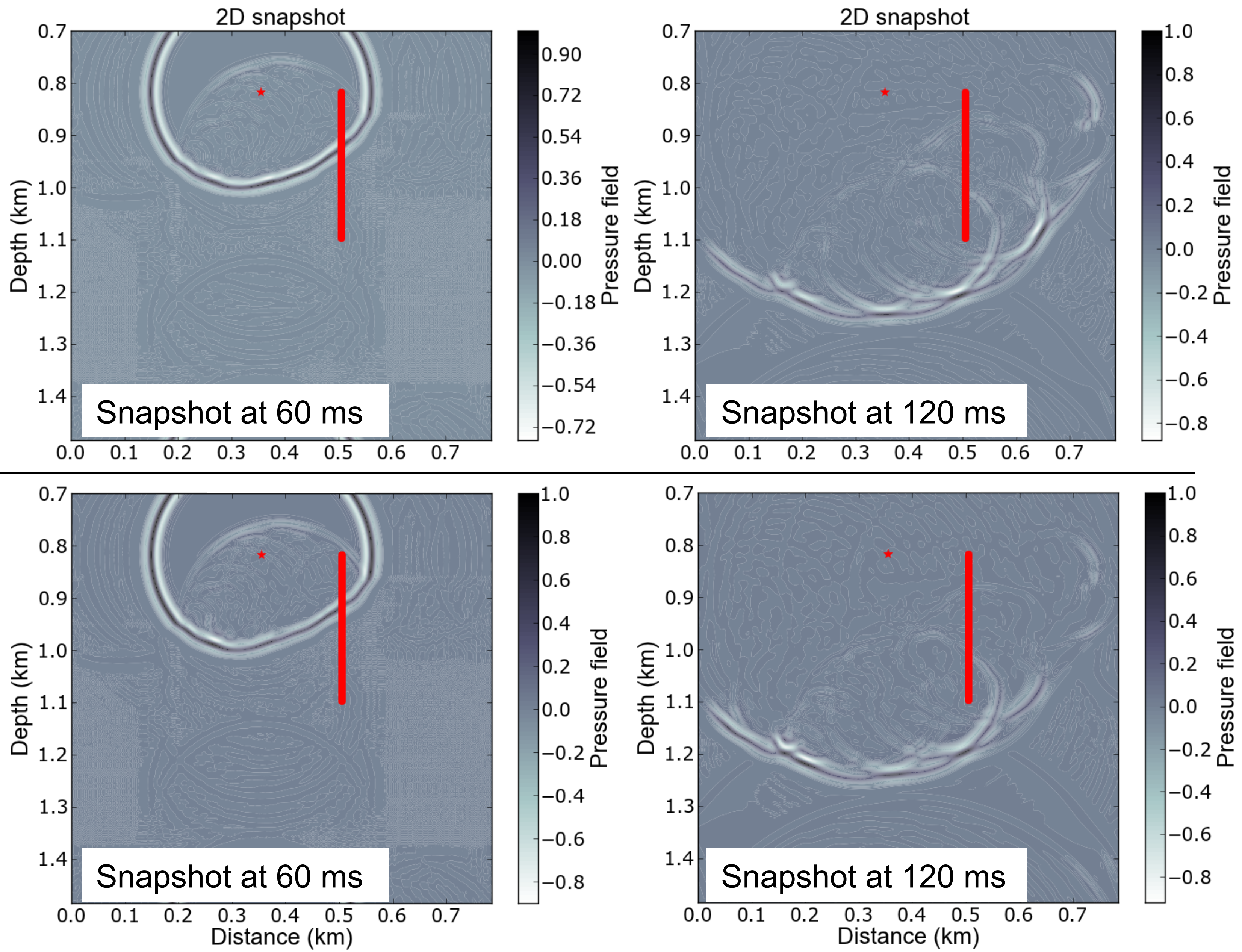
v_x, v_y	= particle velocities
$\sigma_{xx}, \sigma_{yy}, \sigma_{xy}$	= stress component
ρ	= density
f_x, f_y	= body forces
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	= memory variables
λ, μ	= Lamé constants

Seismic numerical modelling

fp=150 Hz

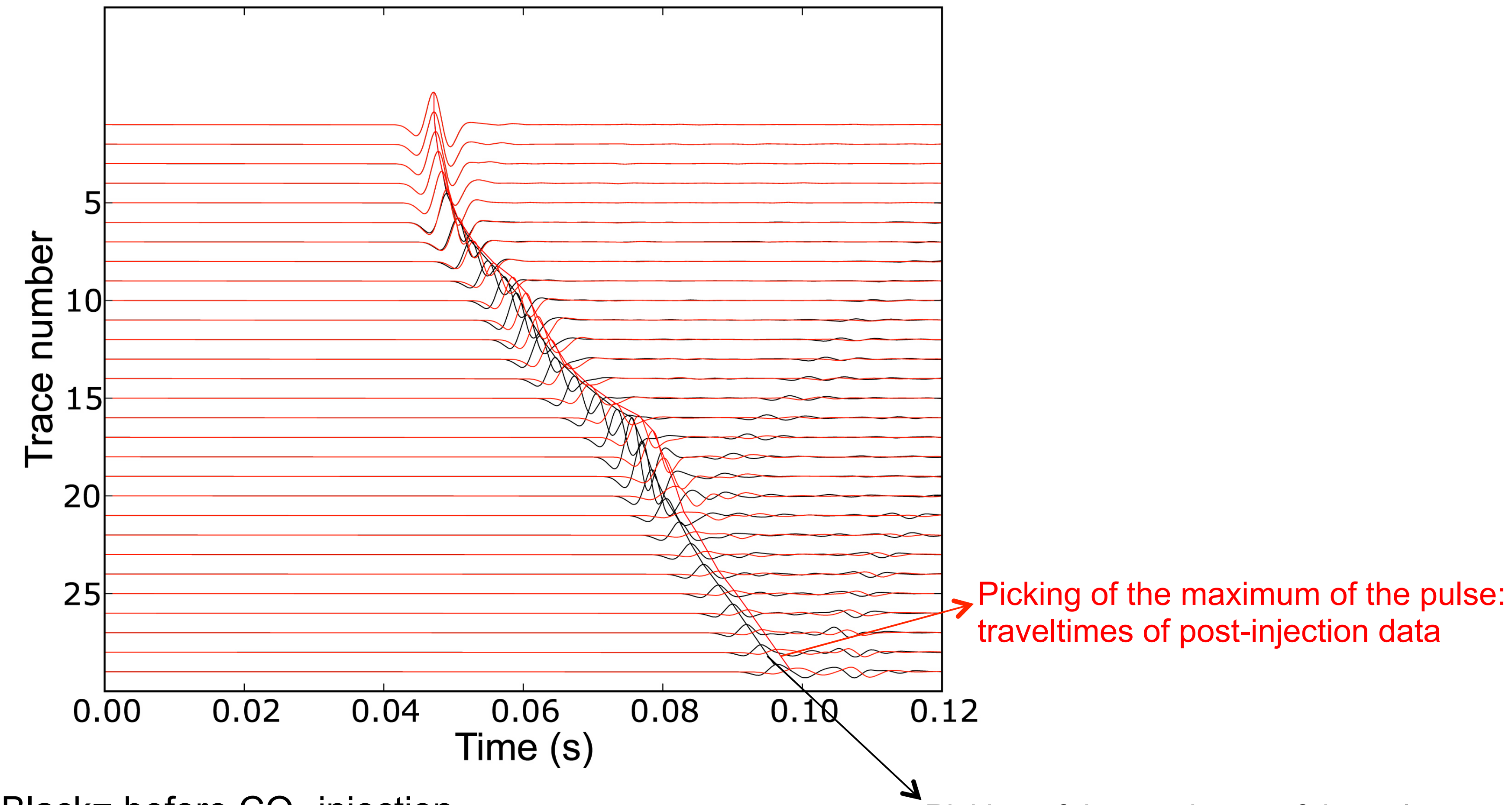
Before CO_2 injection

After CO_2 injection



Seismic numerical modelling

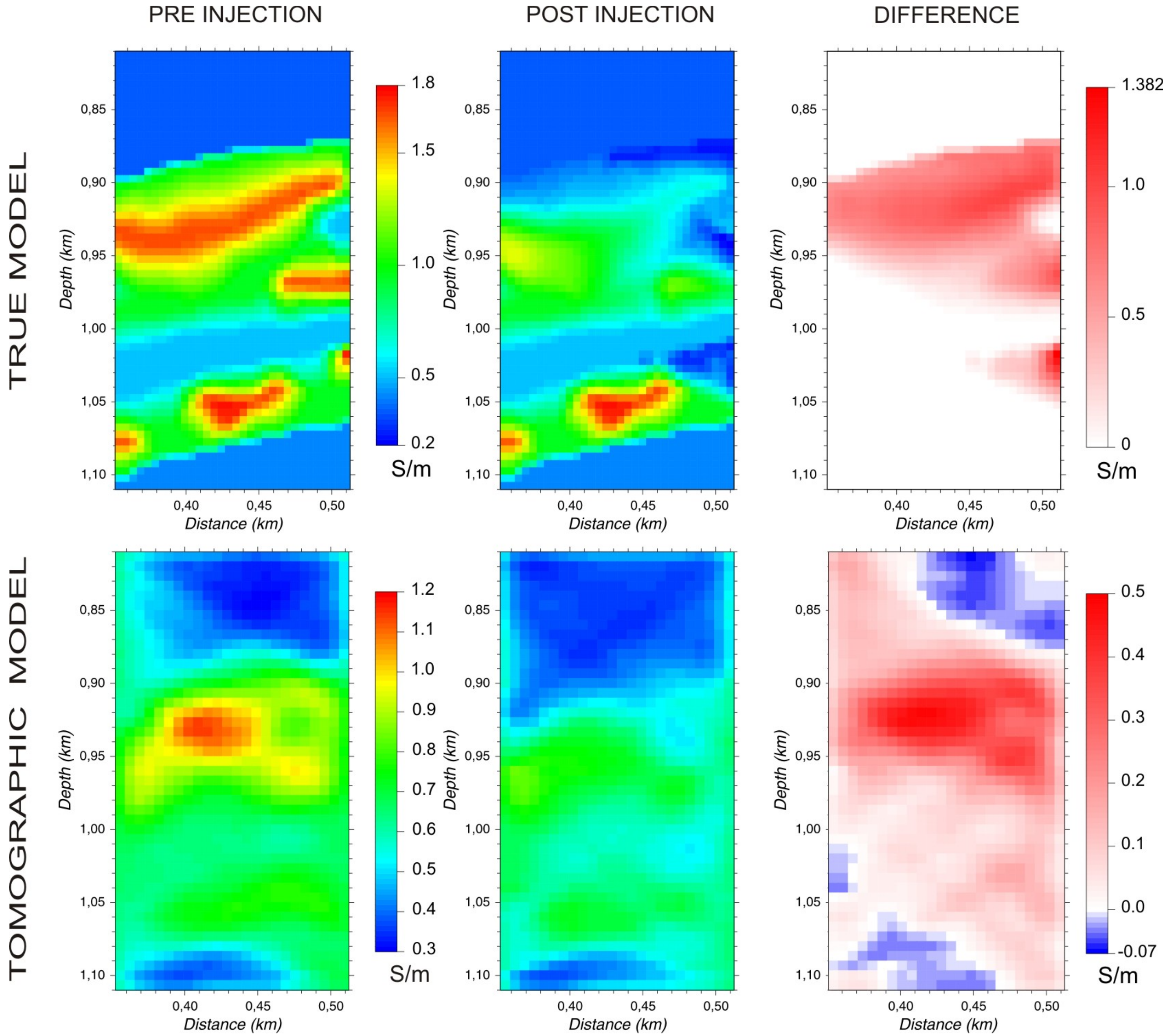
Seismic before-after CO2 injection



Black= before CO_2 injection
Red = after CO_2 injection

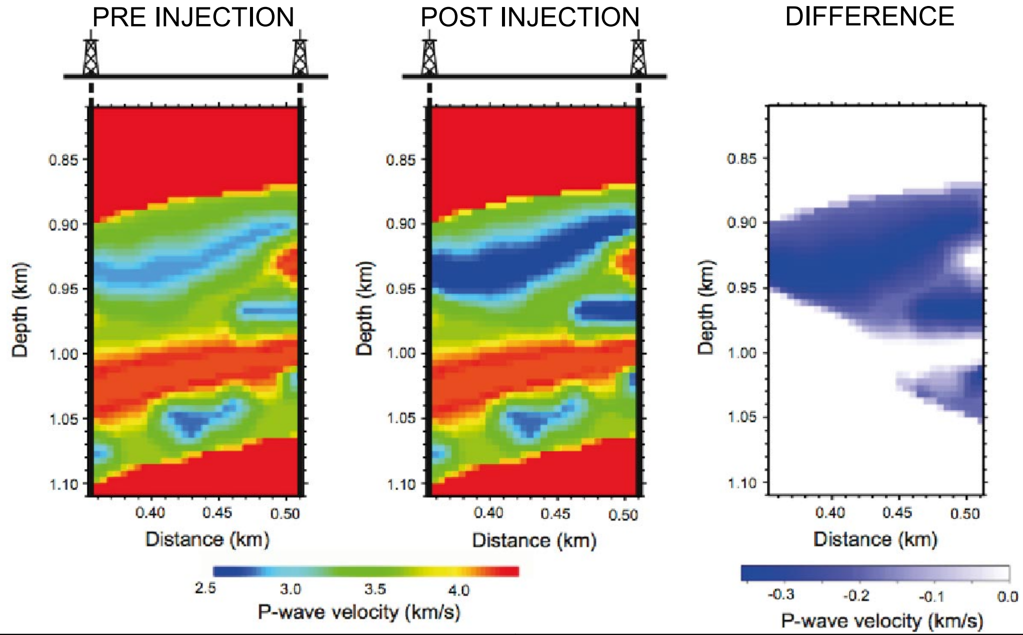
Tomographic inversions

EM tomography

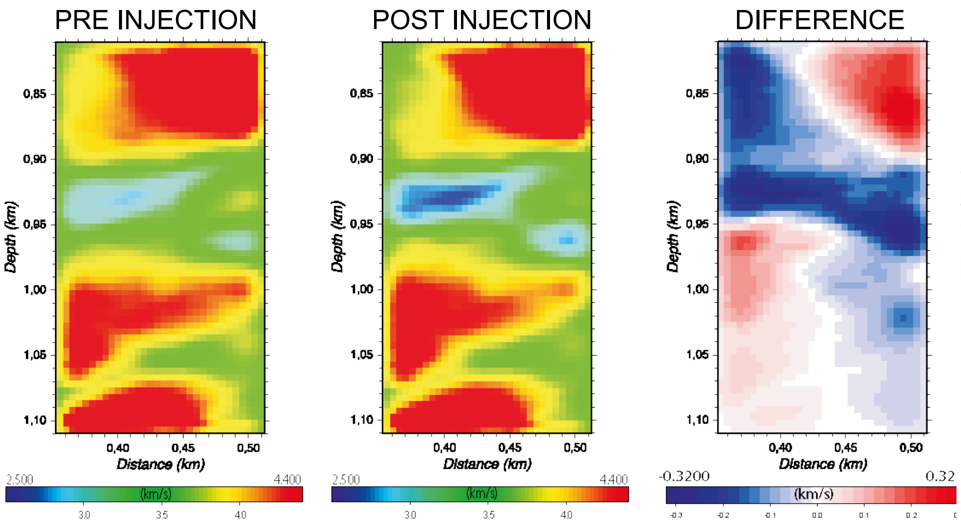


Tomographic inversions

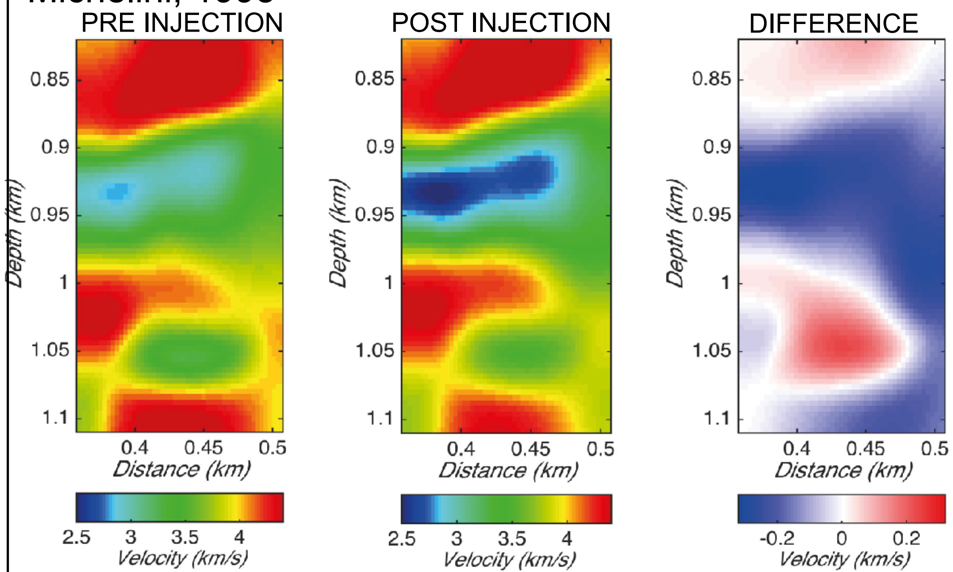
P-wave tomography



CAT – 3D

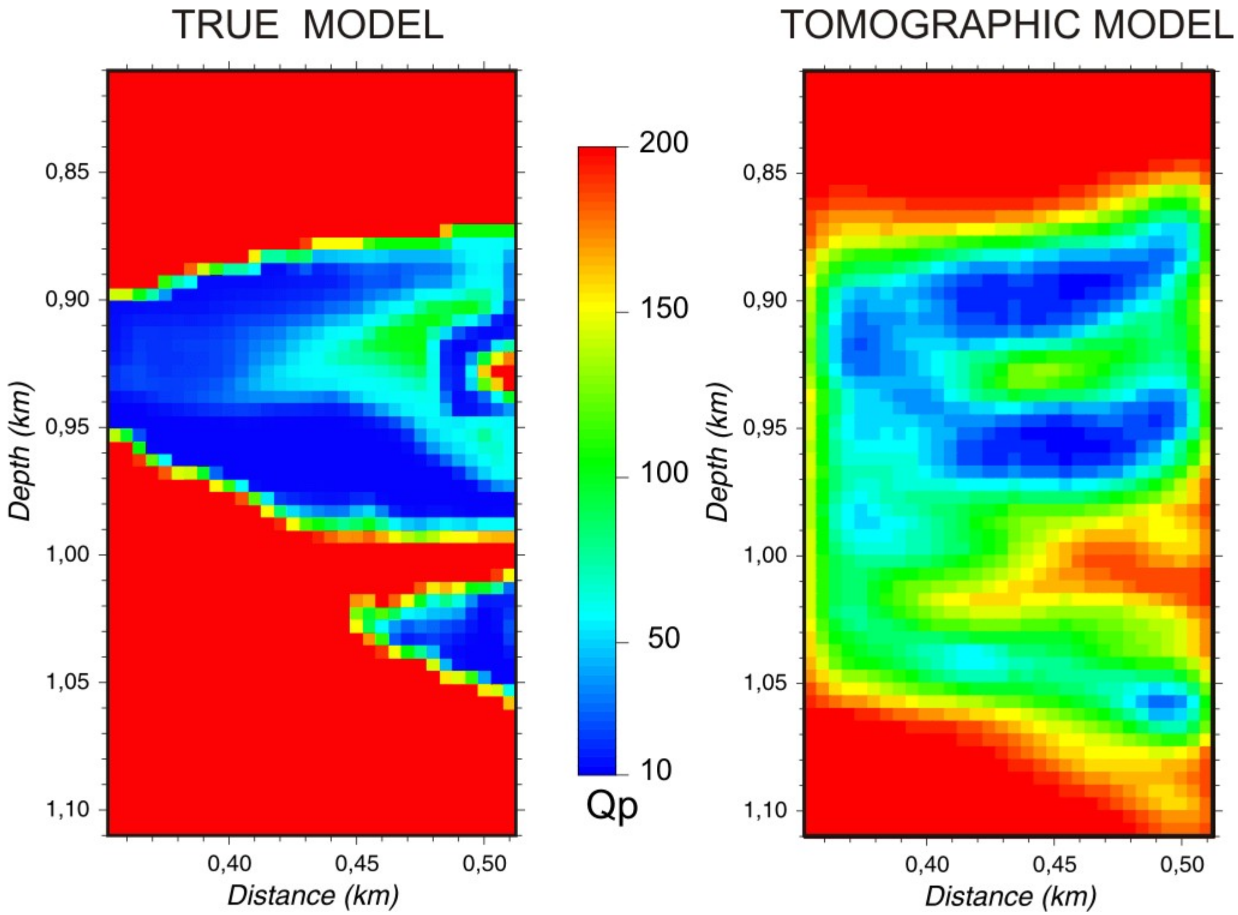


Michelini, 1995



Tomographic inversions

P-wave quality factor



Conclusions

- This study describes an effective methodology to monitor the injection of CO_2 in saline aquifers.
- The rock-physics models give reliable petrophysical properties of shaly sandstones partially saturated with CO_2.
- Tomographic inversions of P-wave velocity, Q_P and electrical conductivity fields allow us to detect the presence of CO_2 after injection.

Future work

- We are improving the methodology by considering saturation and pore pressure in the gas plume computed with fluid flow simulations.
- We are developing and testing a petrophysical inversion method using the tomographic results in order to obtain porosity, clay content and CO_2 saturation.