Time-lapse FWI prediction of CO_2 saturation and pore pressure

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Background

- Quantitative estimation of saturation and pressure is important for conformance verification of CO_2 storage.

- Pressure-saturation discrimination from seismic amplitude.

  Landrø (2001), Meadows (2001), Trani et al. (2011), Grana and Mukerji (2019)…

- FWI prediction of time-dependent CO_2 saturation.

  Queißer and Singh (2012), Dupuy et al. (2021), Hu et al. (2022)

Outline

- **Considerations for the rock physics model**
- Time-lapse FWI framework
- Numerical example

Definition of different pressures

- Overburden pressure:

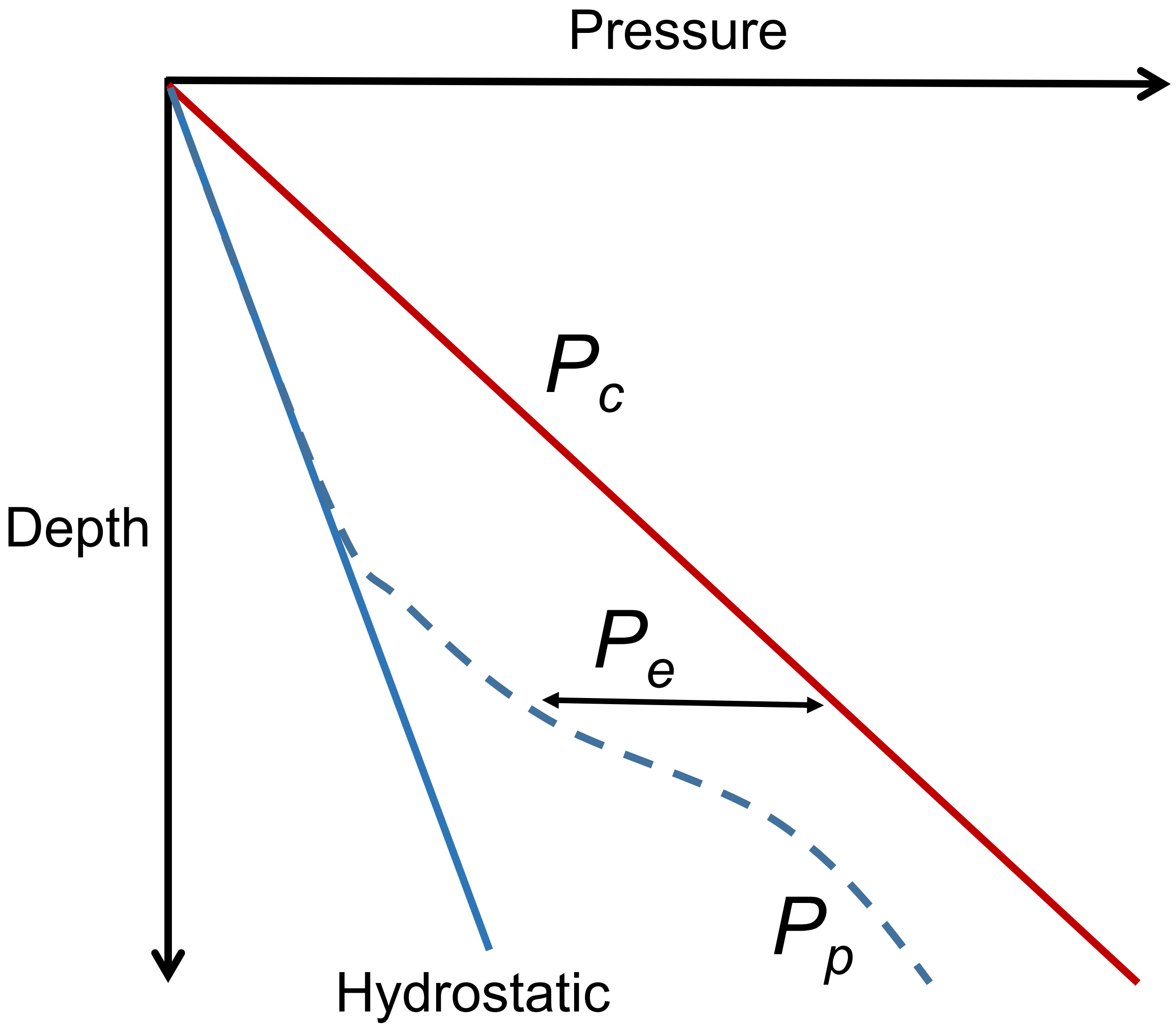
$$P_c = g \int_0^z \rho(z')dz',$$

- Pore pressure (if hydrostatic):

$$P_p = \rho_w g z$$

- Effective pressure:

$$P_e = P_c - \lambda P_p,$$



Pressure model

Landrø (2001)

$$\frac{\Delta V_{\mathrm{P}}}{\overline{V}_{\mathrm{P}}} = a\Delta S + b\Delta {P_e}^2 + c\Delta P_e$$

Eberhart-Phillips (1989)

$$V_{\mathrm{P}} = a + b\phi + c\sqrt{V_{\mathrm{clay}}} + d(P_e - \exp(-kP_e))$$

Hertz–Mindlin (1949)

$$K_{\mathrm{dry}} = \sqrt[3]{X(\phi, V_{\mathrm{clay}})P_e},$$

Macbeth (2004)

$$K_{\mathrm{dry}} = \frac{K^{\infty}}{1 + A_K e^{-\frac{P_e}{P_K}}},$$

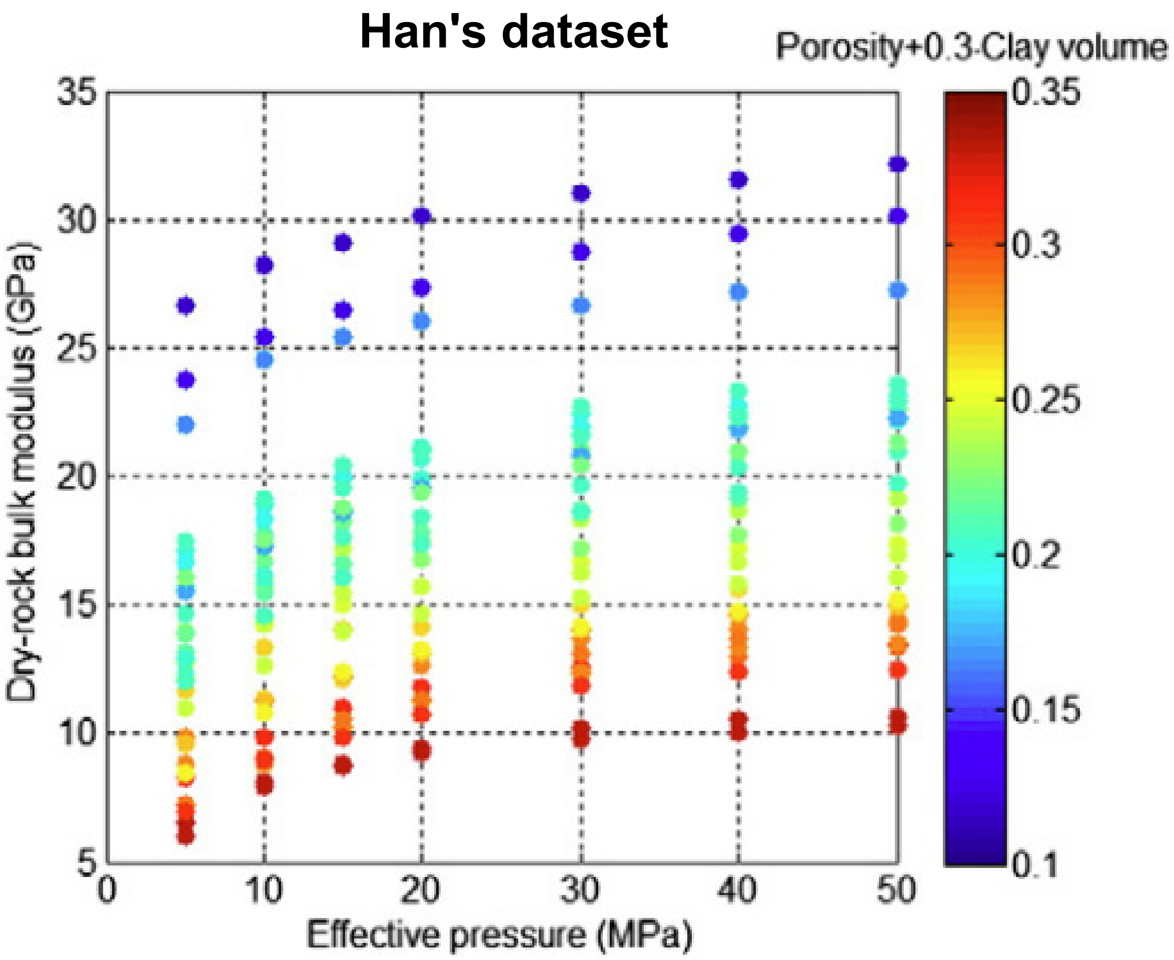
Pressure model

Modified Macbeth model (Grana, 2016)

$$K_{\mathrm{dry}}(P_e) = \frac{K^{\infty}}{1 + \frac{K^{\infty} - K_0}{K_0} e^{-\frac{P_e - P_0}{P_K}}};$$

$$K^{\infty} = \lambda_1(\phi + aV_{\mathrm{clay}}) + \lambda_2,$$

self-similarity



Gassmann's equation:

$$K_{\text{sat}}(S_{\text{co}_2}, P_p) = K_{\text{dry}}(P_p) + \frac{[1 - K_{\text{dry}}(P_p)/K_m]^2}{\phi/K_f(S_{\text{co}_2}, P_p) + (1-\phi)/K_m - K_{\text{dry}}(P_p)/K_m^2}$$

$$G_{\text{sat}}(P_p) = G_{\text{dry}}(P_p)$$

$$\rho_{\text{sat}}(S_{\text{co}_2}, P_p) = (1-\phi)\rho_m + \phi\rho_f(S_{\text{co}_2}, P_p)$$

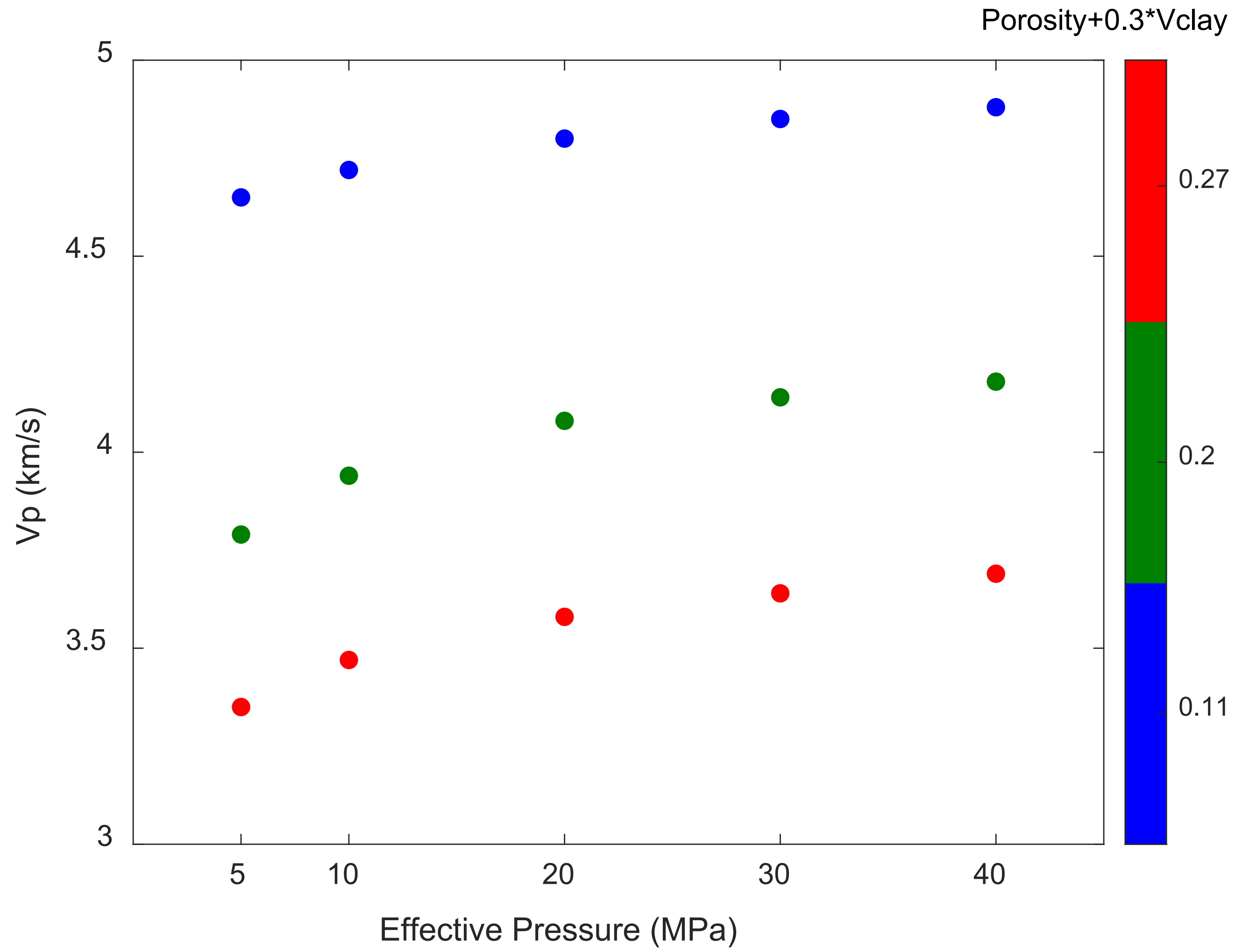
Steps of rock physics modeling

Solid phase:	$K_m = f(K_q, K_c, V_{\mathrm{clay}})$	**Voigt-Reuss-Hill**
Fluid phase:	$K_{\mathrm{co2,w}} = f(T, P_p)$	**Baztle-Wang**
	$K_f = f(K_{\mathrm{co2}}, K_w, S_{\mathrm{co2}})$	**Brie**
Dry rock:	$K_0 = f(K_m, \phi, P_0)$	**Hertz-Mindlin**
	$K_{\mathrm{dry}}(P_e) = f(K_0, P_0, P_e)$	**Modified MacBeth**
Saturated rock:	$K_{\mathrm{sat}} = f(K_m, K_f, K_{\mathrm{dry}}, \phi)$	**Gassmann**

$$\rightarrow \quad (V_{\mathrm{P}}, V_{\mathrm{S}}, \rho) = f(\phi, V_{\mathrm{clay}}, S_{\mathrm{co2}}, P_p)$$

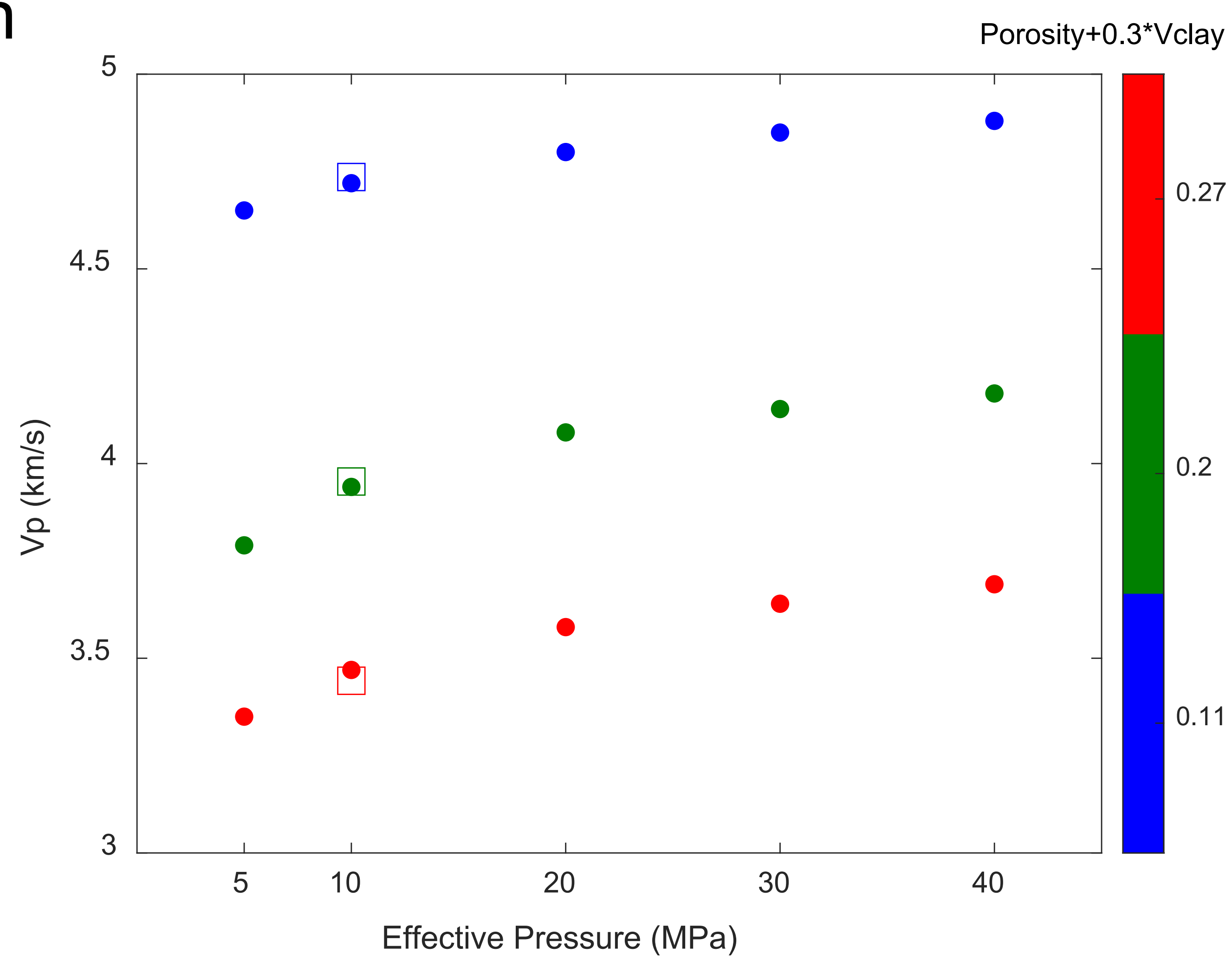
Model calibration

Three samples



Baseline prediction (Hertz-Mindlin)

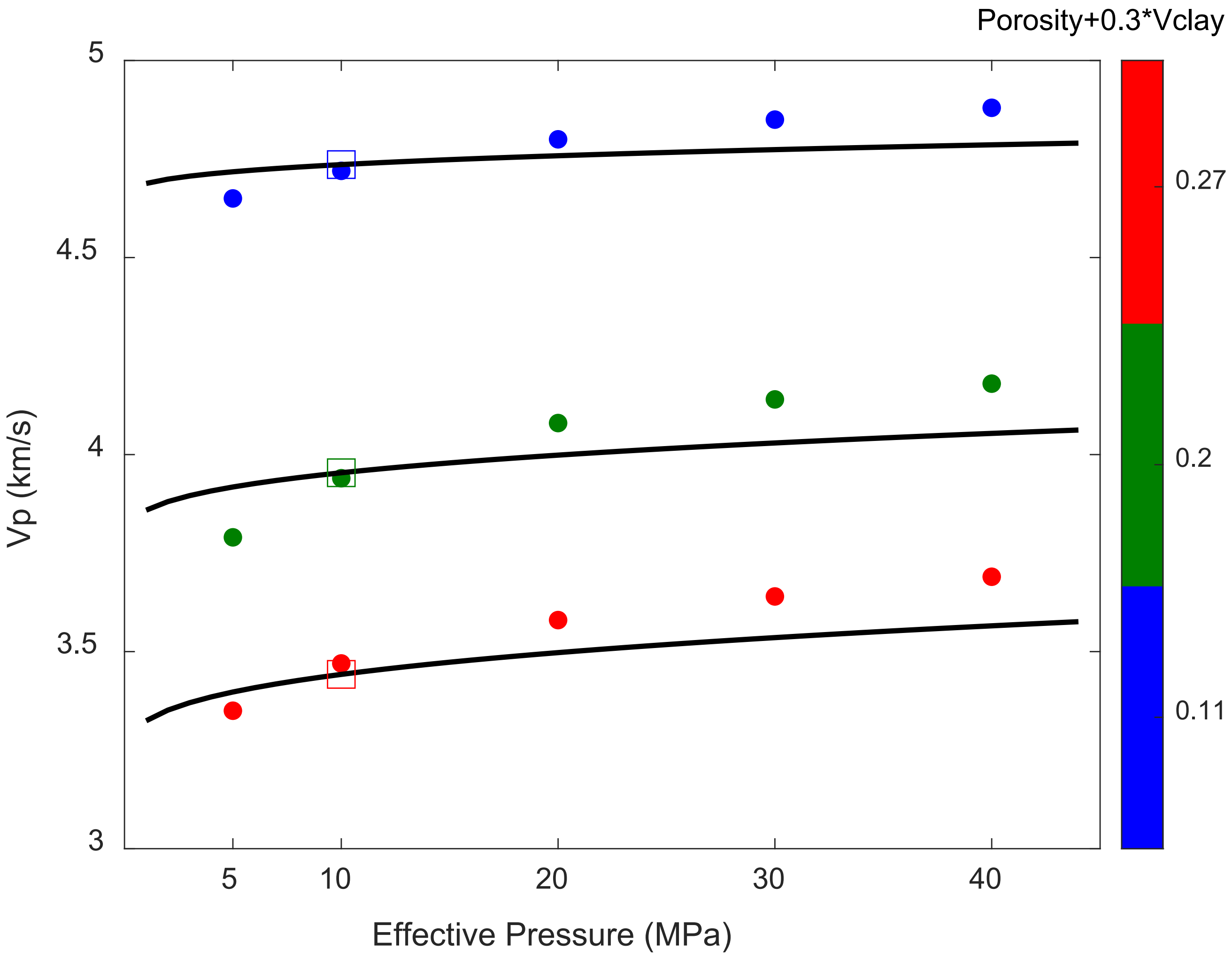
$$K_{\text{dry}} = \sqrt[3]{X(\phi, V_{\text{clay}})P_e},$$



Model calibration

Monitor prediction (Hertz-Mindlin)

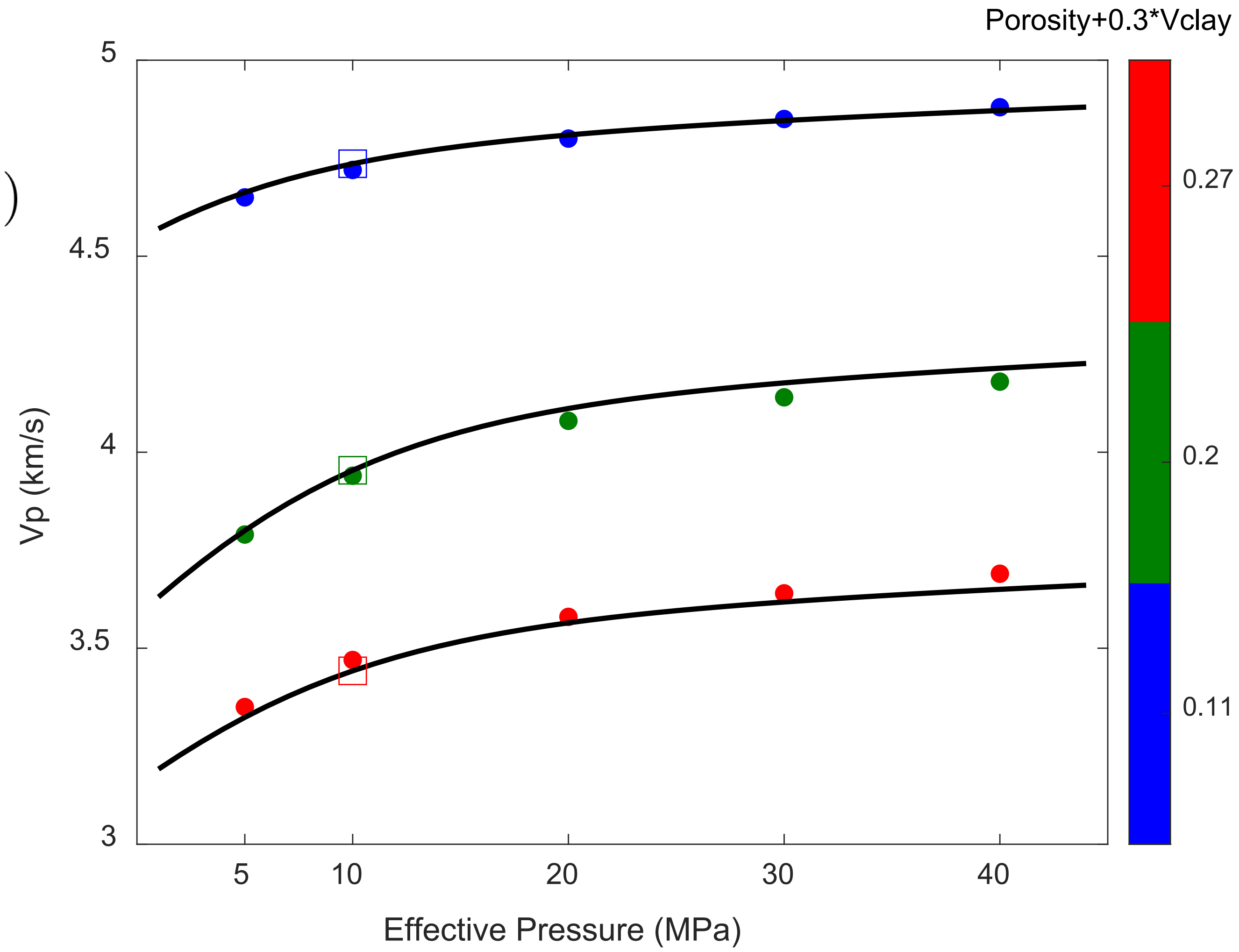
$$K_{\mathrm{dry}} = \sqrt[3]{X(\phi, V_{\mathrm{clay}})P_e},$$



Model calibration

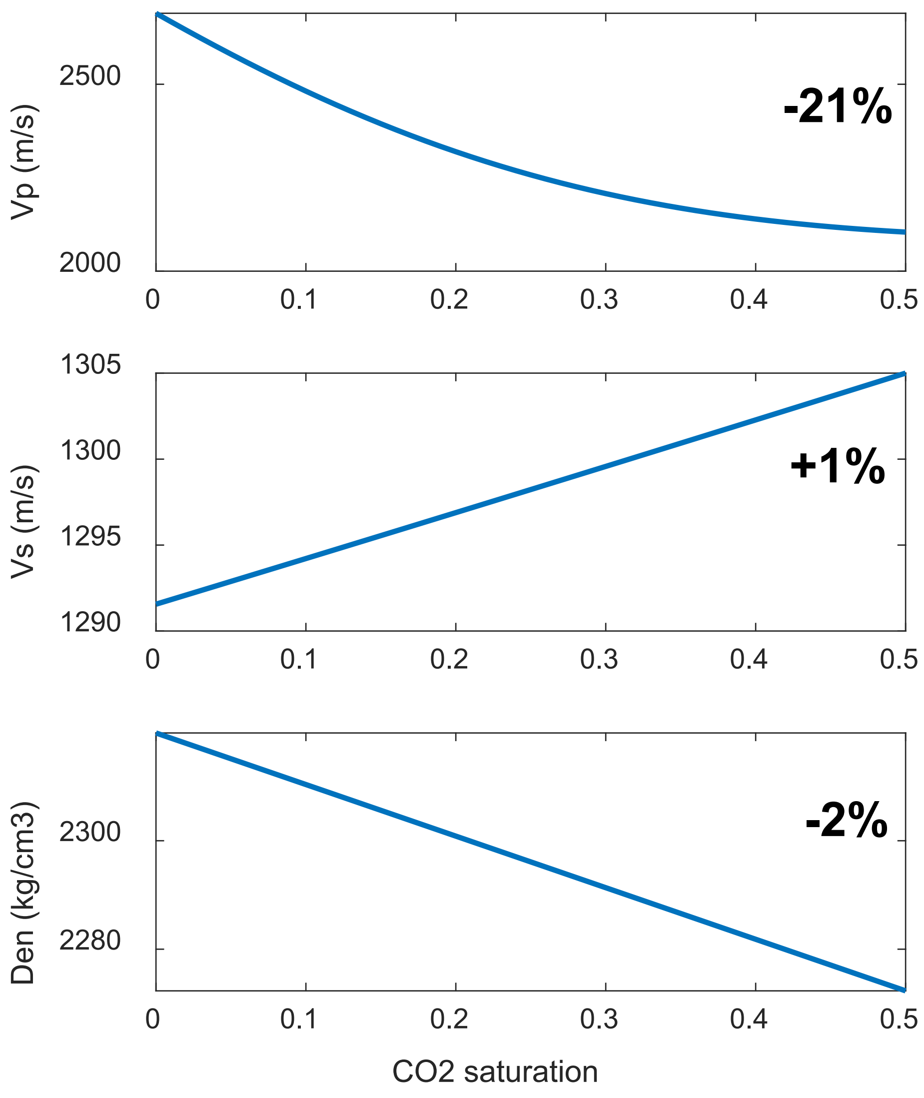
Monitor prediction (Macbeth)

$$K_{\mathrm{dry}}(P_e) = f(K_0, P_0, P_e)$$

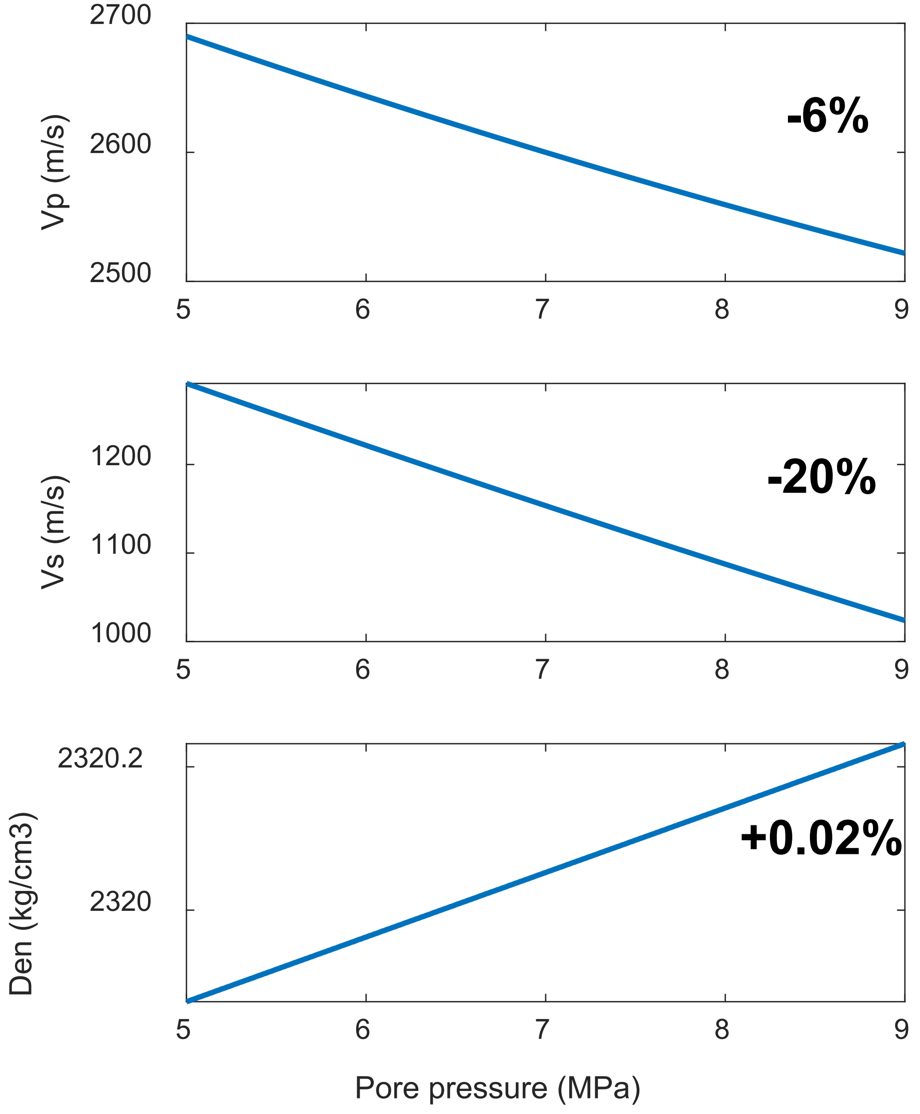


Sensitivity analysis

$$(V_P, V_S, \rho) = f(S_{co2}, P_p = 5)$$



$$(V_P, V_S, \rho) = f(S_{co2} = 0, P_p)$$



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Direct FWI updating of rock properties

- **General problem**

f: Wave propagation model

g: rock-physics model

$$\mathbf{d} = f(\mathbf{m}_e) + \mathbf{n} = f(g(\mathbf{m}_r)) + \mathbf{n}$$

$\mathbf{m}_e$: Elastic properties

$\mathbf{m}_r$: Reservoir properties

- **FWI incorporating rock physics model**

$$\frac{\partial \mathbf{A}}{\partial r_i} = \frac{\partial \mathbf{A}}{\partial e_1}\frac{\partial e_1}{\partial r_i} + \frac{\partial \mathbf{A}}{\partial e_2}\frac{\partial e_2}{\partial r_i} + \frac{\partial \mathbf{A}}{\partial e_3}\frac{\partial e_3}{\partial r_i},$$

(Hu et al, 2021)

$$(e_1, e_2, e_3) = g(r_1, r_2, ..., r_N)$$

1. Baseline model reconstruction (ϕ , V_{clay})

$$E_b = \left\|\mathbf{d}_{\text{obs\_b}}(\phi^t, V^t_{\text{clay}}) - \mathbf{d}_{\text{syn\_b}}(\phi, V_{\text{clay}})\right\|_2 ,$$

2. Monitor model reconstruction (S_{co2} , P_p)

$$E_m = \left\|\mathbf{d}_{\text{obs\_m}}(\phi^t, V^t_{\text{clay}}, S^t_{\text{co2}}, P^t_p) - \mathbf{d}_{\text{syn\_m}}(\phi, V_{\text{clay}}, S_{\text{co2}}, P_p)\right\|_2 ,$$

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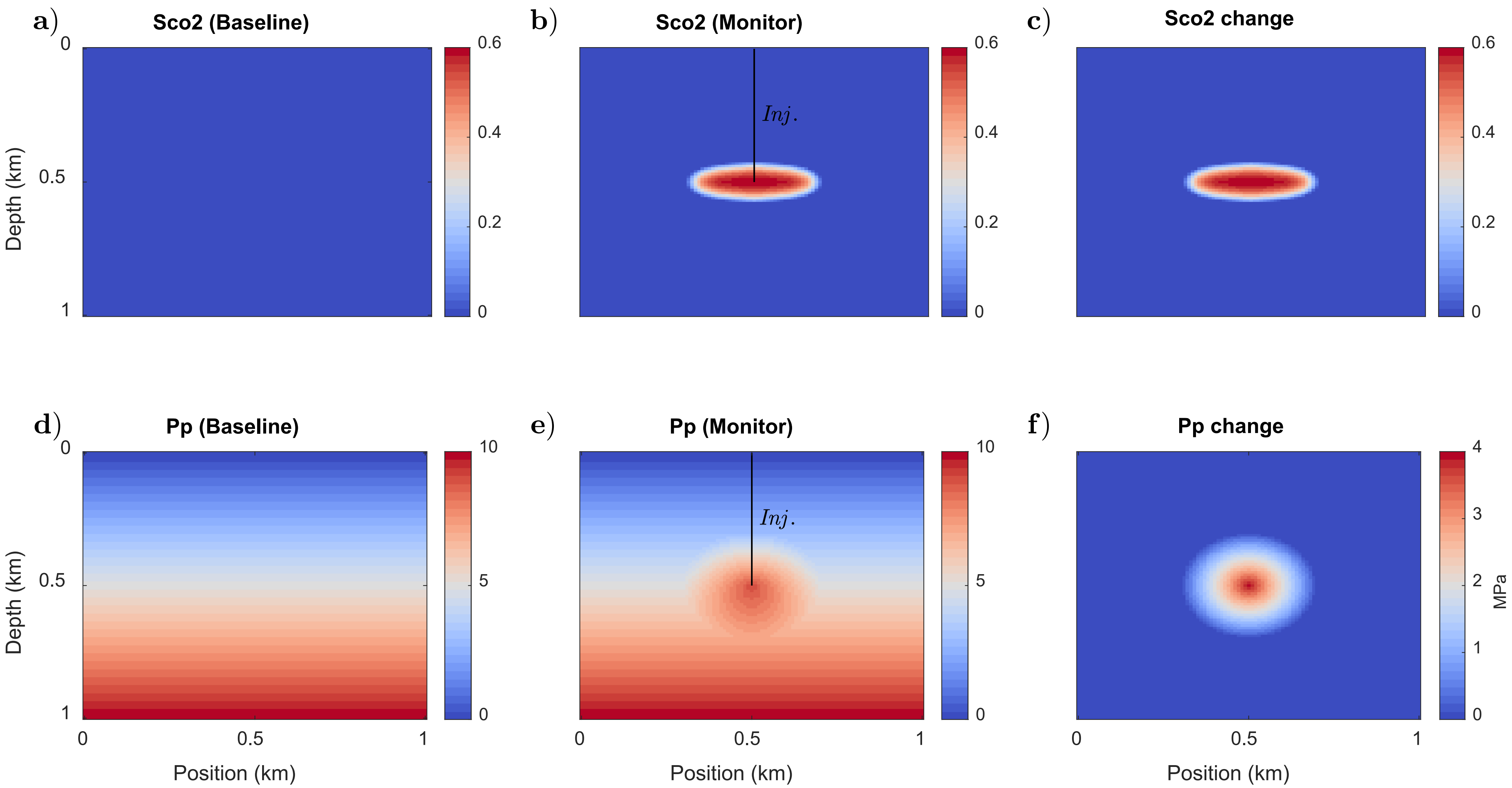
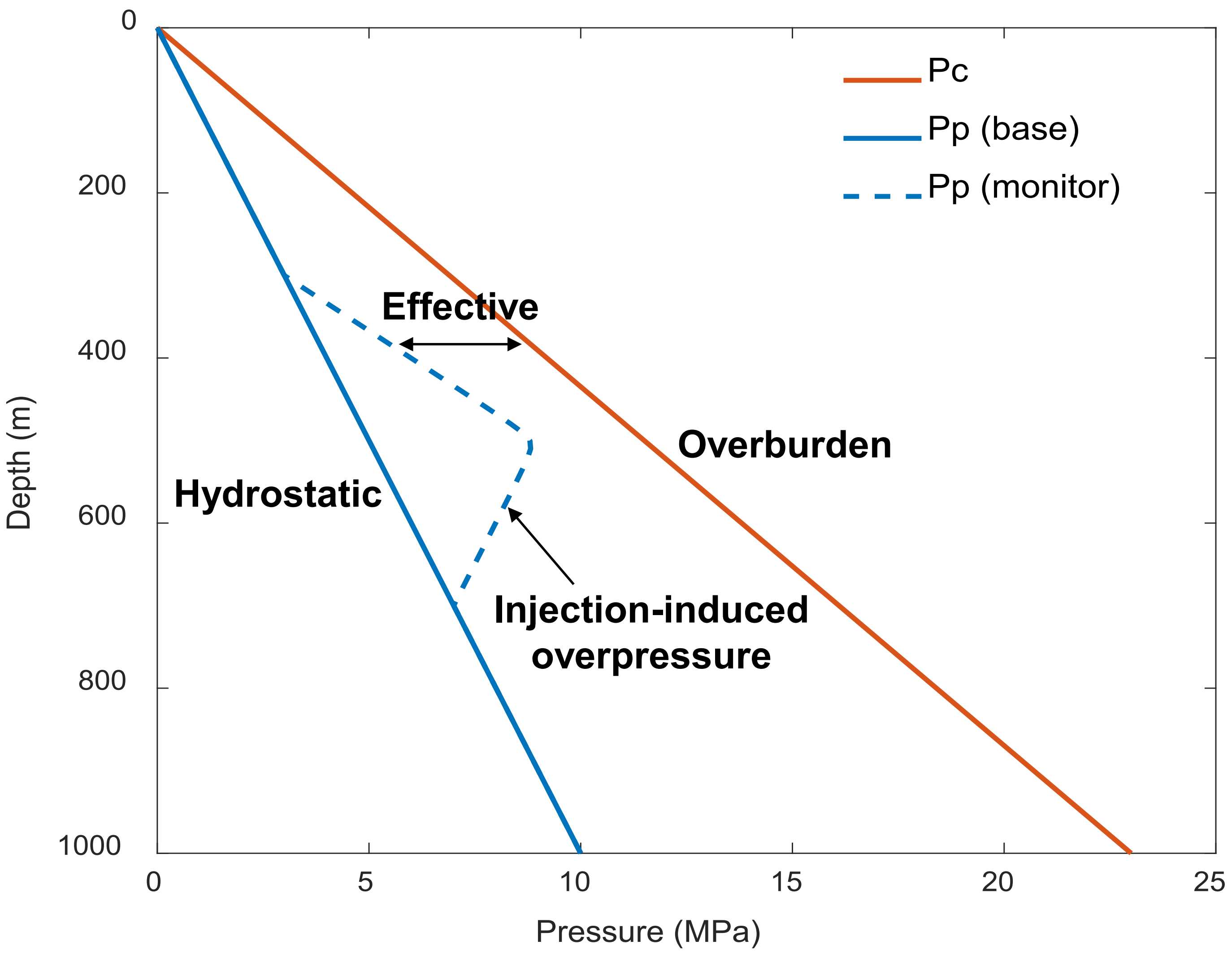
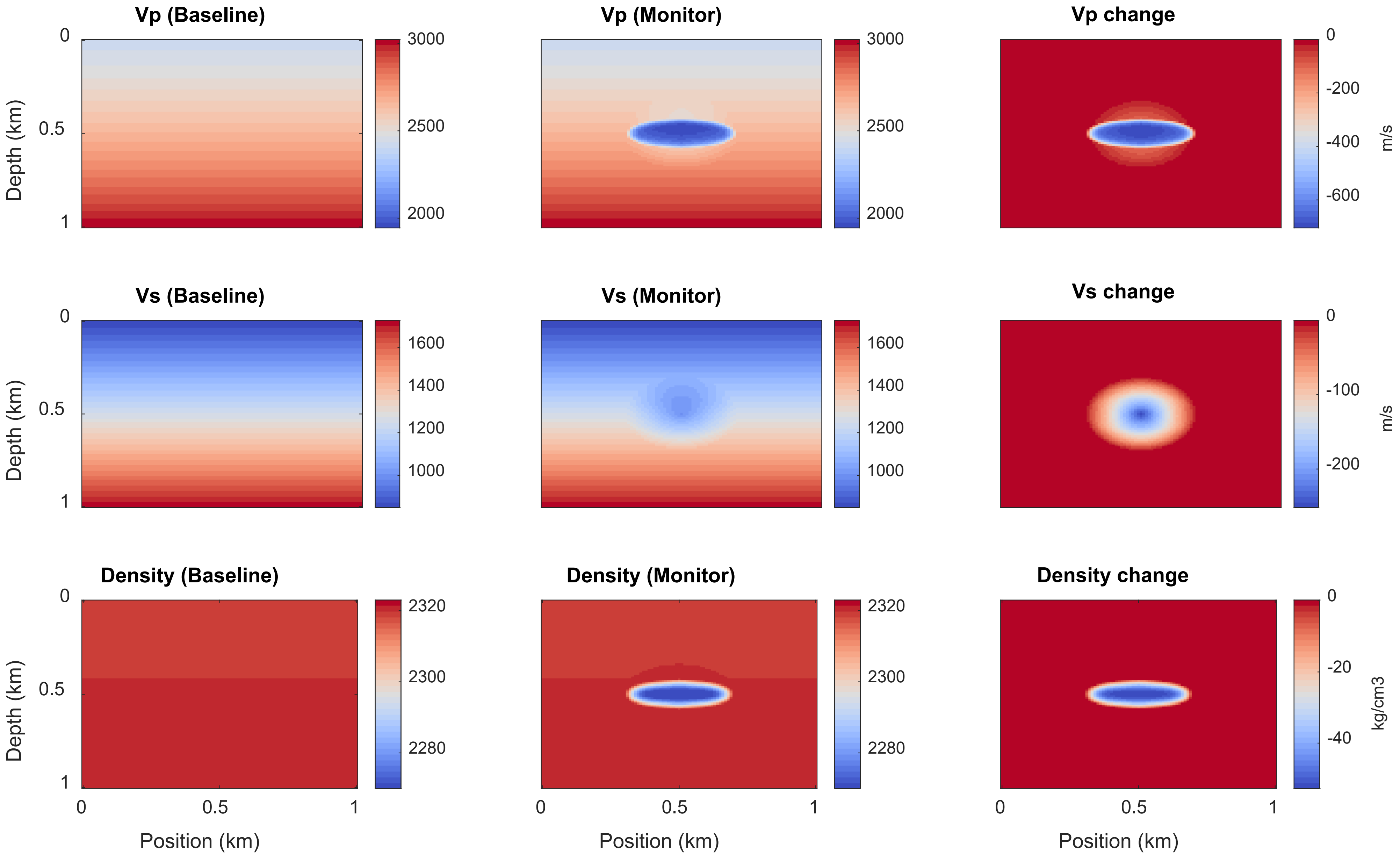
True reservoir model



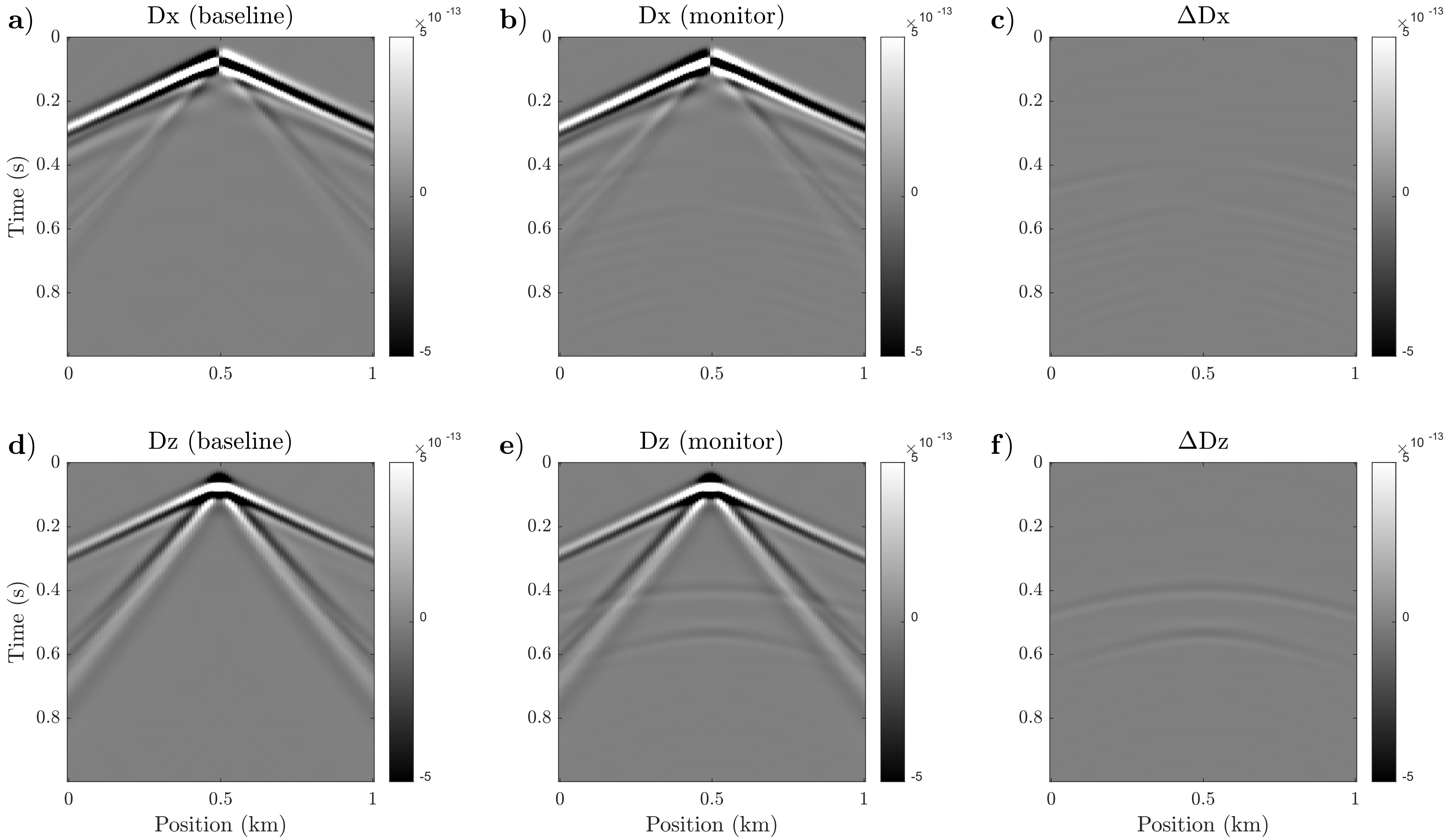
Details of the pressure model



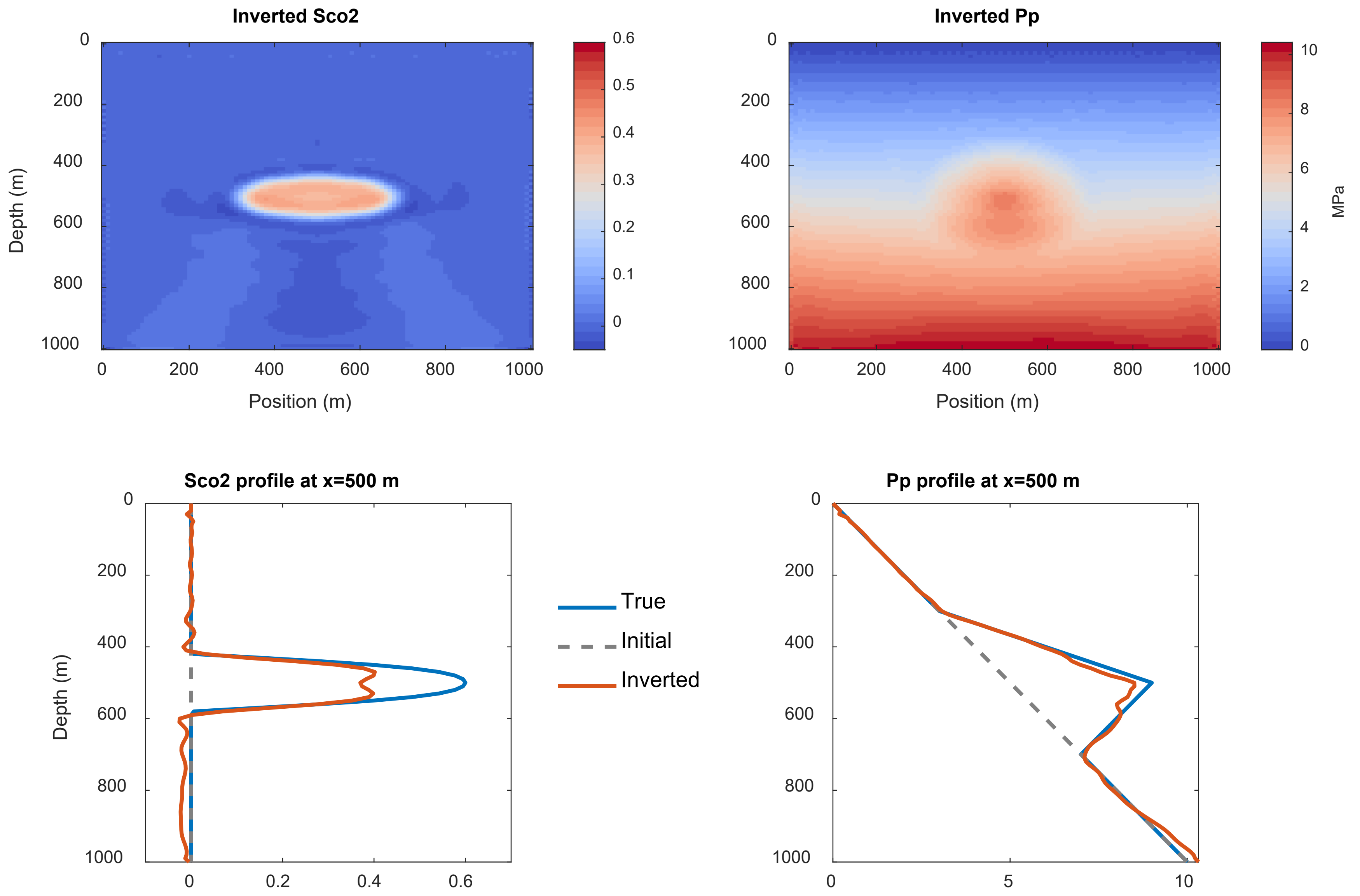
Elastic model



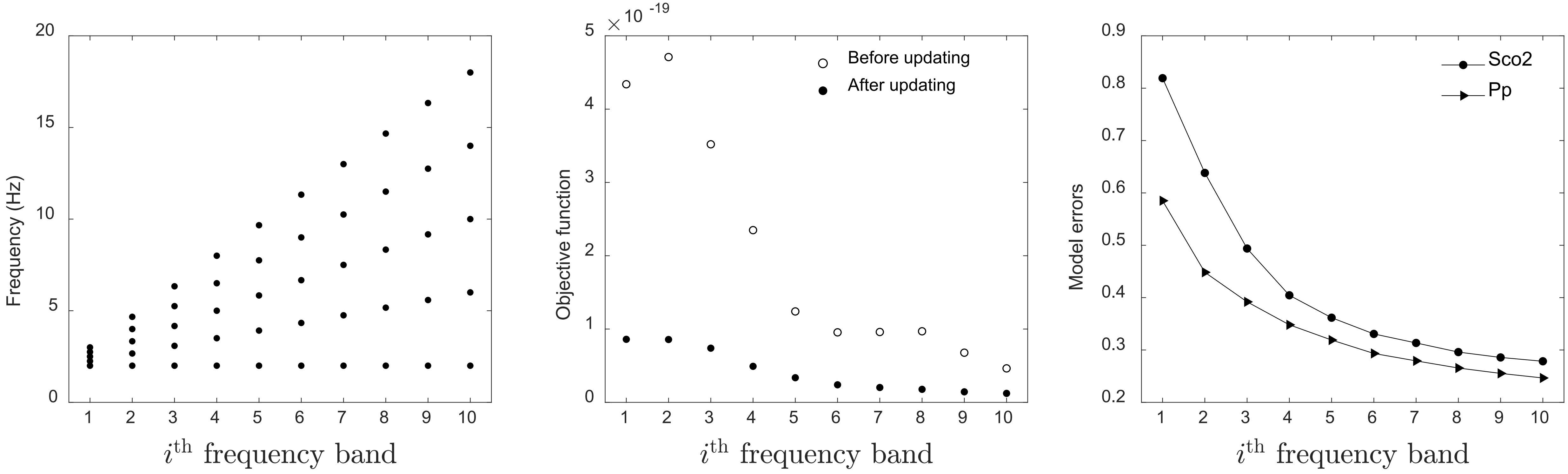
Synthetic data



Inversion result



Convergence properties



Summary

- Outcomes
  - A rock physics model linking porosity, lithology, saturation, and pressure to seismic attributes.
  - An FWI framework for the prediction of dynamic reservoir properties from time-lapse seismic data.
- Challenges
  - Uncertainties in the rock physics relations, baseline estimates, and monitor data.
- Next steps
  - More comprehensive numerical analysis
  - Potential application: CREWES & CMC rapid-repeat surveys.

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