Estimation of rock physics properties via FWI of VSP data recorded by accelerometer and fiberoptic sensors

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Outline

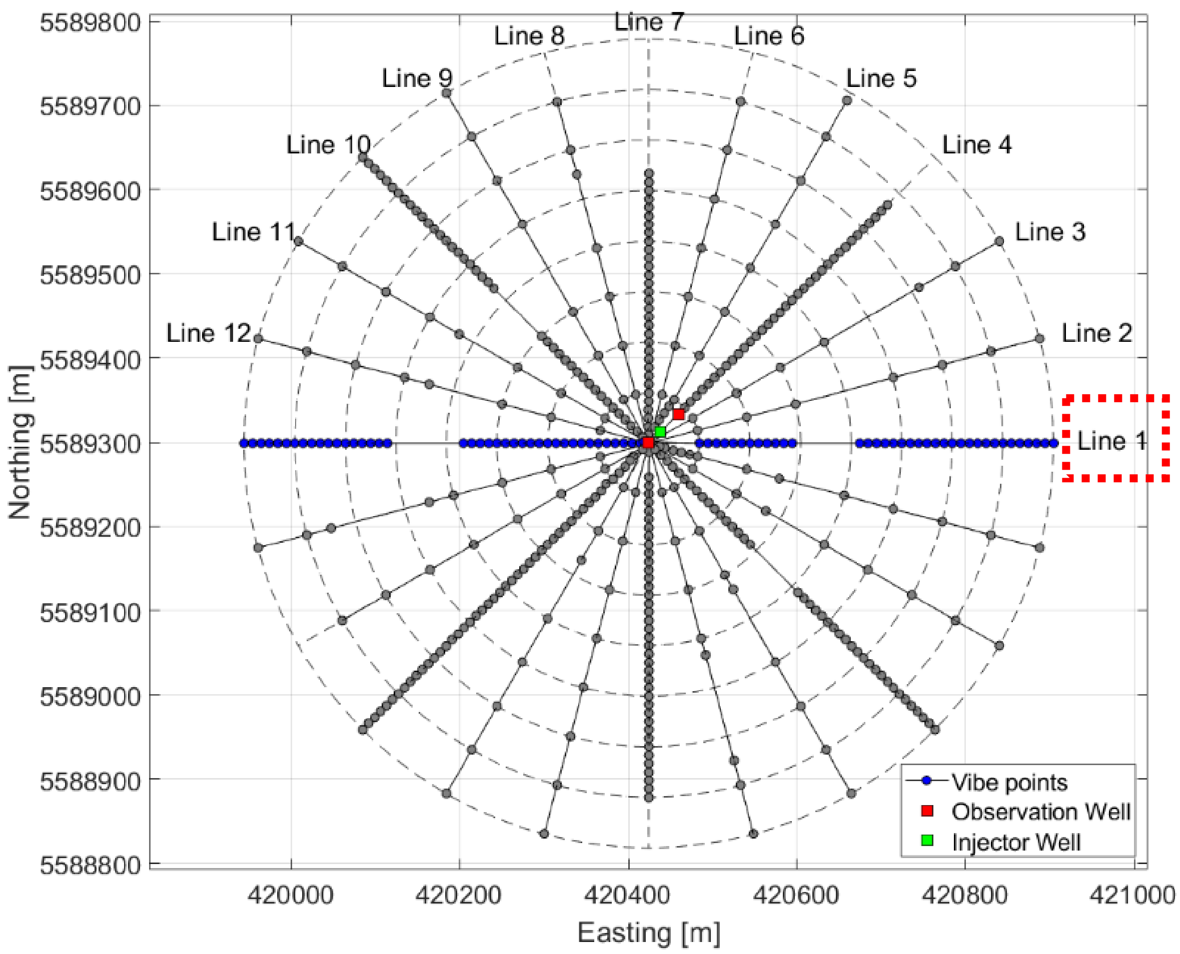
- **Background**
- Elastic FWI
- Rock physics inversion

Background

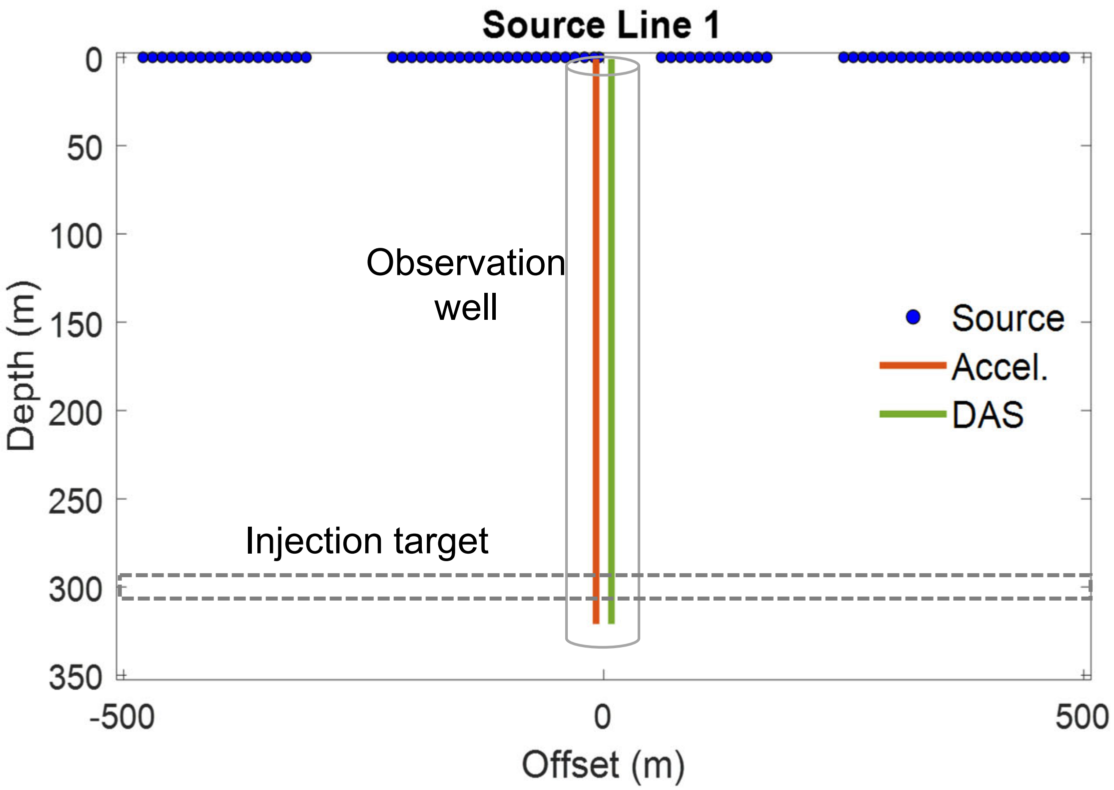

Carbon Management Canada's (CMC) Newell County Facility
A unique Field Research Station for in-field testing to accelerate the development and deployment of technologies to measure, monitor, and verify secure underground storage of CO_2.

2018 3D VSP survey

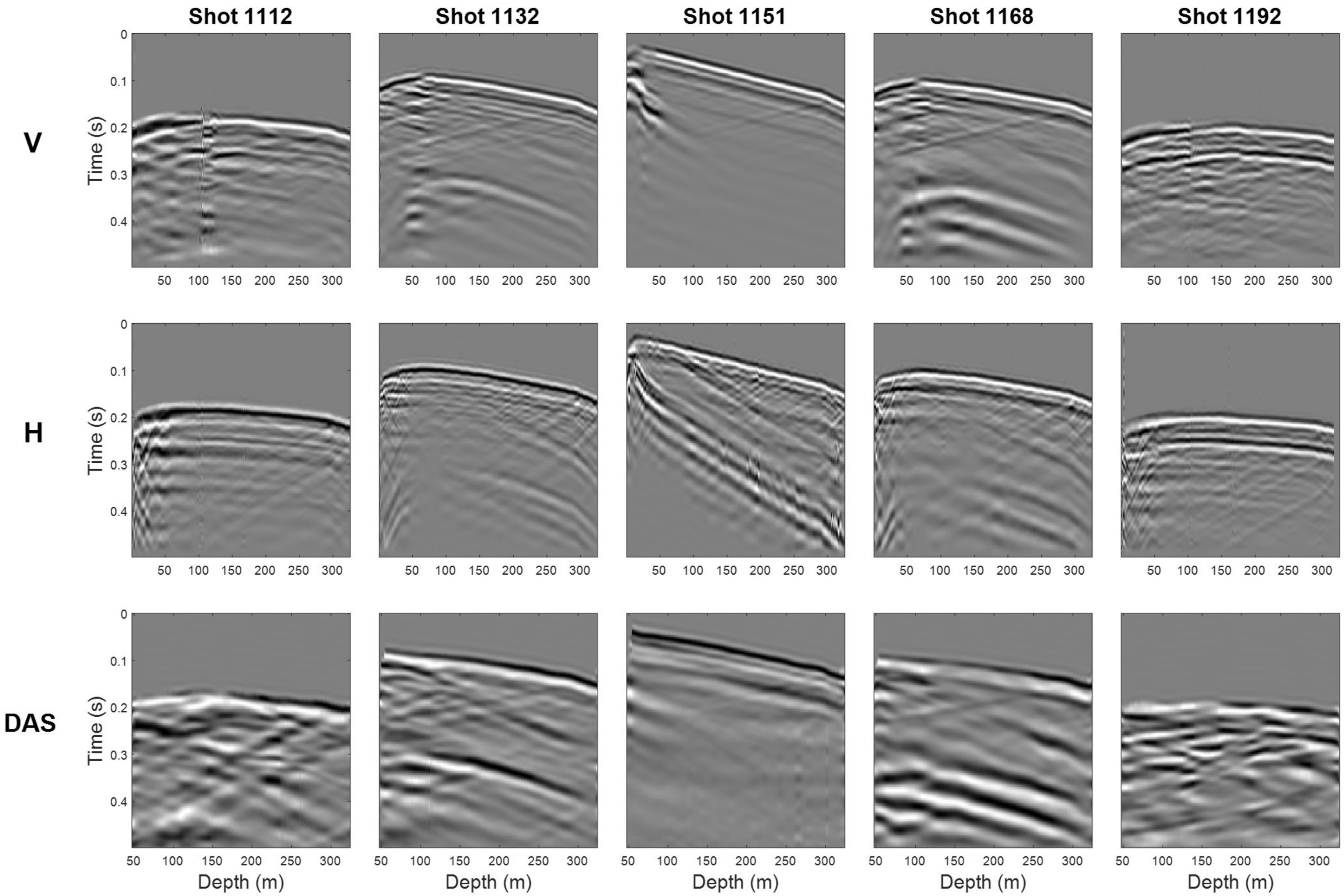
Shot geometry



Section view

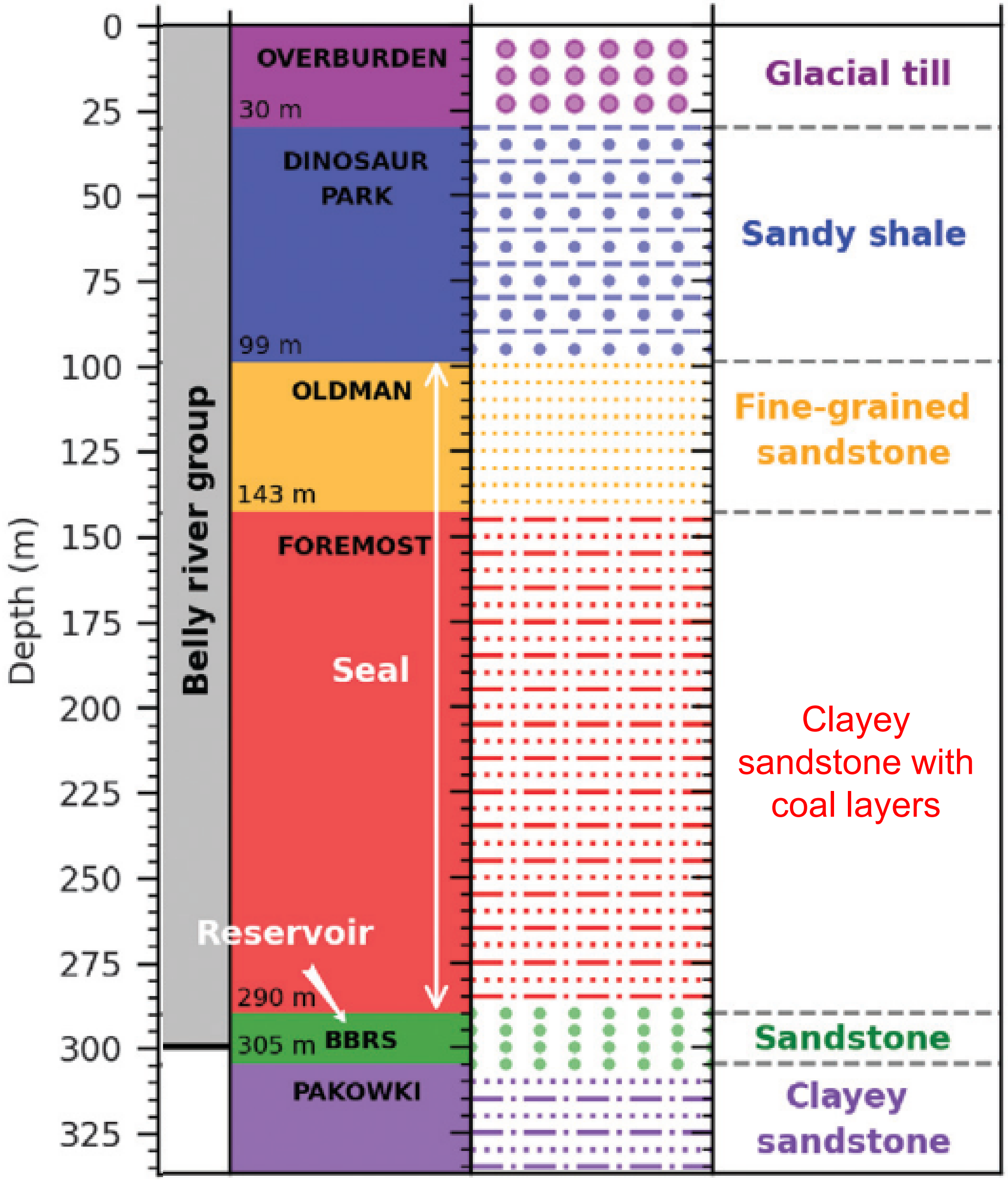


Processed seismic data



Eaid (2021)

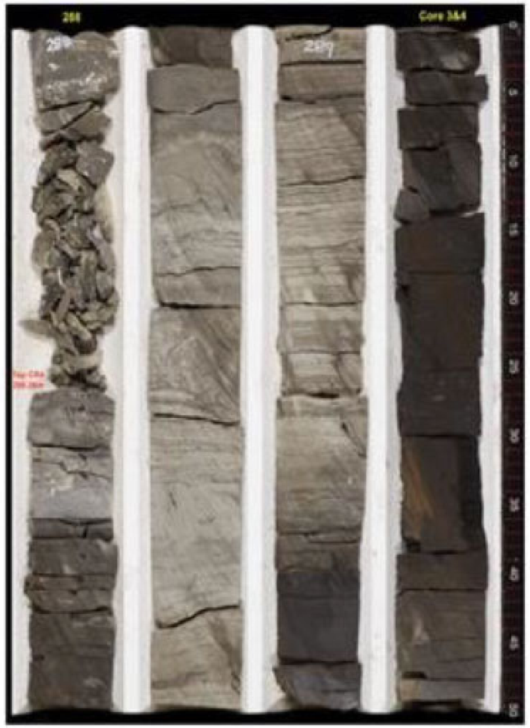
Geology



Pan et al (2023)

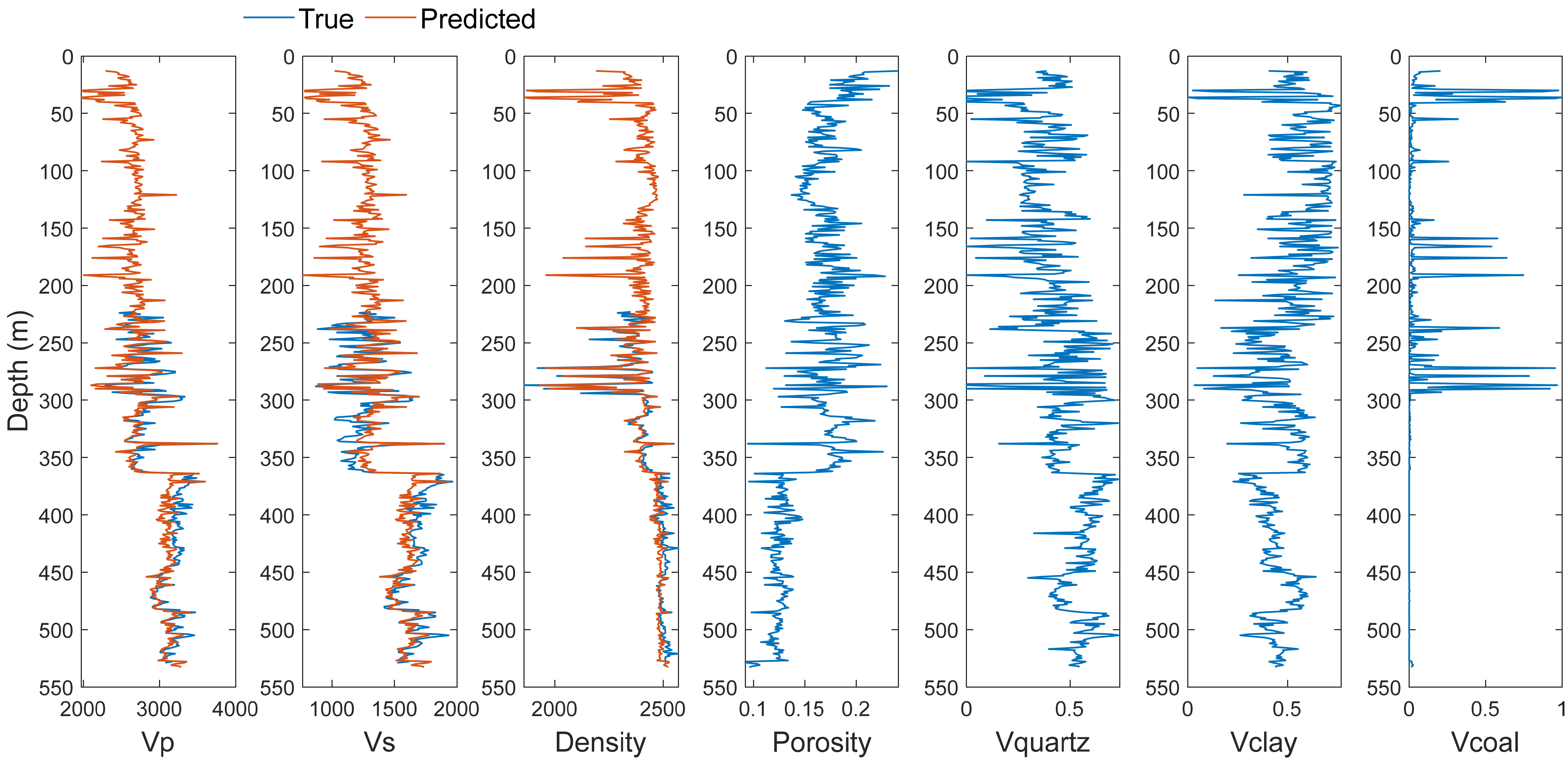
BBRS core (296-298 m)

Caprock (288-290 m)



Macquet et al. (2022)

Well-log data



$$(V_{\mathrm{P}}, V_{\mathrm{S}}, \rho) = g(\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}})$$

- **General problem**

f : Wave propagation model

g : Rock-physics relation

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

Elastic properties

Reservoir properties

$$\underset{\text{Seismic data}}{\mathbf{d}} \xrightarrow{\text{EFWI}} \underset{\text{Elastic Properties}}{\mathbf{m}} \xrightarrow{\text{RPI}} \underset{\text{Reservoir properties}}{\mathbf{r}}$$

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Elastic FWI

- **Constrained optimization problem**

Data

Source term

$$\min_{\mathbf{m}} E = \frac{1}{2}\|\mathbf{R}\mathbf{u} - \mathbf{d}\|_2^2 \quad \text{subject to} \quad \mathbf{A}(\mathbf{m})\mathbf{u} = \mathbf{f}(\omega),$$

Receiver matrix

Impedance matrix

Displacement wavefield

- **Search direction**

Adjoint wavefield

$$\delta\mathbf{m} = -\mathbf{H}^{-1}\ \nabla_{\mathbf{m}} E,$$

where

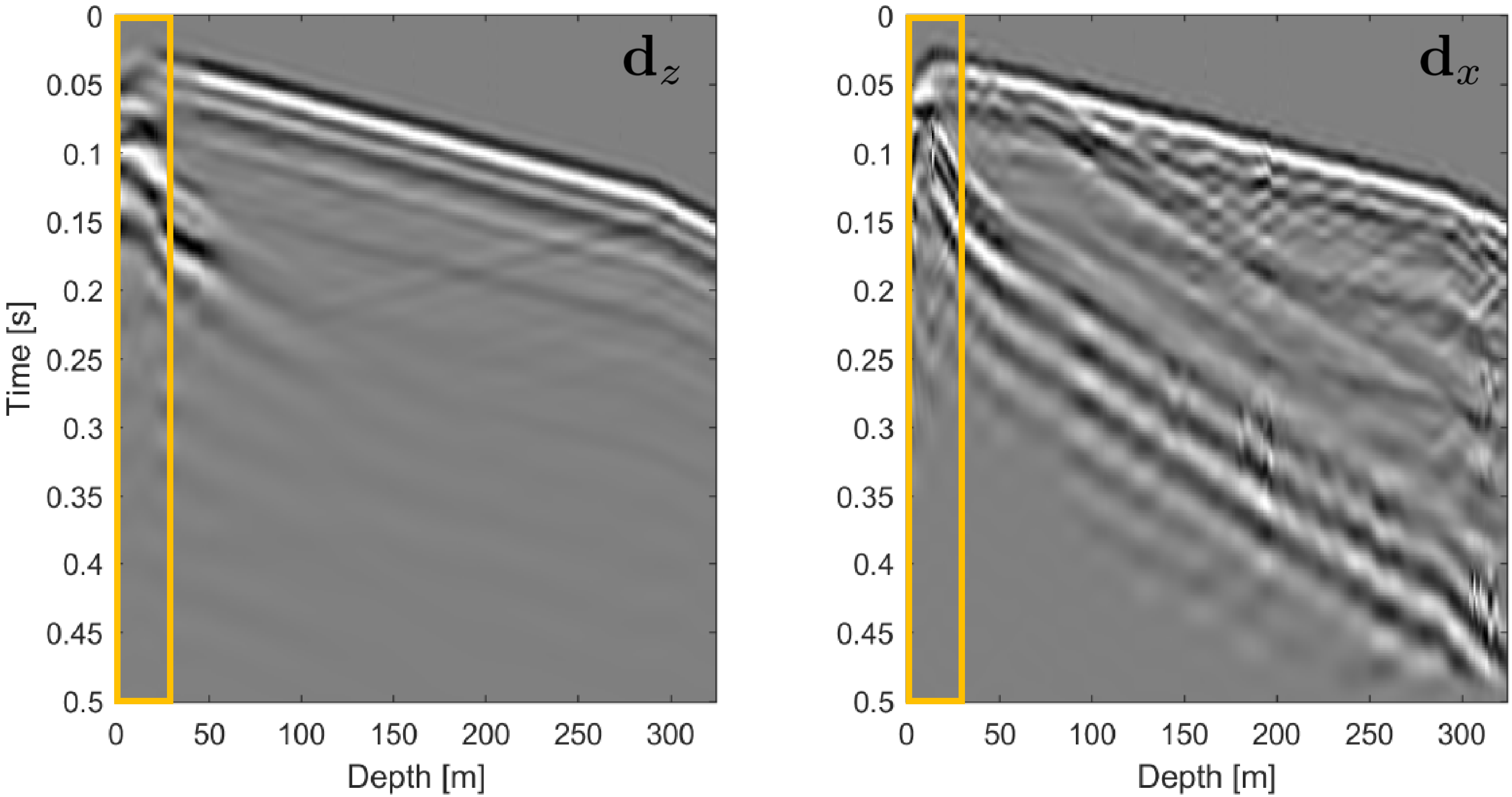
$$\nabla_{m_i} E = \Re\langle \frac{\partial \mathbf{A}}{\partial m_i}\mathbf{u}\ , \lambda\ \rangle.$$

Hessian

Gradient

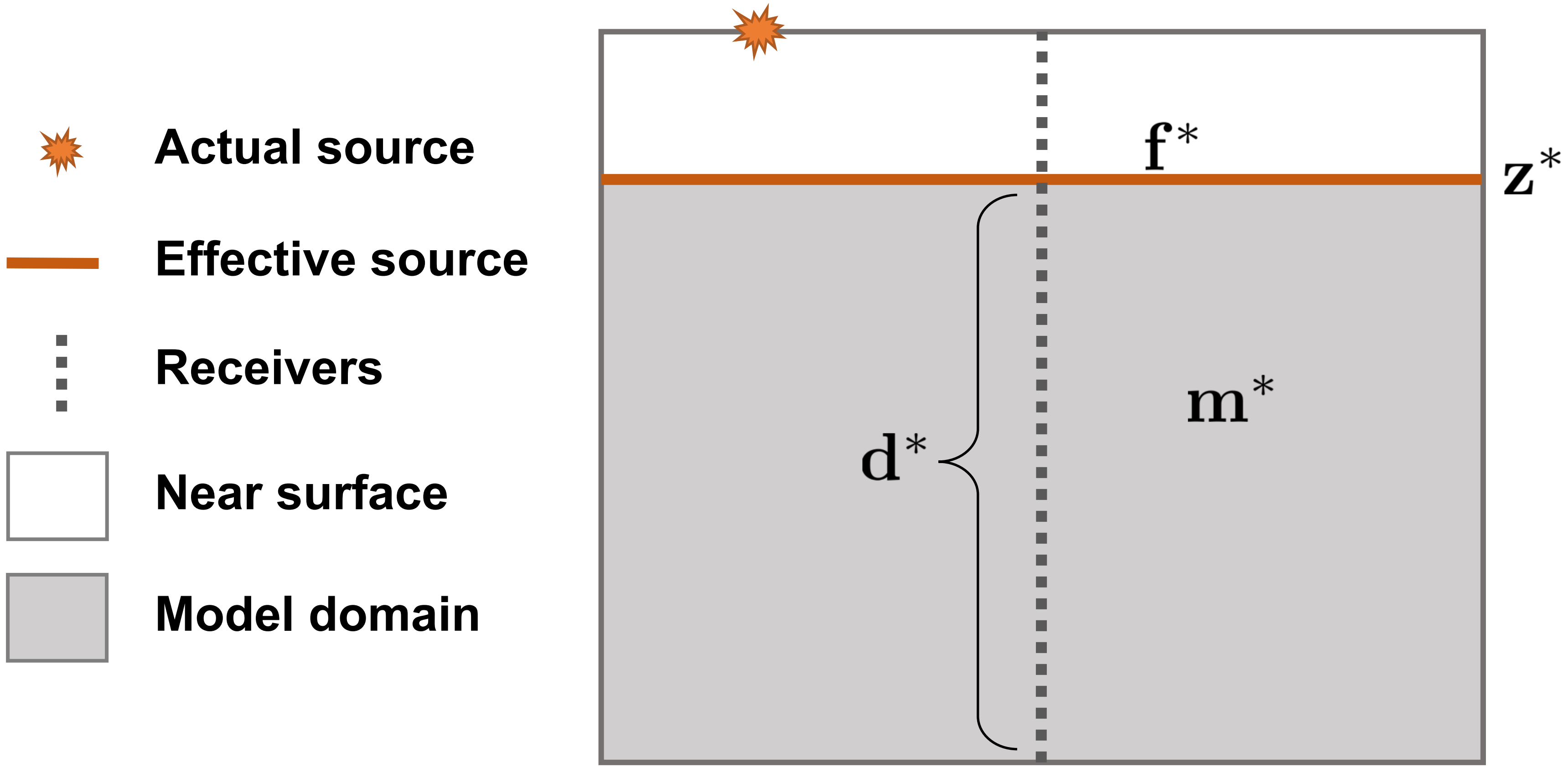
Challenge

- Near-surface complications



- Effective source approach *(Keating, 2021)*

$$\min_{\mathbf{m}^*,\mathbf{f}^*} E = \frac{1}{2}\|\mathbf{R}^*\mathbf{u}^* - \mathbf{d}^*\|_2^2 \quad \text{subject to} \quad \mathbf{A}^*(\mathbf{m}^*)\mathbf{u}^* = \mathbf{f}^*,$$



Challenge

- Incomplete nature of the data

Desirable data qualities for FWI	3C Geophone	DAS
Multicomponent	✓	✗
High S/N	✓	✗
Strong low frequency content	✗	✓
Cost effective dense sampling	✗	✓

FWI strategy

- Modeling strategy to include DAS data in FWI *(Eaid, 2020)*

$$\mathbf{d} = \mathbf{R}\mathbf{u}$$

$$\begin{array}{c} \mathbf{d}_x \\ \\ \mathbf{d}_z \\ \\ \mathbf{e}_t \end{array} \begin{bmatrix} d_x^1 \\ \vdots \\ d_x^{N_g} \\ \hline d_z^1 \\ \vdots \\ d_z^{N_g} \\ \hline e_t^1 \\ \vdots \\ e_t^{N_d} \end{bmatrix} = \begin{bmatrix} & 1 & & & & & & \\ \vdots & & & & & & & \\ & & & & & 1 & & \\ \hline & & 1 & & & & & \\ \vdots & & & & & & & \\ & & & & & & 1 & \\ \hline & w_1 & w_2 & \dots & w_3 & w_4 & & \\ \vdots & & & & & & & \\ & & w_1 & w_2 & \dots & w_3 & w_4 & \end{bmatrix} \begin{bmatrix} u_x^1 \\ u_z^1 \\ u_x^2 \\ u_z^2 \\ \vdots \\ u_x^N \\ u_z^N \end{bmatrix}$$

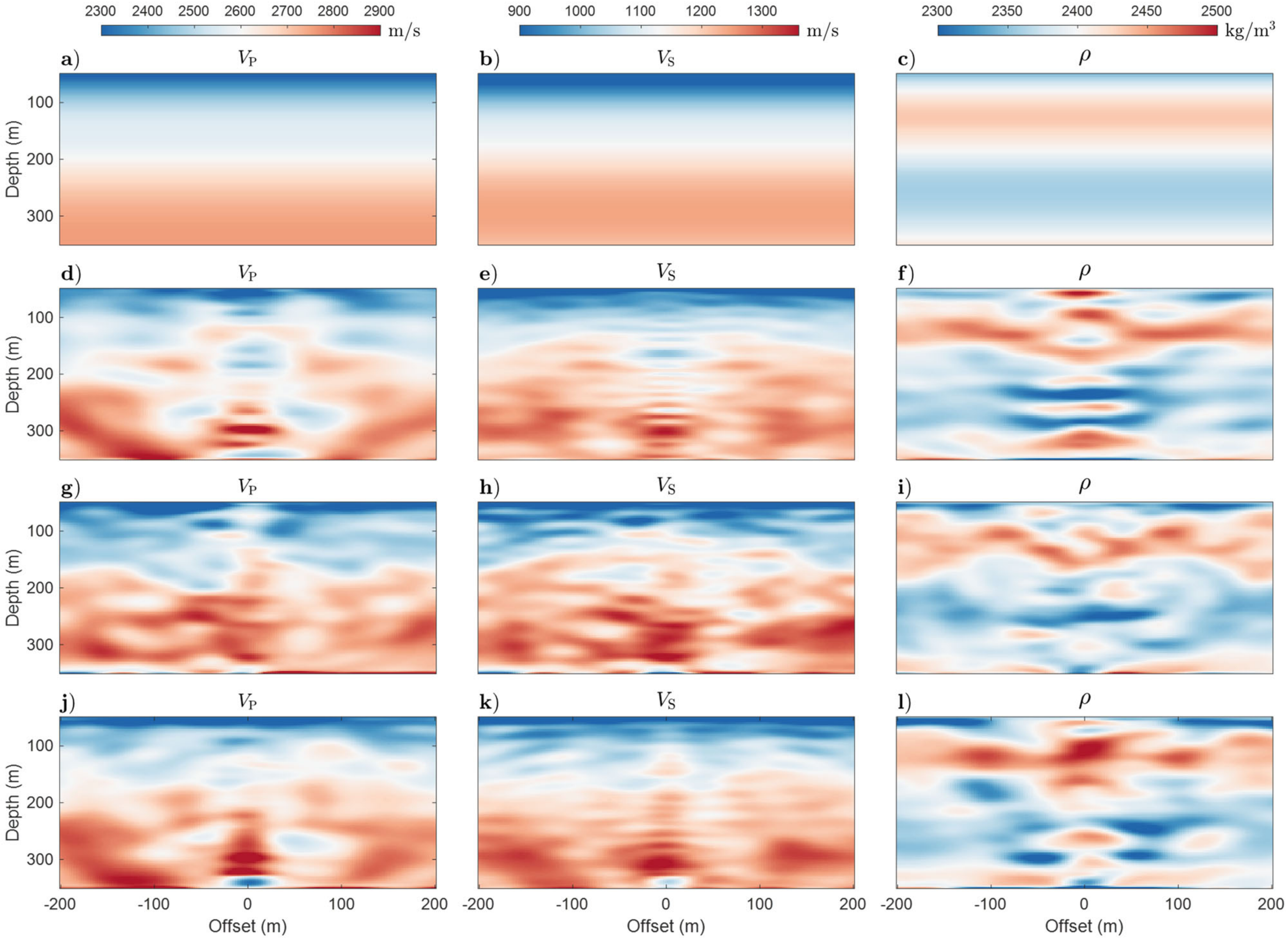
Elastic FWI results

Initial

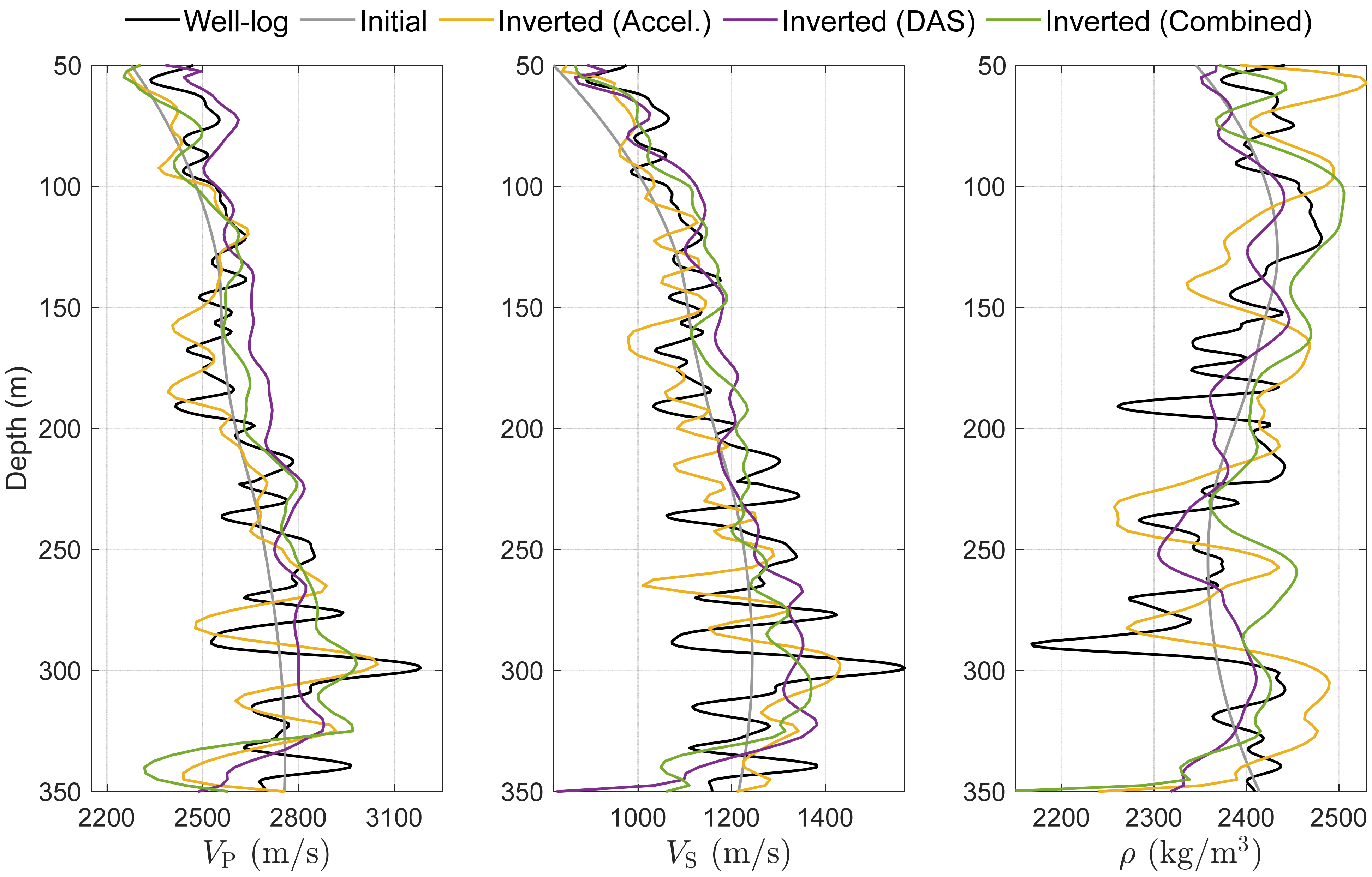
Inverted (Accel.)

Inverted (DAS)

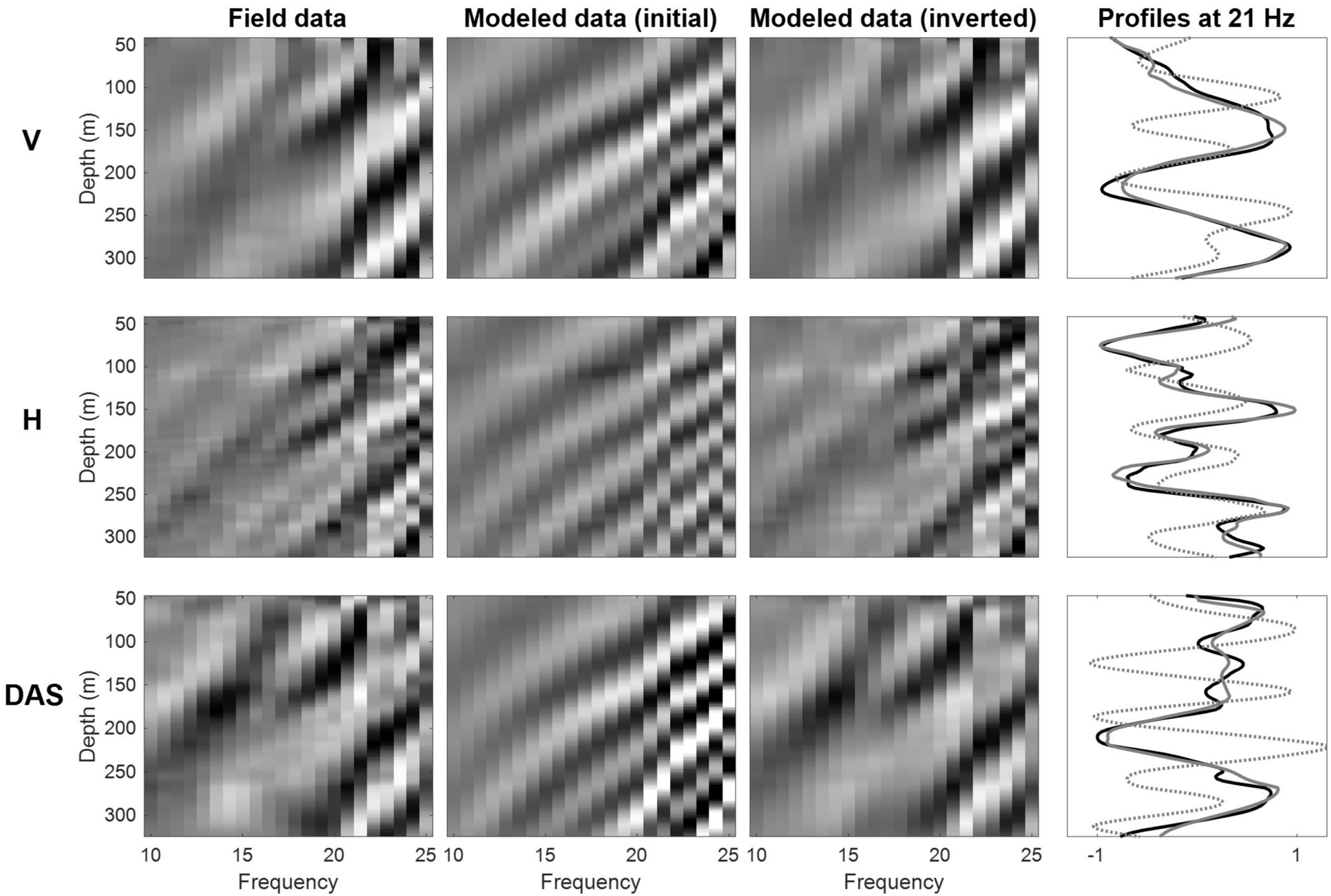
Inverted (Accel.+DAS)



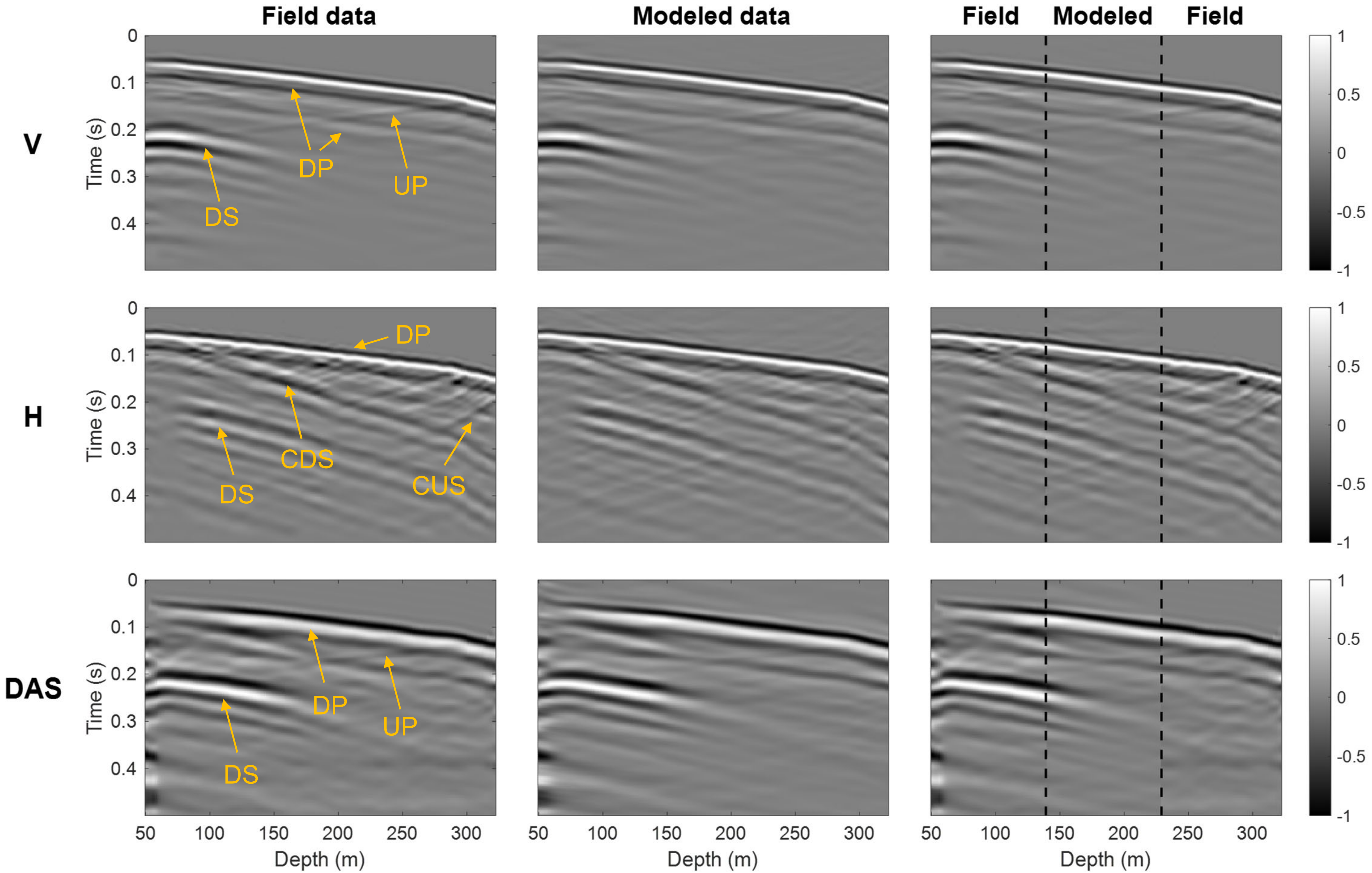
Model profiles at the well location



Data fitting (frequency domain)



Data fitting (time domain)



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- **Rock physics inversion**

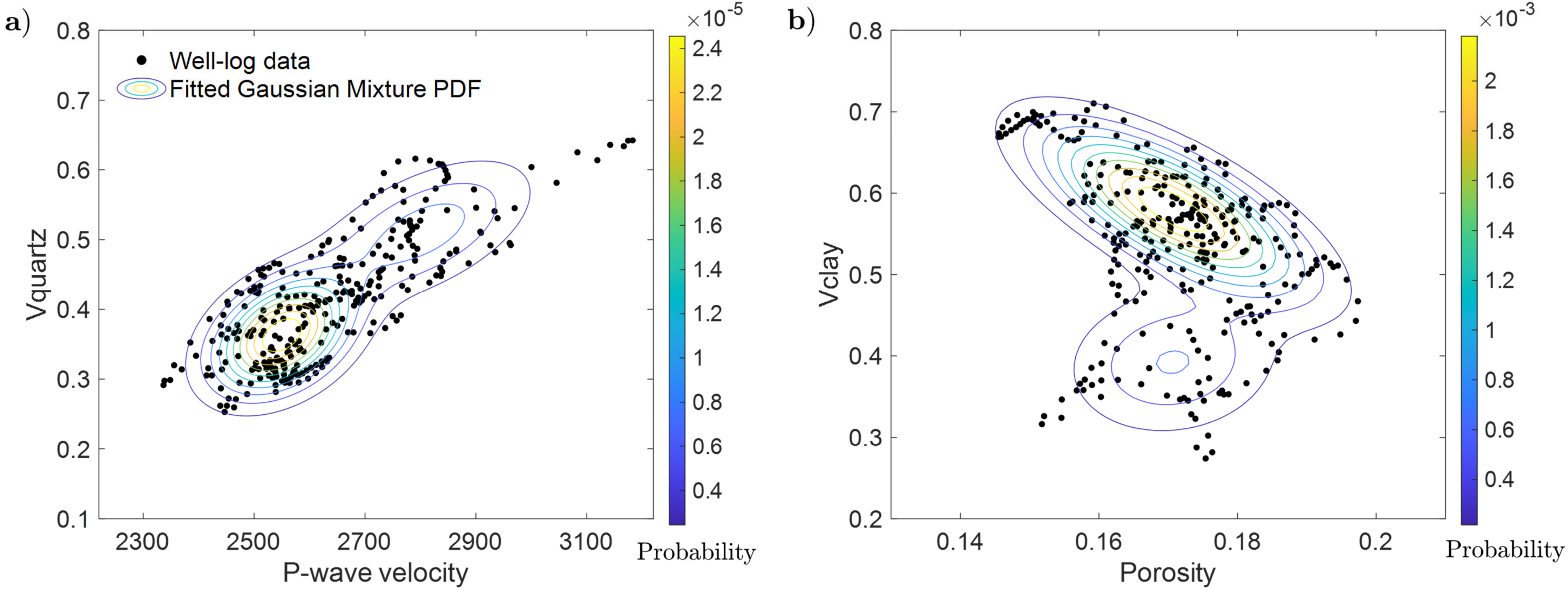
- General problem

$$\mathbf{m} = g(\mathbf{r}) + \mathbf{e},$$

- Bayesian setting

$$P(\mathbf{r}|\mathbf{m}) = \frac{P(\mathbf{r}, \mathbf{m})}{P(\mathbf{m})} = \frac{P(\mathbf{m}|\mathbf{r})P(\mathbf{r})}{P(\mathbf{m})},$$

Rock physics inversion



Rock physics inversion

- Gaussian mixture approach *(Grana and Rossa, 2010)*

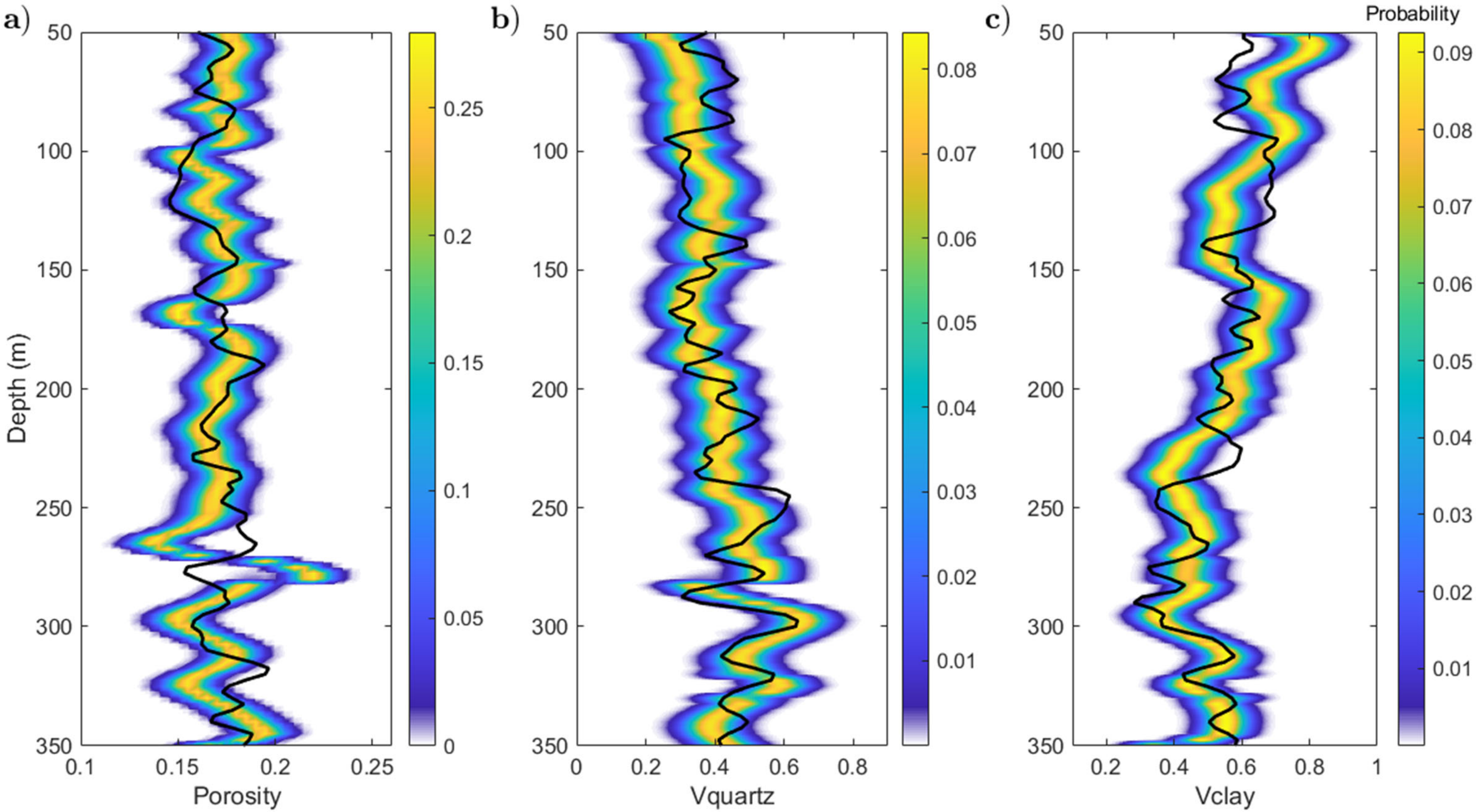
Prior : $$P(\mathbf{r}) = \sum_{k=1}^{N_f} \lambda_k \mathcal{N}(\mathbf{r}; \boldsymbol{\mu}_r^k, \boldsymbol{\Sigma}_r^k),$$

Joint : $$P(\mathbf{r},\mathbf{m}) = \sum_{k=1}^{N_f} \lambda_k \mathcal{N}(\mathbf{y}; \boldsymbol{\mu}_y^k, \boldsymbol{\Sigma}_y^k), \quad \text{where} \quad \mathbf{y} = (\mathbf{r},\mathbf{m}),$$

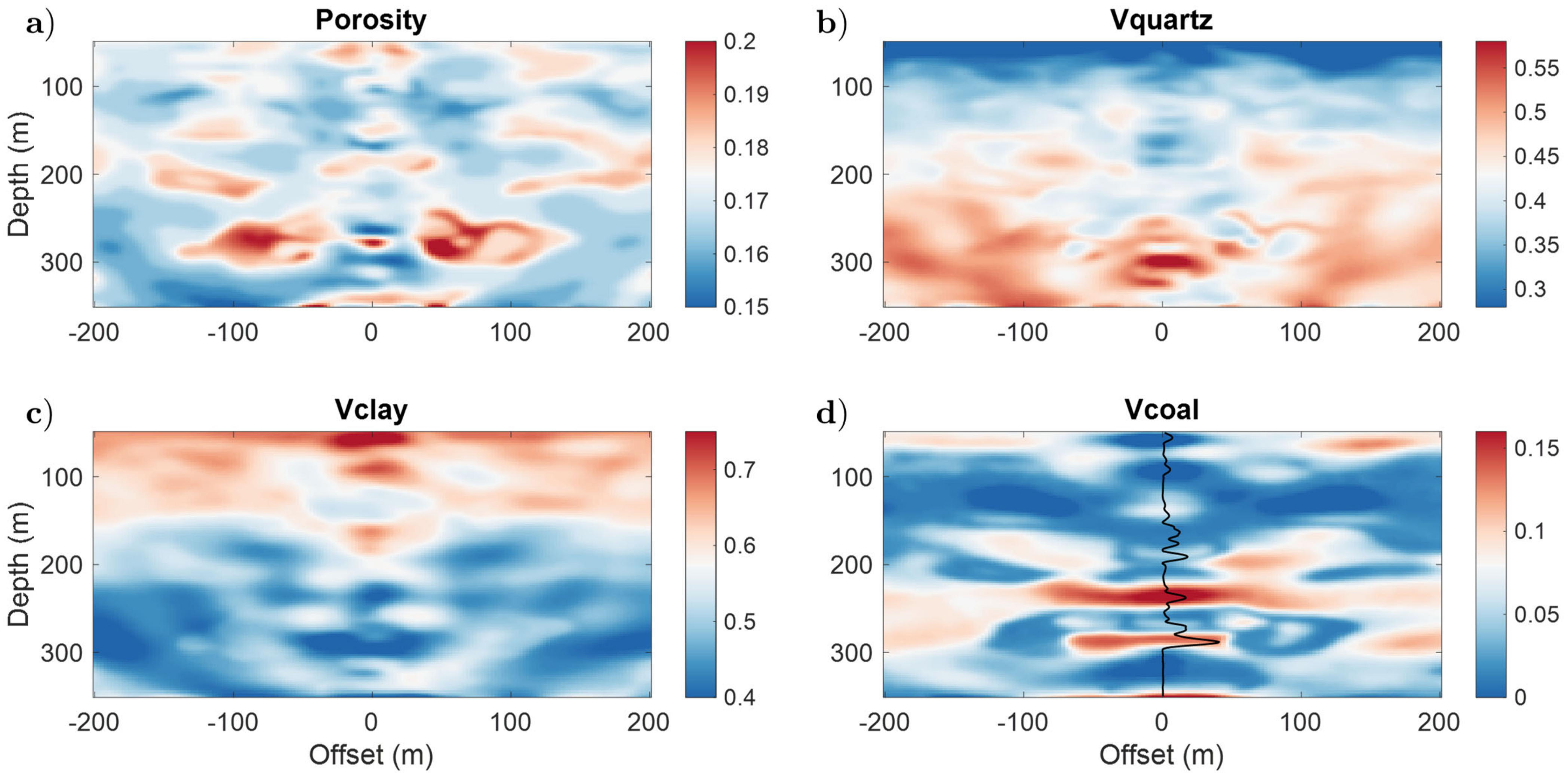
Posterior : $$P(\mathbf{r}|\mathbf{m}) = \sum_{k=1}^{N_f} \lambda_k^{'} \mathcal{N}(\mathbf{r}; \boldsymbol{\mu}_{r|m}^k, \boldsymbol{\Sigma}_{r|m}^k),$$

with
$$\boldsymbol{\mu}_{r|m}^k = \boldsymbol{\mu}_r^k + \boldsymbol{\Sigma}_{r,m}^k (\boldsymbol{\Sigma}_{m,m}^k)^{-1} (\mathbf{m} - \boldsymbol{\mu}_m^k)$$
$$\boldsymbol{\Sigma}_{r|m}^k = \boldsymbol{\Sigma}_{r,r}^k - \boldsymbol{\Sigma}_{r,m}^k (\boldsymbol{\Sigma}_{m,m}^k)^{-1} \boldsymbol{\Sigma}_{m,r}^k.$$

Inversion results at the well location



MAP solution (2D)



Summary

- We applied a sequential inversion scheme combining elastic FWI and rock physics to a VSP dataset including accelerometer and DAS measurements.
- Our key strategies include an effective source approach to cope with near-surface complications, a modeling strategy to simulate DAS data, and a Bayesian Gaussian mixture approach to predict rock properties.
- The proposed methodology can be extended to time-lapse analysis, to predict dynamic reservoir properties such as CO2 saturation and pore pressure.

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