Rock physics analysis of well-log data

Qi Hu, Kris Innanen, and Marie Macquet

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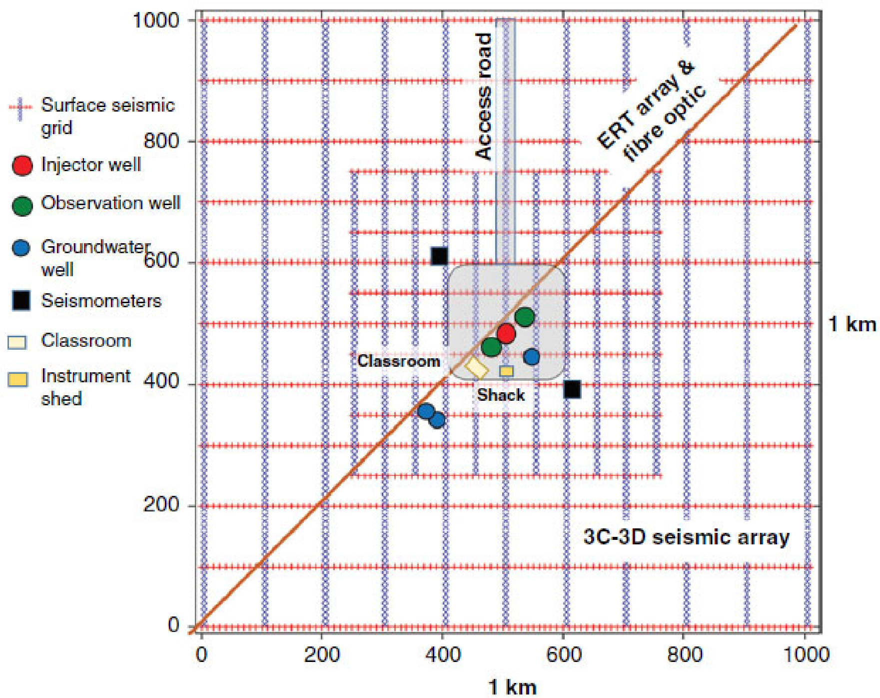
NSERC CRSNG
UNIVERSITY OF CALGARY
FACULTY OF SCIENCE
Department of Geoscience
Carbon Management Canada

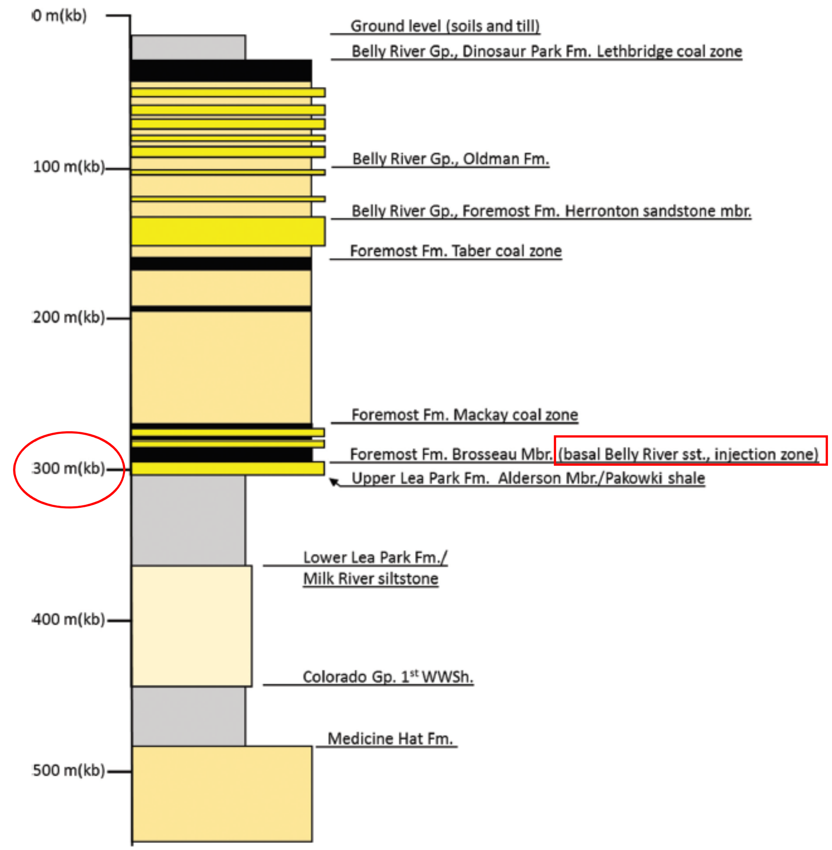
Outline

- **Background: the Countess 10-22 well**
- Rock physics modeling
- Rock physics interpretation

Background



Layout of the FRS, showing the seismic acquisition grid and well locations (Lawton, 2019)



Stratigraphic succession in the Injection well (Countess 10-22)

Wireline logs in Countess 10-22

- **Acquired (2015):**

gamma ray, caliper, resistivity, dipole sonic, bulk density, etc

For study

$V_{\mathrm{P}} - V_{\mathrm{S}} - \rho$

- **Interpreted** using Schlumberger's elemental log analysis (ELAN) :

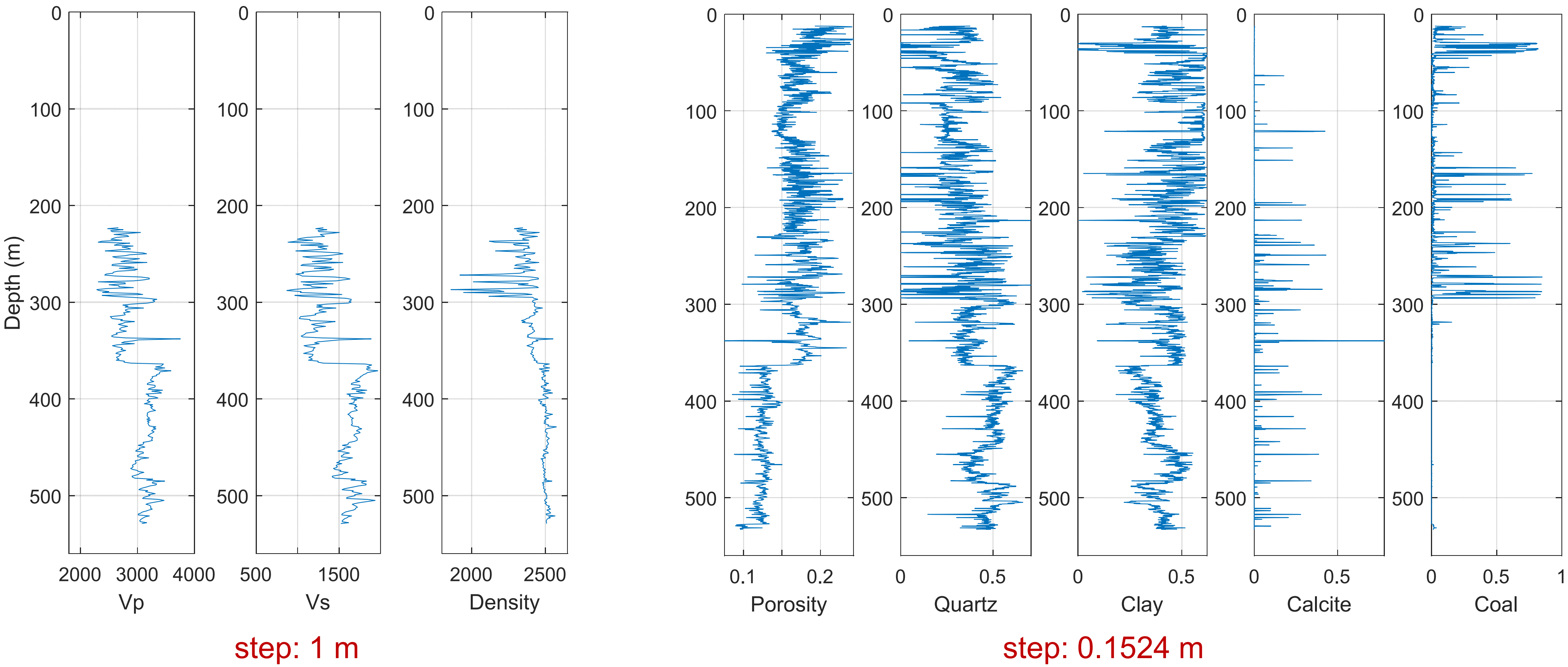
porosity, permeability, solid and fluid compositions, etc.

Porosity,
solid and fluid compositions

Background

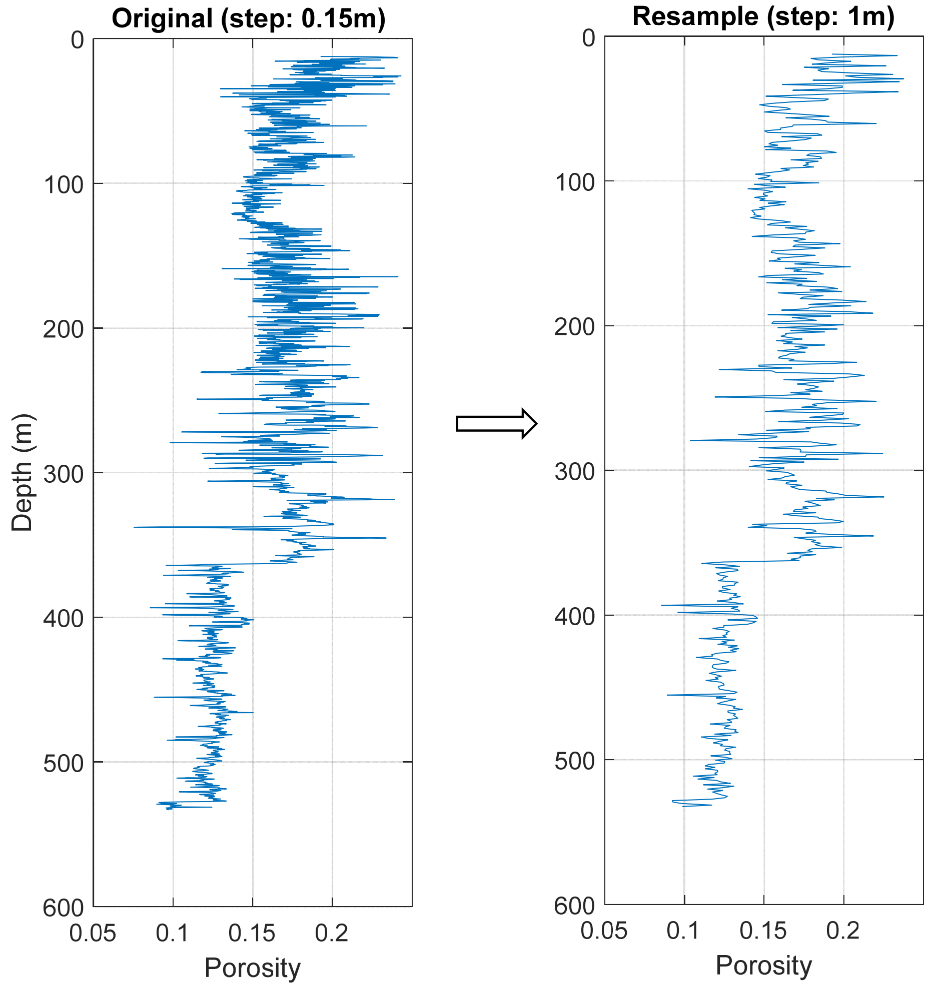
Goal: Establish a link between rock physics properties and elastic parameters.

$$(V_{\mathrm{P}}, V_{\mathrm{S}}, \rho) = f(\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}}, V_{\mathrm{ca}}, V_{\mathrm{co}}, \ldots) \quad f\text{: Rock-physics model}$$



Background

Resampling



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- Injection well (Countess 10-22) at the FRS
- **Rock physics modeling**
- Rock physics interpretation

Rock physics modeling

- **Rock physics model**

Dry rock
(Soft-sand model)

Two endpoints

Solid phase $(\phi = 0\ )$ **(Voigt-Reuss-Hill)**

Dry rock at $\phi_c \approx 0.4$ **(Hertz-Mindlin)**

$$K_0 = \frac{1}{2}\left[\sum_{i=1}^{N} f_i K_i + \left(\sum_{i=1}^{N} f_i / K_i\right)^{-1}\right].$$

$$K_{\mathrm{HM}} = \left[\frac{n^2(1-\phi_c)^2 G_0^2}{18\pi^2(1-v_0)^2} P_{\mathrm{e}}\right]^{1/3}$$

Interplolate $\phi \in (0, \phi_c)$ **using Hashin-Strikman upper bounds**

$$K_{\mathrm{dry}} = \left(\frac{\phi/\phi_c}{K_{\mathrm{HM}} + 4/3G_{\mathrm{HM}}} + \frac{1-\phi/\phi_c}{K_0 + 4/3G_{\mathrm{HM}}}\right)^{-1} - 4/3G_{\mathrm{HM}},$$

Saturated rock
(Gassmann's equation)

$$K_{\mathrm{sat}} = K_{\mathrm{dry}} + \frac{(1-K_{\mathrm{dry}}/K_0)^2}{\phi/K_f + (1-\phi)/K_0 - K_{\mathrm{dry}}/K_0^2}$$

Brie's fluid mixing: $K_f = (K_{\mathrm{liquid}} - K_{\mathrm{gas}})(1-S_{\mathrm{gas}})^3 + K_{\mathrm{gas}},$

Rock physics modeling

Rock type:

4 mineral components (quartz, clay, calcite, coal)

2 fluid components (water and CO_2)

Fixed values:

Table 1. Rock physics parameters used in this study

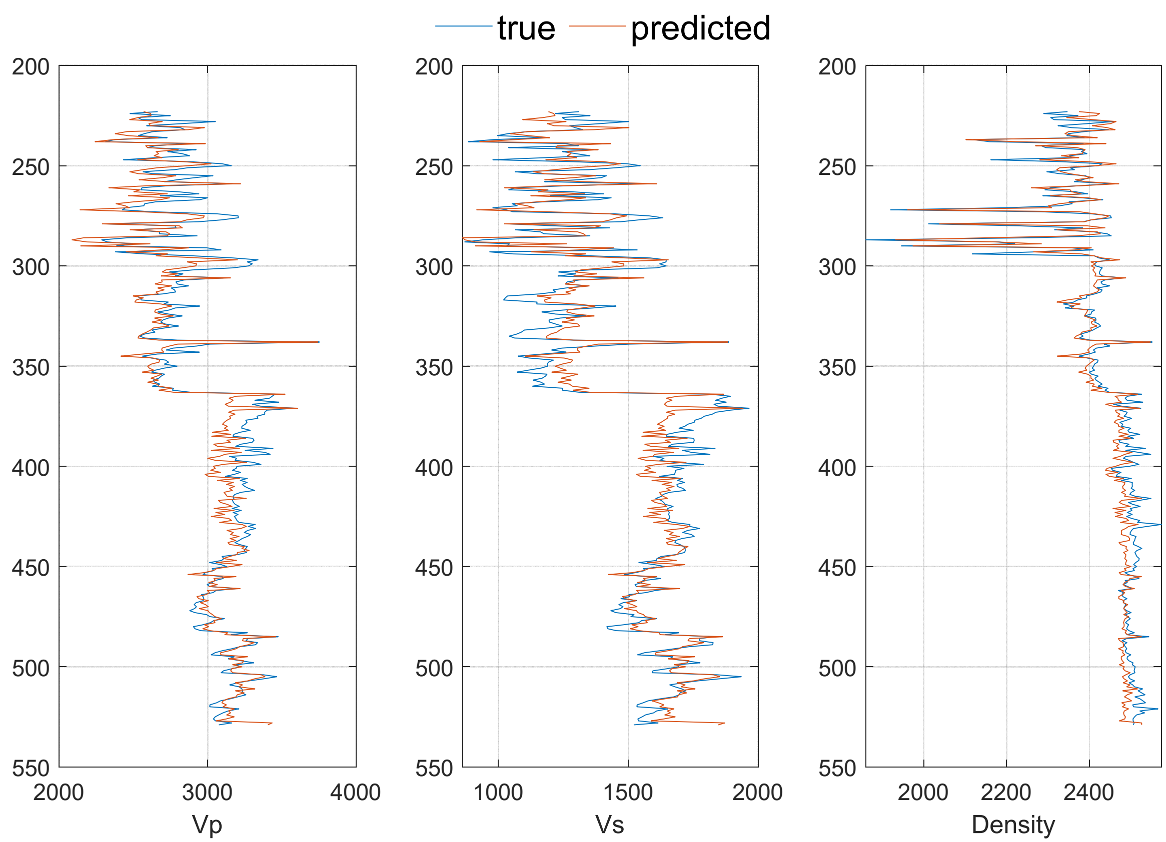
Parameter	Value	Parameter	Value
Quartz bulk modulus	37 GPa	Coal bulk modulus	8 GPa
Quartz shear modulus	44 GPa	Coal shear modulus	3 GPa
Quartz density	2.65 g/cm^3	Coal density	2 g/cm^3
Clay bulk modulus	25 GPa	Water bulk modulus	2.2 GPa
Clay shear modulus	9 GPa	Water density	1 g/cm^3
Clay density	2.6 g/cm^3	CO_2 bulk modulus	0.01 GPa
Calcite bulk modulus	76.8 GPa	CO_2 density	0.4 g/cm^3
Calcite shear modulus	32 GPa	Critical porosity	0.36
Calcite density	2.71 g/cm^3	Degree of adhesion	0.5

Parameters of interest:

$$(V_\text{P}, V_\text{S}, \rho) = f(\phi, V_\text{qu}, V_\text{cl}, V_\text{ca}, V_\text{co}, S_{\text{co}_2}, P_\text{eff})$$

Rock physics modeling

Validation:



Average errors: 3.4% , 5.5% , 1%

Rock physics modeling

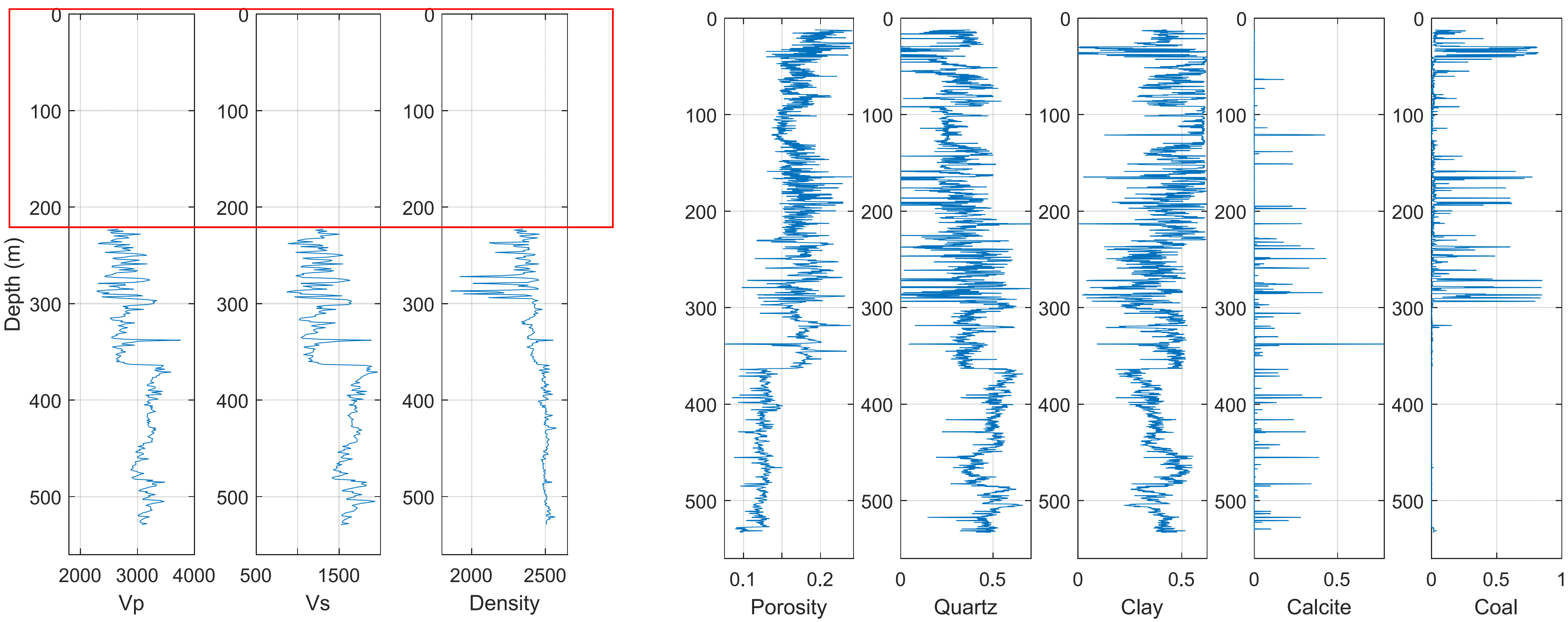
$$(V_{\mathrm{P}}, V_{\mathrm{S}}, \rho) = f(\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}}, V_{\mathrm{ca}}, V_{\mathrm{co}}, S_{\mathrm{co_2}}, P_{\mathrm{eff}})$$

Use of rock physics model:

1. Constructing well logs (especially Vs)

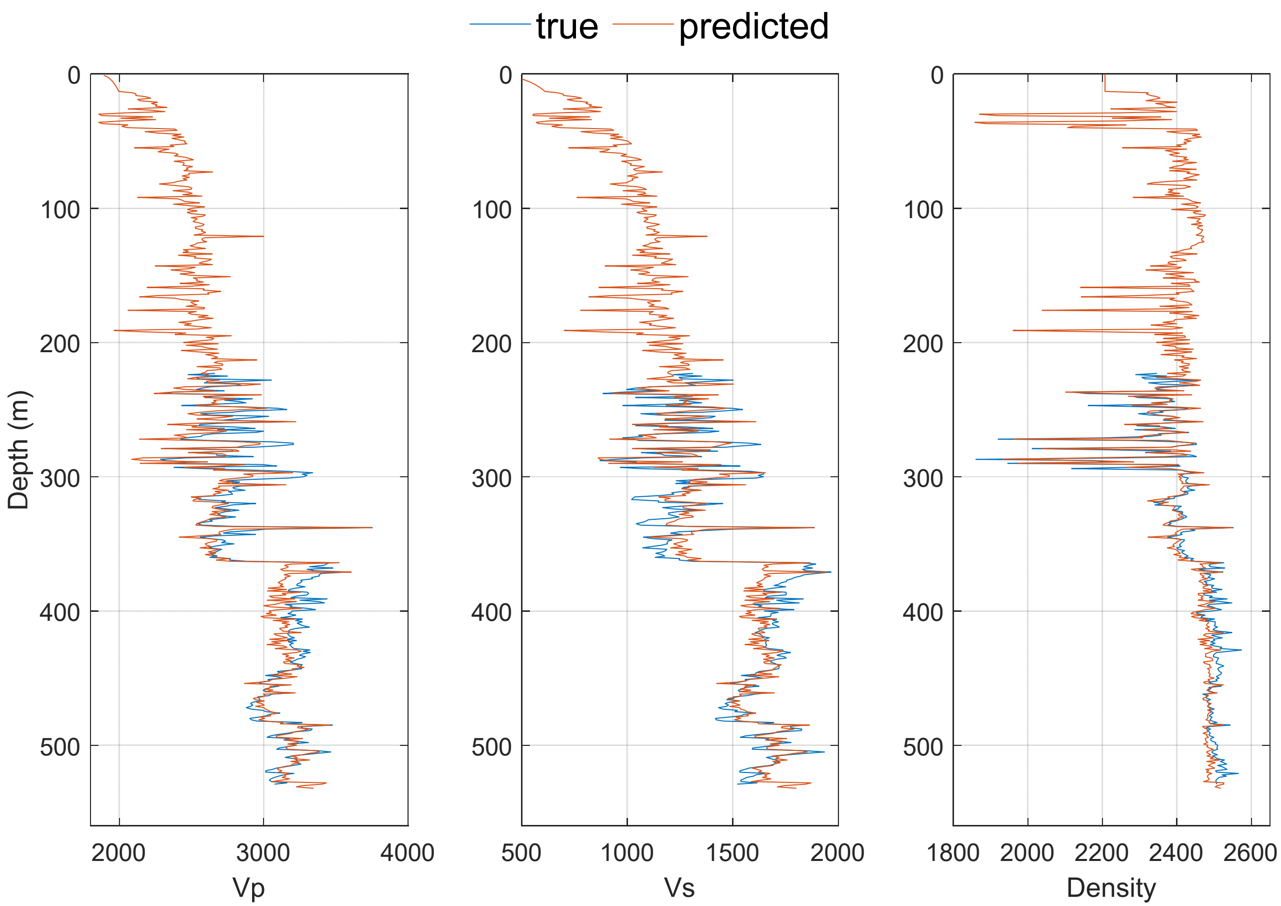
2. Interpretation of rock and fluid properties

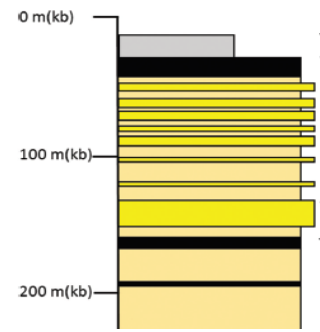
Background



Rock physics modeling

Constructing the shallow section of Vp, Vs, and density logs





Outline

- Injection well (Countess 10-22) at the FRS
- Rock physics modeling
- **Rock physics interpretation**

Rock physics interpretation

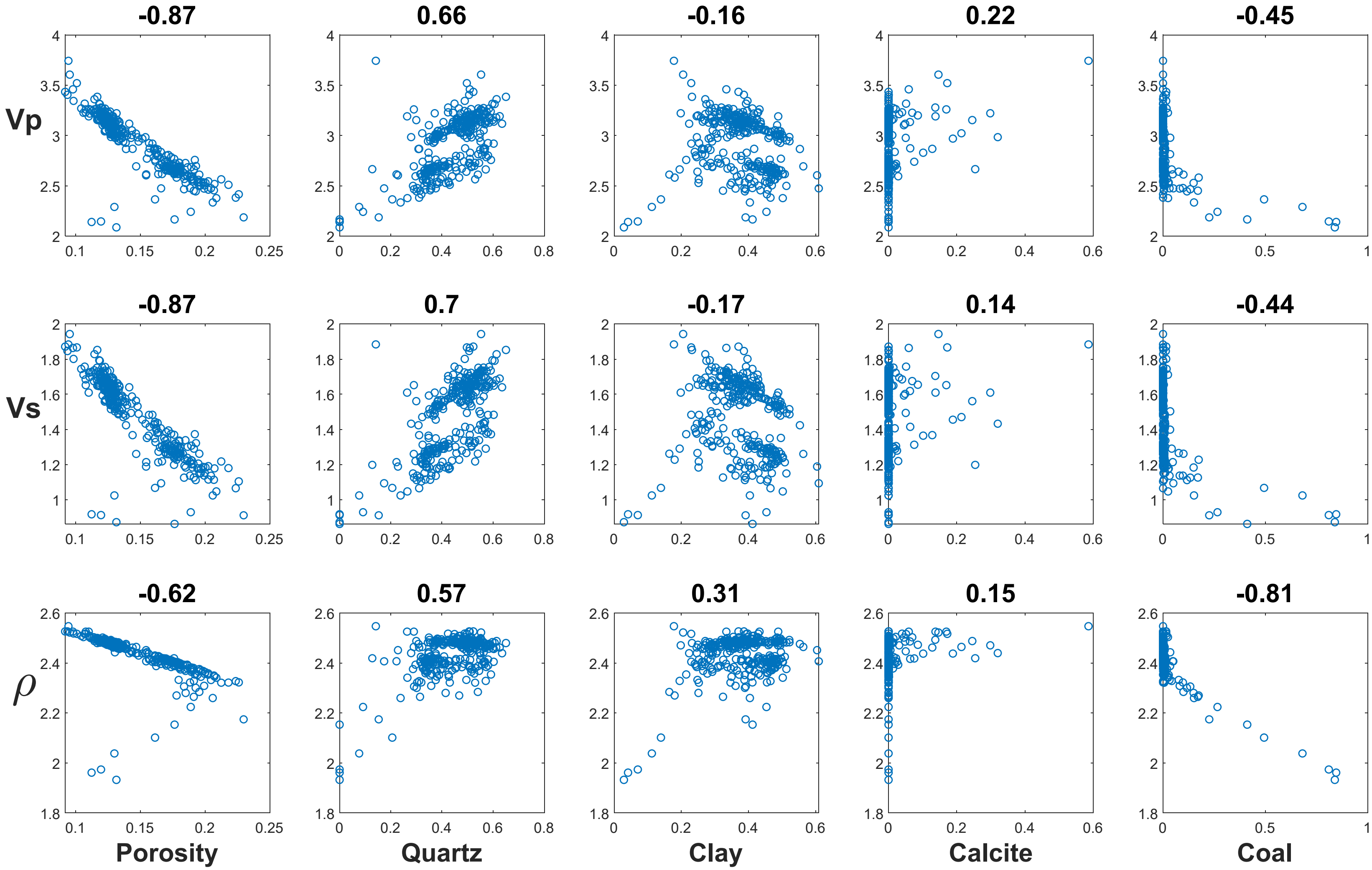
Estimation of rock physics properties from seismic elastic attributes:

$$(V_{\mathrm{P}}, V_{\mathrm{S}}, \rho) = f(\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}}, V_{\mathrm{ca}}, V_{\mathrm{co}}, S_{\mathrm{co_2}}, P_{\mathrm{eff}})$$

Nonlinear inverse problem

Is empirical relationship available?

Rock physics interpretation



Rock physics interpretation

Estimation of rock physics properties from seismic elastic attributes:

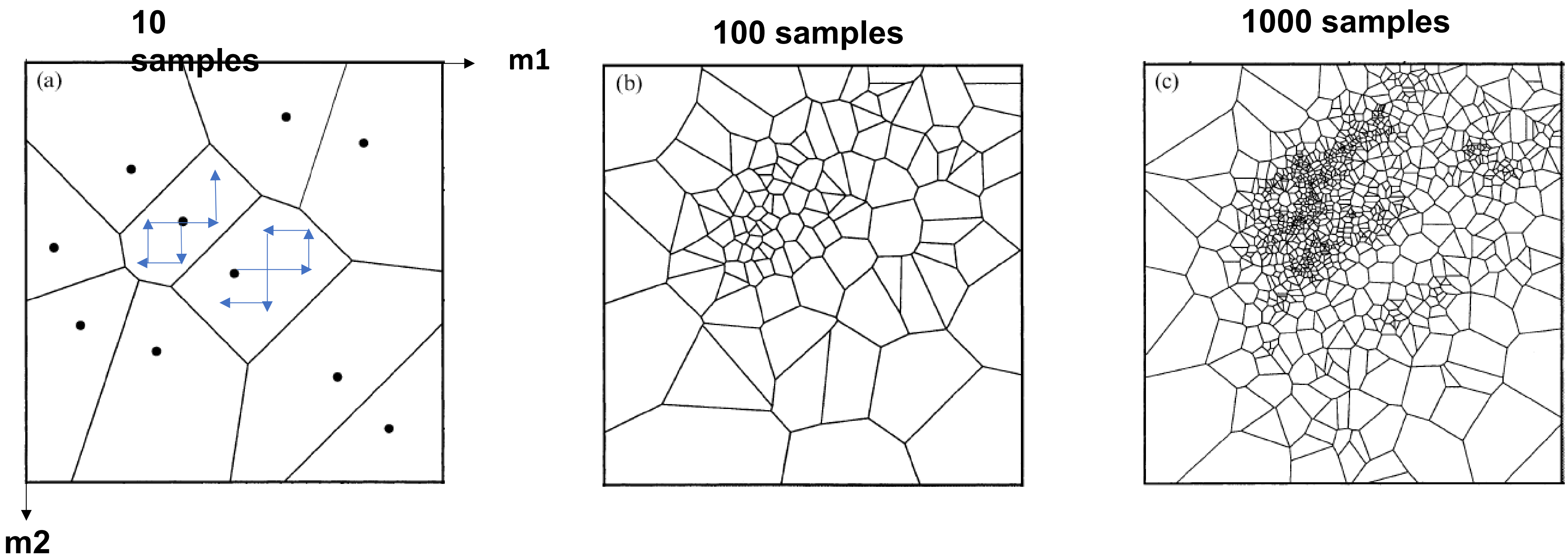
$$\underbrace{(V_{\mathrm{P}}, V_{\mathrm{S}}, \rho)}_{\mathbf{d}} = f(\underbrace{\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}}, V_{\mathrm{ca}}, V_{\mathrm{co}}, S_{\mathrm{co_2}}, P_{\mathrm{eff}}}_{\mathbf{m}})$$

Misfit function: $E(\mathbf{m}) = \|\mathbf{d} - f(\mathbf{m})\|^2$

Optimization: Neighborhood algorithm (directed Monte-Carlo)

Rock physics interpretation

- Neighborhood algorithm (NA)

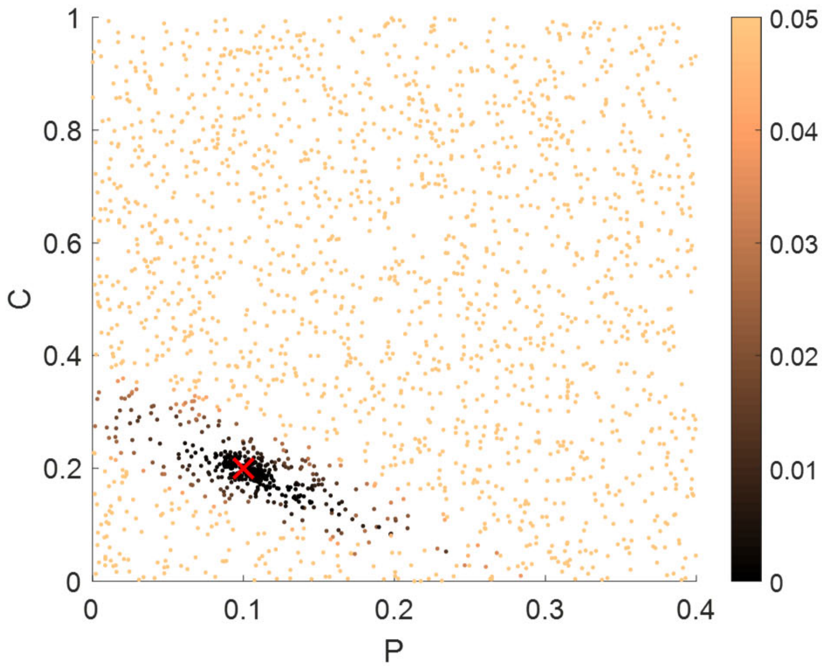


Sambridge, 1999

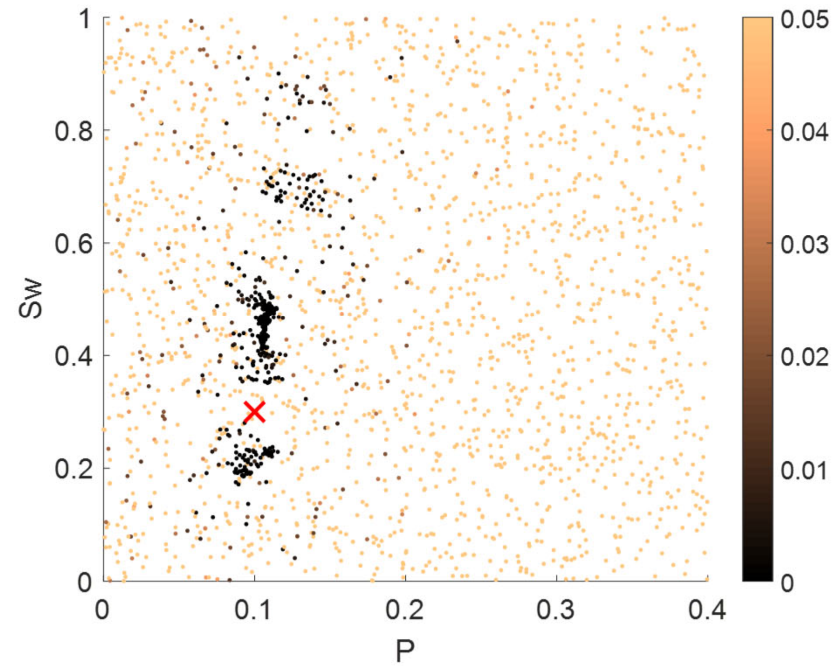
Rock physics interpretation

- Neighborhood algorithm (NA)

Good estimate



Poor estimate



Hu, 2020 CREWES sponsors meeting

Rock physics interpretation

Estimation of rock physics properties from seismic elastic attributes:

$$\underbrace{(V_{\mathrm{P}}, V_{\mathrm{S}}, \rho)}_{\mathbf{d}} = f\underbrace{(\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}}, V_{\mathrm{ca}}, \cancel{V_{\mathrm{co}}}, S_{\mathrm{co_2}}, P_{\mathrm{eff}})}_{\mathbf{m}}$$

$$(V_{\mathrm{P}}, V_{\mathrm{S}}) \qquad (\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}}, V_{\mathrm{ca}})$$

$$(V_{\mathrm{P}}) \qquad (\phi, V_{\mathrm{cl}}, S_{\mathrm{co_2}})$$

$$(\phi, V_{\mathrm{cl}})$$

$$(\phi, S_{\mathrm{co_2}})$$

……

Depending on the type of data available

Depending on the complexity of target rock

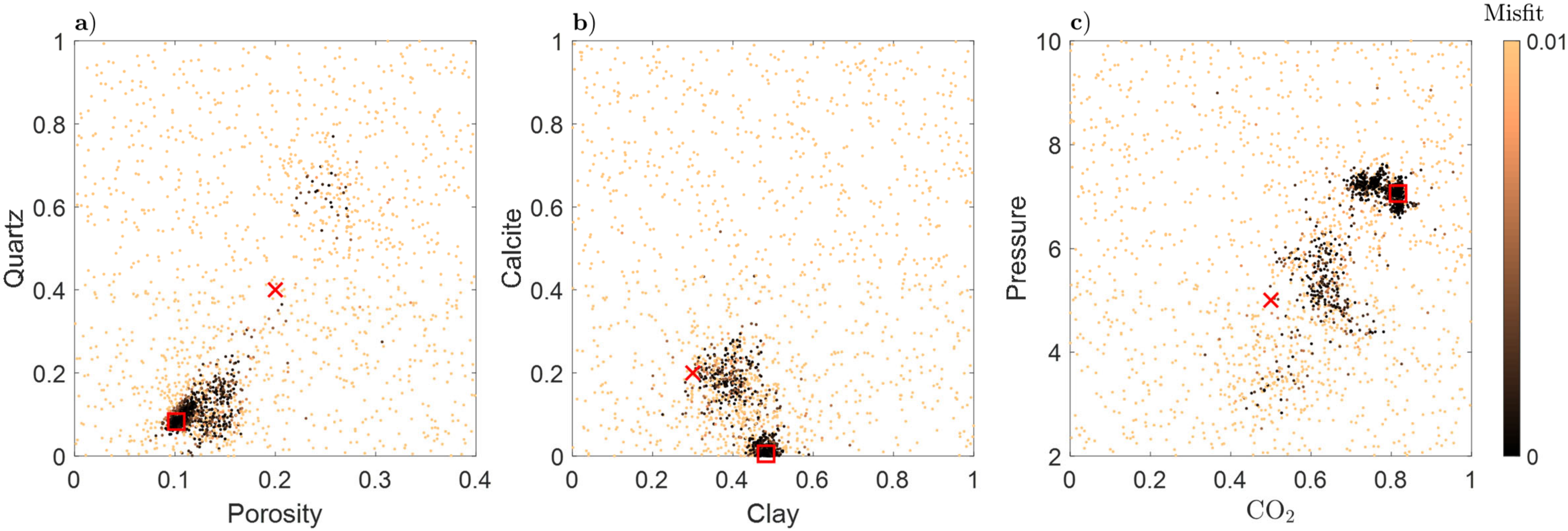
Rock physics interpretation

Cases:

- 6 unknowns: porosity (Ø) + 4 minerals (V_q, V_{cl}, V_{ca}, $\cancel{V_{co}}$) + 2 fluids ($\cancel{S_w}$, S_{co2}) + pressure
- 4 unknowns: porosity (Ø) + 4 minerals (V_q, V_{cl}, V_{ca}, $\cancel{V_{co}}$) + 1 fluid ($\cancel{S_w}$)
- 3 unknowns: porosity (Ø) + 2 minerals ($\cancel{V_q}$, V_{cl}) + 2 fluids ($\cancel{S_w}$, S_{co2})
- 2 unknowns: porosity (Ø) + 2 minerals ($\cancel{V_q}$, V_{cl}) + 1 fluid ($\cancel{S_w}$)
- 2 unknowns: porosity (Ø) + 1 mineral ($\cancel{V_q}$) + 2 fluids ($\cancel{S_w}$, S_{co2})

Rock physics interpretation

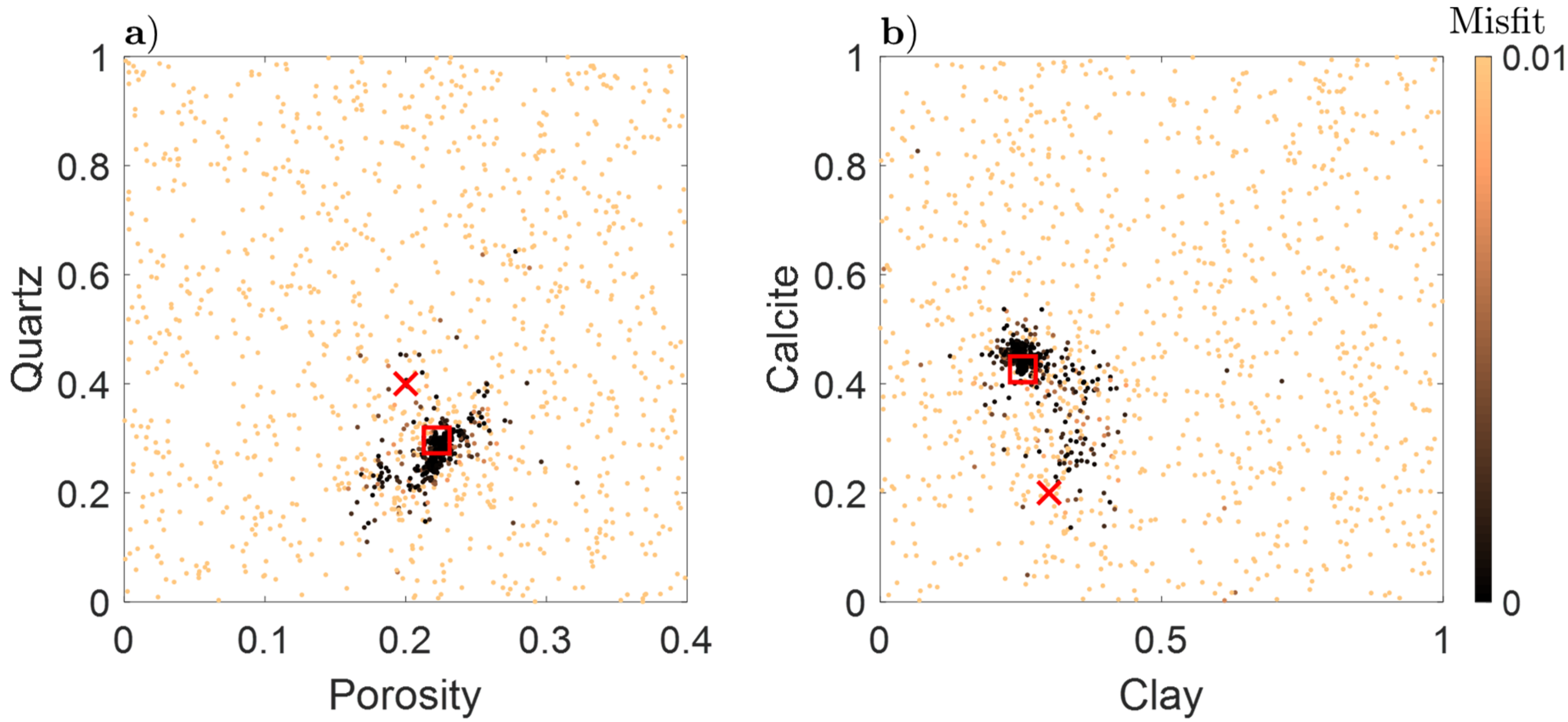
- 6 unknowns: porosity (Ø) + 4 minerals (V_q, V_{cl}, V_{ca}, $\cancel{V_{co}}$) + 2 fluids ($\cancel{S_w}$, S_{co2}) + pressure



Data: $(V_\mathrm{P}, V_\mathrm{S}, \rho)$

Rock physics interpretation

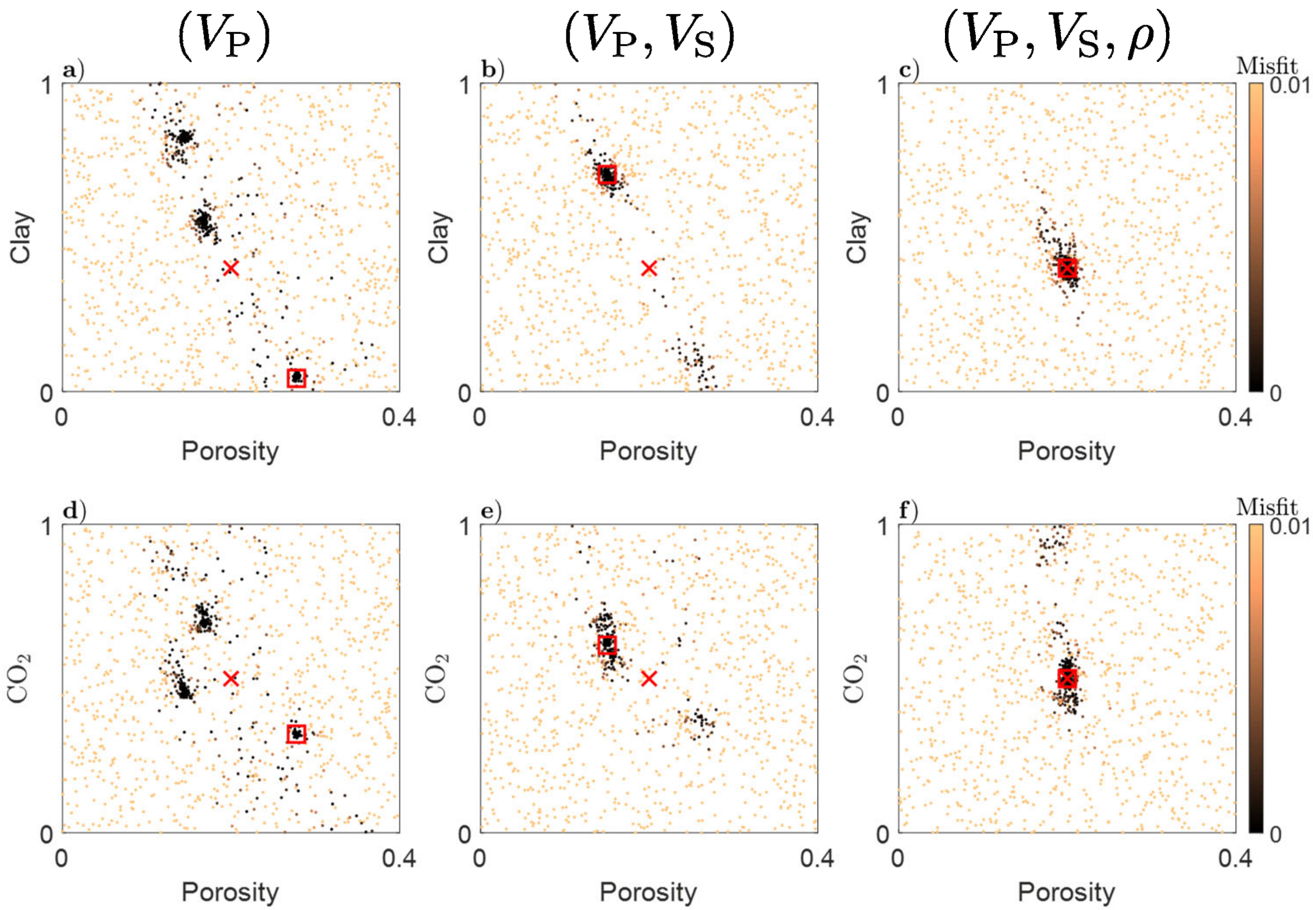
- 4 unknowns: porosity (Ø) + 4 minerals (V_q, V_{cl}, V_{ca}, ~~V_{co}~~) + 1 fluid (~~S_w~~)



Data: $(V_\mathrm{P}, V_\mathrm{S}, \rho)$

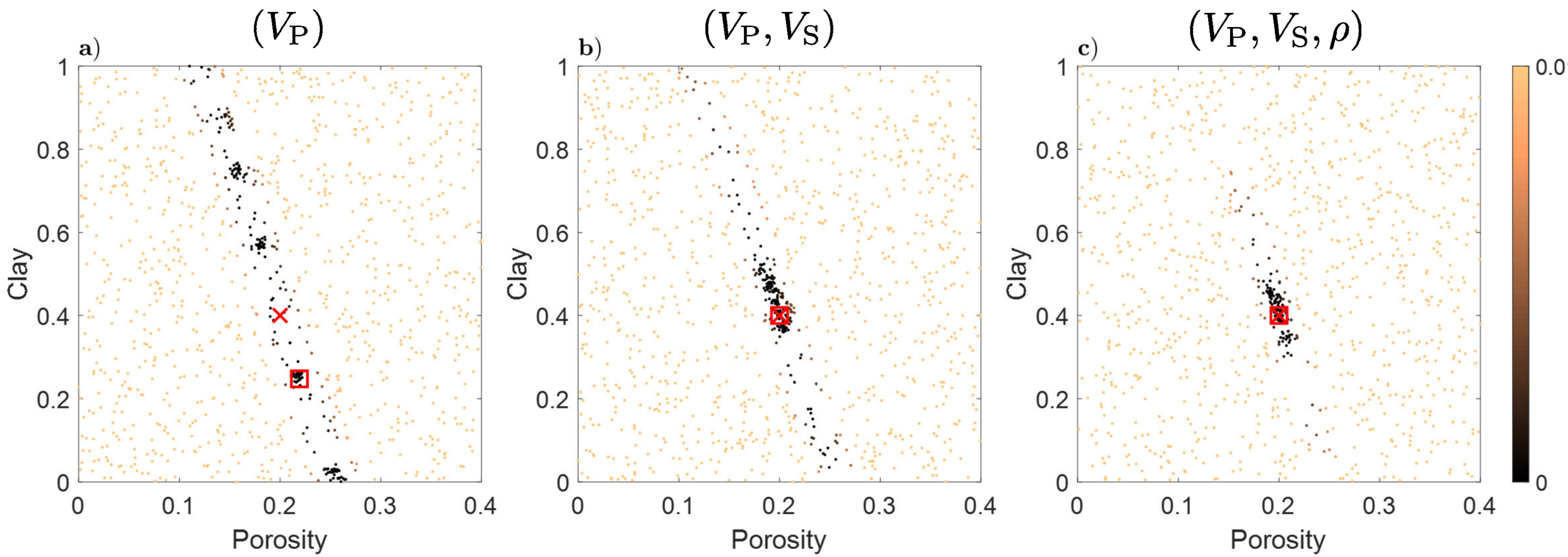
Rock physics interpretation

- 3 unknowns: porosity (Ø) + 2 minerals ($\cancel{V_q}$, V_{cl}) + 2 fluids ($\cancel{S_w}$, S_{co2})



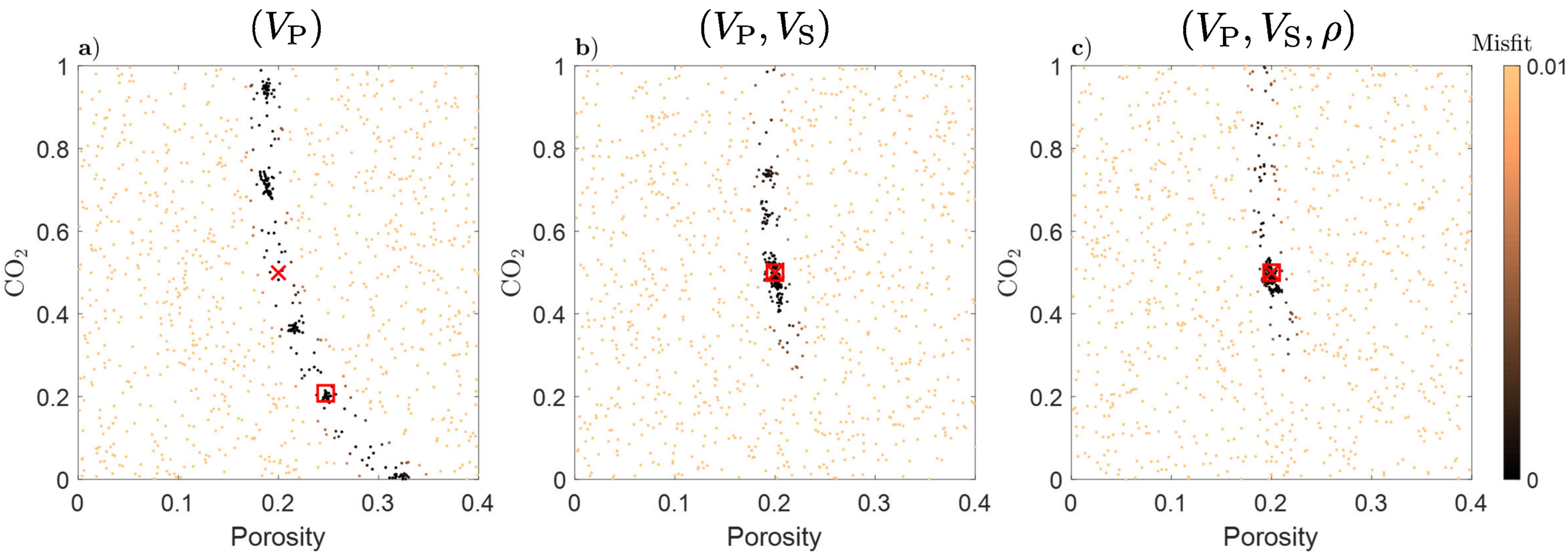
Rock physics interpretation

- 2 unknowns: porosity (Ø) + 2 minerals ($\cancel{V_q}$, V_{cl}) + 1 fluid ($\cancel{S_w}$)



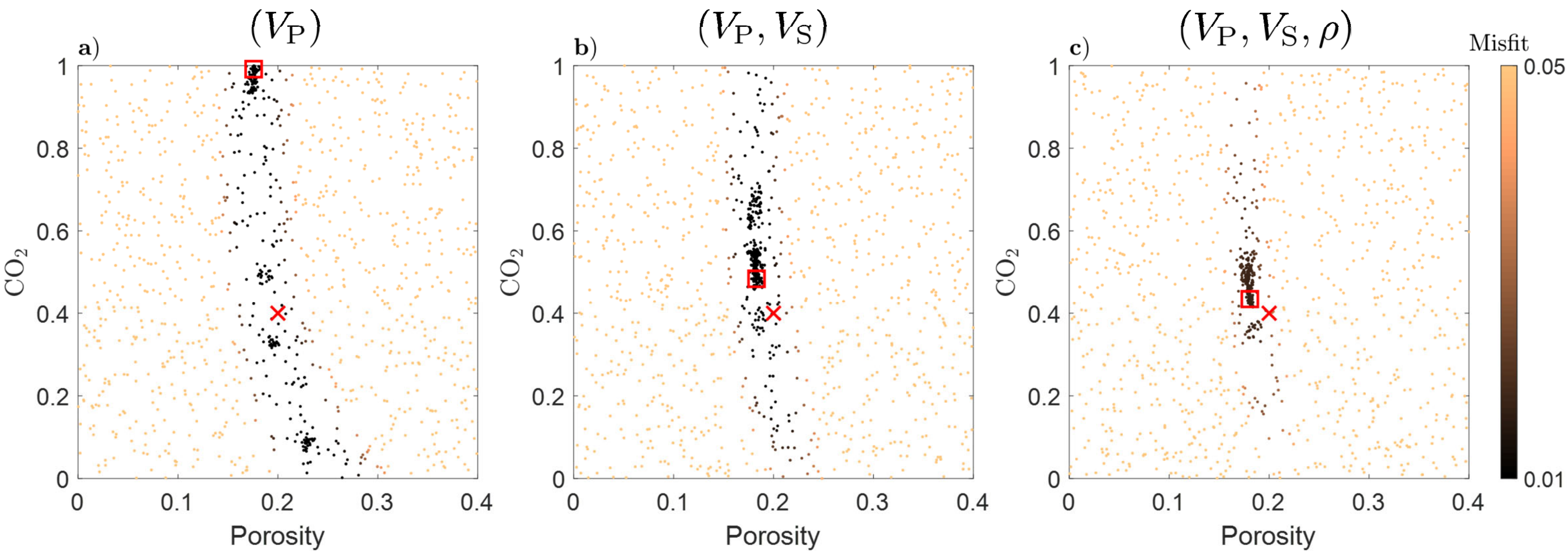
Rock physics interpretation

- 2 unknowns: porosity (Ø) + 1 mineral ($\cancel{V_q}$) + 2 fluids ($\cancel{S_w}$, S_{co2})



Rock physics interpretation

Add 5% error to Vp, Vs, and 10% error to density



Rock physics interpretation

What we learn from the sensitivity study:

1. Estimation of rock physics properties is very difficult if the number of parameters is larger than the number of data, because we randomly search a model space with infinitely many solutions.

2. The estimation is very accurate as soon as the system is not underdetermined.

3. Including shear velocity and density as input data can largely reduce the uncertainty in rock physics interpretation (a motivation to choose elastic inversion over acoustic inversion)

Summary

- We present a rock physics workflow to convert reservoir properties to seismic attributes at the CaMI FRS.
- The rock physics model is used to construct the shallow section of velocity and density logs. The result shows a good agreement with the local geology.
- To estimate rock physics properties from seismic attributes, It is best to include enough input data or focus on limited solid and fluid phases by making appropriate assumptions on the others.

Acknowledgments

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