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Rock physics analysis of CaMI.FRS well-log data

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Summary

We present a rock physics workflow based on the soft-sand model to convert reservoir properties (e.g., porosity, lithology, fluid saturation, and pressure) to seismic elastic attributes (e.g., velocity, density, and modulus) at the CaMI Field Research Station, Alberta, Canada. The soft-sand model is selected based on the geological setting of the study region and its visible fit to the well-log data. We use this model to predict the missing sections of velocity and density logs. The results show a good agreement with the local geology. We further carry out sensitivity studies using a directed Monte-Carlo method for the estimation of reservoir properties from seismic attributes. We illustrate that the rock physics inverse problem is highly underdetermined with non-unique solutions. To obtain accurate estimates, it is best to include enough input data or focus on limited solid and fluid phases by making appropriate assumptions on the others. Because the rock physics model used in the study is validated using well data, our analysis should be applicable to the regional area centered on the well.

Methods

1. Rock physics modeling

A significant number of rock physics models have been developed, based on experimental data or physical theories or both, to relate the elastic properties of rock to porosity, mineralogy and pore fluid (Mavko et al., 2020). We consider a rock physics model based on the soft-sand model combined with Gassmann's equations and the density equation. In the soft sand model, Hertz-Mindlin equations are used to compute the bulk and shear moduli of the dry rock K_{HM} and G_{HM} at the critical porosity ϕ_c:

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

$$G_{\mathrm{HM}} = \frac{2+3f-v_0(1+3f)}{5(2-v_0)}\left[\frac{3n^2(1-\phi_c)^2 G_0^2}{2\pi^2(1-v_0)^2} P_{\mathrm{e}}\right]^{1/3}, \tag{2}$$

where G_0 and v_0 is the shear modulus and Poisson's ratio of the solid phase, which are calculated using the Voigt–Reuss–Hill average. n is the coordination number, f is the degree of adhesion between the grains, and P_e is the effective pressure. The dry rock moduli at a given porosity ϕ are estimated by interpolating the elastic moduli at zero porosity (solid phase) and at critical porosity using the modified Hashin-Shtrikman lower bounds:

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

$$G_{\mathrm{dry}} = \left(\frac{\phi/\phi_c}{G_{\mathrm{HM}}+\xi} + \frac{1-\phi/\phi_c}{G_0+\xi}\right)^{-1} - \xi \text{ , where } \xi = \frac{G_{\mathrm{HM}}}{6}\frac{9K_{\mathrm{HM}}+8G_{\mathrm{HM}}}{K_{\mathrm{HM}}+2G_{\mathrm{HM}}}. \quad (4)$$

With Gassmann's equations, the bulk and shear moduli of the saturated rock are

$$K_{\mathrm{sat}} = K_{\mathrm{dry}} + \frac{\left(1-K_{\mathrm{dry}}/K_0\right)^2}{\phi/K_f+(1-\phi)/K_0-K_{\mathrm{dry}}/K_0^2}, \quad G_{\mathrm{sat}} = G_{\mathrm{dry}}, \quad (5)$$

where K_f is the bulk modulus of the fluid phase calculated using the Brie's equation. The density of the saturated rock ρ is computed as a weighted average of the densities of mineral and fluid components. The velocities as functions of the elastic moduli and density are then

$$V_{\mathrm{P}} = \sqrt{\frac{K_{\mathrm{sat}}+\frac{4}{3}G_{\mathrm{sat}}}{\rho}}, \quad V_{\mathrm{S}} = \sqrt{\frac{G_{\mathrm{sat}}}{\rho}}. \quad (6)$$

2. Rock physics inversion

The inverse problem consists in the extraction of models (rock physics parameters) from input data (elastic attributes) and is formulated as

$$\mathbf{d} = f(\mathbf{m}), \quad (7)$$

where the model vector $\mathbf{m}$ comprises of six rock physics parameters: porosity, CO_2 saturation, effective pressure, and volume fractions of quartz, clay, and calcite; the data vector $\mathbf{d}$ comprises of velocities V_{P}, V_{S} and density ρ. The function f is the rock physics model. The optimization aims to minimize a scalar function describing the discrepancy between the observed data d_{obs} and calculated data $f(\boldsymbol{m})$ (by forward modeling):

$$\mathrm{E}(\mathbf{m}) = \frac{1}{2}\left[\left(\mathbf{d}_{\mathrm{obs}} - f(\mathbf{m})\right)^{\mathrm{T}}\left(\mathrm{d}_{\mathrm{obs}} - f(\mathbf{m})\right)\right]. \quad (8)$$

For the optimization method, we use the neighborhood algorithm (Sambridge, 1999), which makes use of the geometrical constructs known as Voronoi cells to derive the search in model space.

Results

1. Validation of the rock physics model

The CaMI Field Research Station (FRS) is located in Newell County, southwest of Brooks, Alberta. The injection of CO_2 at a shallow depth of approximately 300 meters is designed to simulate leakage of CO_2 from a deeper and larger CO_2 storage project (Lawton et al., 2019, Macquet et al., 2019). A comprehensive log suite was acquired at the injection well, including the V_{P}, V_{S} and ρ logs. The wireline logs were interpreted using Schlumberger's elemental log analysis (ELAN), providing the porosity and mineral composition logs as shown in Figure 1.

Using these logs as input in the rock physics model, the predicted velocity and density logs match closely the real one (Figure 2), with an average error of 3.4% for V_{P}, 5.5% for V_{S}, and 1% for ρ. The rock physics model is then used to construct the shallow section (0-223m) of V_{P}, V_{S}, and ρ

logs. The results are consistent with the stratigraphic succession at the well location, especially at the coal zone where the elastic properties are supposed to decrease significantly.

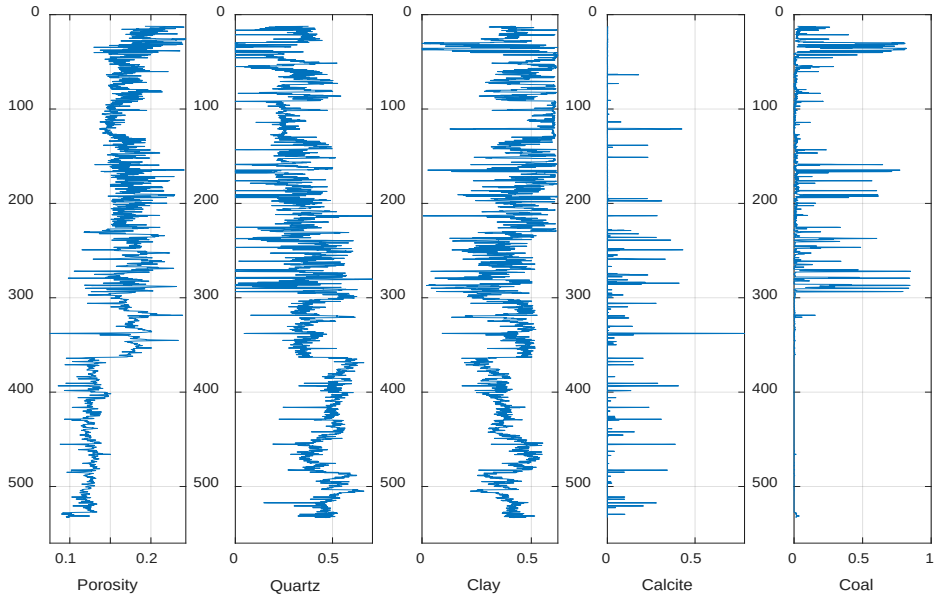

Figure 1: ELAN logs: porosity and volume fractions of quartz, clay, calcite, and coal.

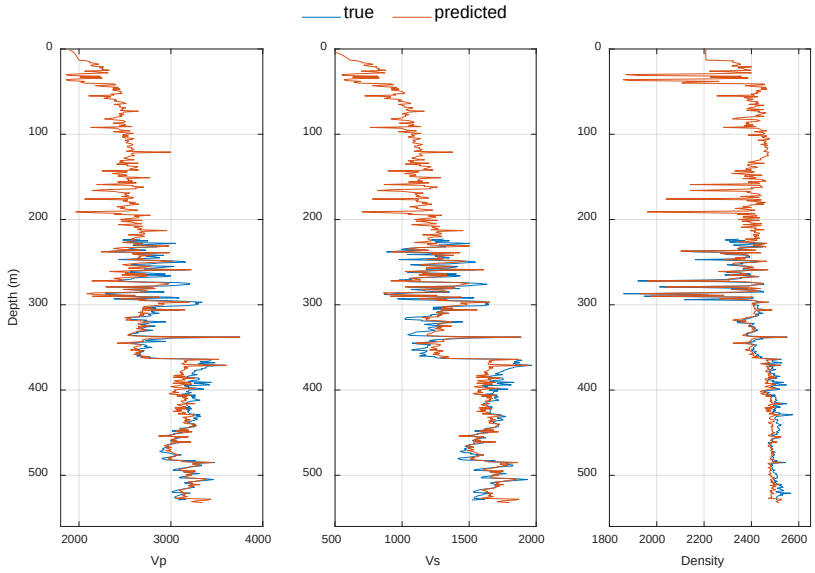

Figure 2: Predicted velocity and density logs versus real logs.

2. Inversion experiments

In the previous section, we built a rock physics model with 6 variables:

$$(V_{\mathrm{P}}, V_{\mathrm{S}}, \rho) = f\left(\phi, V_{\mathrm{qu}}, V_{\mathrm{cl}}, V_{\mathrm{ca}}, S_{\mathrm{co_2}}, P_{\mathrm{eff}}\right). \quad (9)$$

Based on this model, we conduct sensitivity analysis for the estimation of rock physics properties from seismic attributes. Different combinations of model unknowns are considered:

1) 6 unknowns: porosity, the volume fractions of quartz, clay, and calcite, CO_2 saturation, and effective pressure;
2) 4 unknowns: porosity and the volume fractions of quartz, clay, and calcite.
3) 3 unknowns: porosity and the volume fractions of quartz and clay.
4) 2 unknowns: porosity and the clay volume.
5) 2 unknowns: porosity and the CO_2 saturation.

The data are computed with the same algorithm (i.e., the rock physics model) for observed and computed data in inversion. We first run tests from case 1 to case 5 with the exact input data. We then repeat case 5 adding noise to the data. We find:

a) If the number of model parameters is larger than the number of data, the inversion system is underdetermined with non-unique solutions. As a result, none of the model unknowns can be reliably estimated (Figure 3).
b) The estimation is very accurate as soon as the system is not underdetermined, but even so it is recommended to include more data to improve the convergence.
c) Compared to using only V_{P}, including imperfect V_{S} and ρ data can still largely reduce the uncertainty in rock physics interpretation (Figure 4).

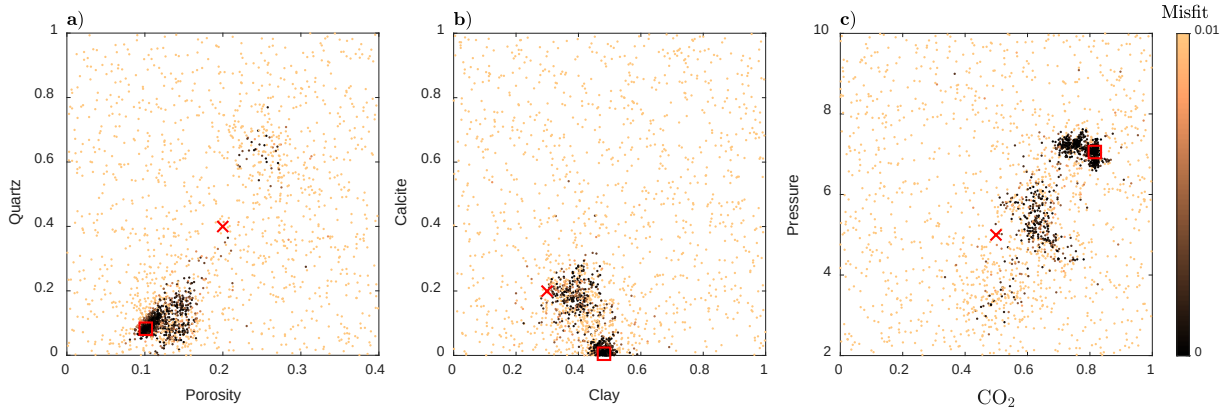

Figure 3: Inversion of 6 variables from (V_{P}, V_{S}, ρ). Red cross: true model. Red square: inverted model.

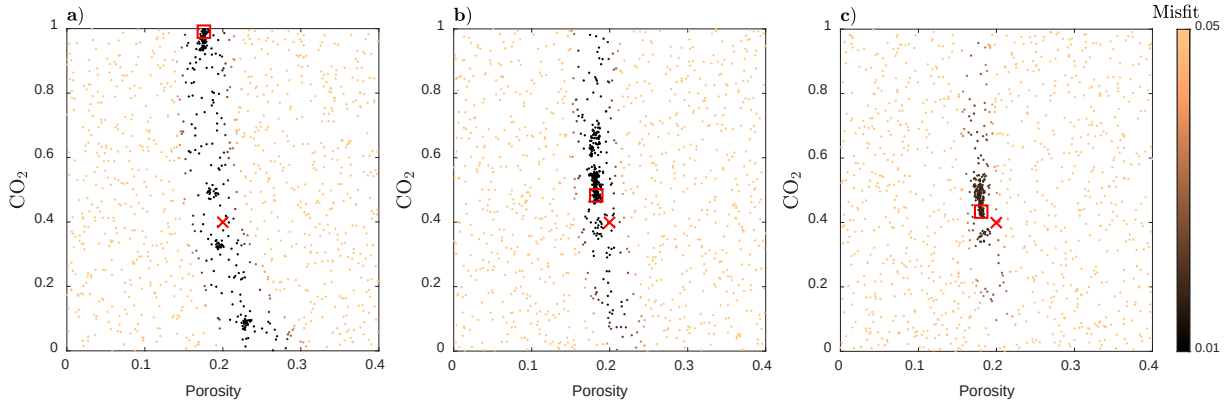

Figure 4: Inversion of porosity and CO_2 saturation from (a) V_P, (b) (V_P, V_S), and (c) (V_P, V_S, ρ). 5% error and 10% error are added V_S and ρ, respectively.

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